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Electrical Power Distribution Systems

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Tata McGraw Hill Education Private Limited

NEW DELHI

McGraw-Hill Offices

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Kuala Lumpur Lisbon London Madrid Mexico City Milan Montreal
San Juan Santiago Singapore Sydney Tokyo Toronto

Tata McGraw Hill

Published by Tata McGraw Hill Education Private Limited,
7 West Patel Nagar, New Delhi 110 008

ISBN (13): 978-0-07-015141-3
ISBN (10): 0-07-15141-5

Managing Director: *Ajay Shukla*
Head—Higher Education Publishing: *Vibha Mahajan*
Manager—Sponsoring: *Shalini Jha*
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Controller—Production: *Rajender P Ghansela*
General Manager—Production: *B L Dogra*

Typeset at Text-o-Graphics, B1/56 Arawali Apartment, Sector 34, Noida 201301 and printed at
Pashupati Printers Pvt. Ltd., 1/429/16, Gali No. 1, Friends Colony, Industrial Area, G.T. Road,
Shahdara, Delhi 110 095

Cover Printer: Rashtriya Printers

RCLYCRQFRQQQX

Dedicated to

My Wife, Late V Narasamma

The Friend and guide for 38 years

Left me Alone in 2005

Contents

Preface

Electrical distribution is one of the most important wings in Electrical Power Industry but is given less importance. For most efficient, reliable and uninterrupted, electrical power supply, proper planning and protection in distribution of power is important. Conventionally, this topic is treated as one or two chapters in Electrical Power System courses and only few universities offer it as a separate course.

About twenty years back, when it was introduced as an elective course for PG courses and later for undergraduate courses, there was no proper book that could be referred by either the students or the teachers. Reference was mainly made to the IEEE Std.. 141 of 1976 (Electrical Power Distribution for Industrial Practices) and also to Electrical Power Distribution Engineering by Turan Gonen which mainly dealt with the practices and systems adopted in US and the American continent. These procedures adopted and other technical aspects were quite different and are neither seen or practiced in India.

Electrical distribution mainly deals with transportation of electrical energy from main transmission stations to the customer premises and deals with both low voltages (less than 1000 V) and medium voltage (1000 V to less 33,000 V) of three-phase dc and other special systems like 1500 V or 3000 V dc and 25 kV ac traction systems.

The topics dealt with in this book are

(a) Distribution system : voltages for primary and secondary distribution
(b) Nature of loads and load modelling
(c) Overhead lines and cables
(d) Voltage drop and power loss in lines and feeders
(e) Reactive power compensation and capacitor applications
(f) Substation equipment, grounding and substation automation
(g) System faults and protection,
(h) Metering and tariffs
(i) Voltage control, system planning and automation

All the topics included in Electrical Power Distribution courses are dealt with and a few additional topics added to have a comprehensive idea over Electrical Power Distribution. This book will also help the electrical engineers working in power distribution as well as industrial distribution to improve the quality of power supply. A few worked examples, review questions, multiple choice and short questions are added at the end of each chapter to help the student have better understanding of the topics.

The book is divided into 12 chapters. **Chapter 1** briefly introduces supply systems and distribution practices. **Chapter 2** discusses load characteristics and load modeling. **Chapters 3 and 4** explain overhead lines and cables, and distribution feeders respectively. **Chapter 5** deals with primary and secondary distribution networks. Voltage drop and power loss calculations are explained in **Chapter 6**.

Chapter 7 discusses reactive power compensation and applications of capacitors, while equipment, loading and grounding of substations is dealt with in **Chapter 8**. **Chapter 9** is on faults and over-voltages in distribution systems. **Chapter 10** explains the various types of protection used in devices. **Chapter 11** discusses metering, instrumentation and tariffs. Finally, **Chapter 12** deals with system planning and automation in voltage control.

The Web supplements can be accessed at

http:/www.mhhe.com/kamaraju/epds and contains

Instructor Resources:	Answers of selected problems, Model syllabus
Student Resources:	Interactive quiz, Web links for further reading

Sincere thanks are also due to the reviewers who took out time to review the book. Their names are given below.

Mairaj–ud–din Mufti	*NIT Srinagar, Jammu and Kashmir*
Zakir Hussain	*NIT Hamirpur, Himachal Pradesn*
Saradindu Ghosh	*NIT Rourkela, Orissa*
Abhi Mohapatra	*College of Engineering and Technology Bhubaneswar, Orissa*
Ninad Totre	*Lokmanya Tilak College of Engineering Navi Mumbai, Maharashtra*
L Rajshekhar Goud	*G Pulla Reddy Engineering College Kurnool, Andhra Pradesh*
S S Tulasi Ram	*JNTU College of Engineering Kakinada, Andhra Pradesh*
K Lakshmi	*K S Rangasamy College of Technology Tiruchengode, Tamil Nadu*
P A Balakrishnan	*Mahalingam College of Engineering, Anna University, Pollachi, Tamil Nadu*
A Nirmal Kumar	*Bannari Amman Institute of Technology, Anna University, Coimbatore, Tamil Nadu*

The author would like to express his sincere thanks to Tata McGraw Hill Education Private Limited. who readily agreed to publish the book.

The author is grateful to his students and former colleagues who encouraged him to take up this work.

Hyderabad

May 2009 **V Kamaraju**

List of Symbols

A	:	area
A, B, C	:	3 ph. Phase Sequance
C	:	Capacitance
C. B.	:	Circuit Breaker
C.T.	:	Current Transformer
C	:	Contribution factor
C_f	:	Coincidance factor
D	:	Diameter, Spacing
D	:	Load density KVA / km^2
F	:	Farad, Fault Position
G.I.S	:	Gas Insulated System or substation
I	:	Current
I_l	:	Line Current
K	:	Relay Constant
L	:	Inductance
N	:	Neutral of 3-ph system
O	:	Origin
P	:	Power (kW or MW)
P.T	:	Potential Transformer
Q	:	Reactive power KVAR or RKVA
S	:	Apparent power KVA or MVA
S.S.	:	Substation
T	:	Temperature, time interval
V	:	Voltage
Vb	:	Base Voltage
Vr	:	Receiving end voltage
Vs	:	Sending end voltage
V.D	:	per unit voltage drop, regulation
% V.D.	:	percentage voltage drop or regulation
X	:	Total reactance
Z	:	Total impedance
Z_f	:	Fault impedance
Z_g	:	Ground impedance
Z_l	:	Line impedance
Z_t	:	Transformer impedance
a	:	area
a	:	Symmetrical component operator = $1\angle 120^\circ$
$1, a, a^2$	:	Symmetrical component operators
f	:	frequency
g	:	ground point
i	;	instantanous current
i_l	:	current per unit length
j	:	complex operator $\sqrt{-1}$ or $1\angle 90^\circ$
k	:	regulation constant or regulation factor
l	:	length, length of a line
p.f	:	power factor
p.u	:	per unit
r	:	radius, resistance / unit length
r, θ	:	polar co-ordinates
t	:	time
x	:	reactance / unit length
x,y,z	:	cartisian co-ordinates
z	:	impedance / unit length
α	:	temperature coe. of resistance
δ	:	phase angle difference between V_s and V_r
ε	:	permittility
ε_0	:	absolute permittility $\left(\frac{1}{36\pi}\times 10^{-9}\right)$ F/m
ϕ	:	impedance angle
μ	:	micro, permiability
μ_0	:	absolute permiability = $4\pi \times 10^{-7}$ H/m
ω	:	angular frequency = $2\pi f$
Δf	:	frequency deviation
Δ	:	incremental elemental value
Δ	:	Delta Connection in 3 Ph. System.

One

An outline of Electrical Power Supply Systems and distribution systems is presented in this chapter. Different types of power supply practice of dc and ac systems are explained and the scope of the book is indicated.

Supply System and Distribution Practices

Introduction

Electrical energy is one form of energy which is generated, transported and utilized most in modern days. Unlike other forms of energy it is not available naturally. The most easy form of conversion is form mechanical energy to electrical energy and vice-versa. The other forms of conversion like solar to electrical, chemical energy to electrical etc. is less efficient and more tedious. Most of the electrical energy is generated where the fuel or resources are available, i.e., near coal mines or water falls and reservoirs. Modern power stations are of large sizes ranging from 500 MW to 2000 MW or more, each generator size being 100 to 500 MW. The present generation in our country is more than 100 GW.

The power generated is to be transported from the generating stations through transmission lines over long distances. Typical transmission voltages range from 220 kV to 765 kV or more (1100 kV in USA, Russia etc.) and is distributed to various utilities through sub-transmission and distribution network, usually the transmission network, inter-connected and forms a GRID through the substations each local or bulk load is connected to a substation and the power is transmitted. Most of transmission systems used are 3-phase ac 50 or 60 Hz. D.C Transmission systems are coming up as inter connecting networks.

A typical subtranmission and distribution system is shown in fig 1.1.

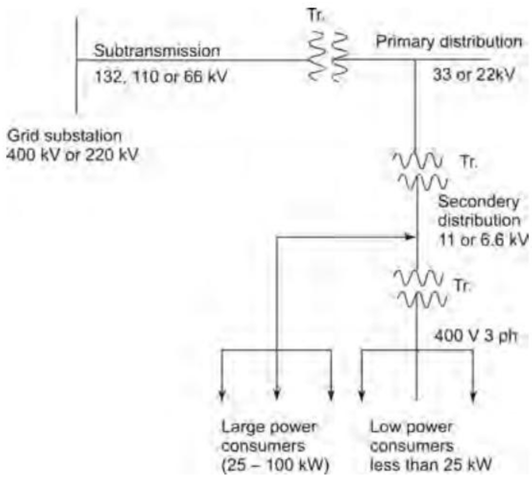


Fig. 1.1 *Typical subtransmission and distribution network*

The electrical distribution network or system will be the supply system to the electrical power consumers of the following:

(a) Smaller requirement typically less than about 25 kVA (20 kW) through single phase 230 V or 3-phase 400 V.

These loads may be domestic agricultural, commercial etc.

(b) Larger power requirement more then 20 kW (25 kVA) supplied through 3ph systems.

Example: Industrial loads, commercial loads, special loads like electric traction, chemical plants, etc.

Electrical utilities or loads may be in general, grouped as

(i) *Mechanical loads*: Motor loads and drives

(ii) *Chemical utilities:* metal extraction through electrolysis process, electroplating, etc,

(iii) *Heating loads*: furnaces etc,

(iv) Lighting and illumination

(v) Power converters and electronics,

The supply system should ensure that the voltage level to be maintained at ±6% of the declared voltage level [{i. e.} 400 V, 3Ph/230 V.1Ph ±6%]

Electrical power is the product of voltage (V)currents (I)and power factors i.e., $P = VI \cos\theta$. Since the current is carried by conductors of finite size and a voltage drop occurs in the conductors due to its resistance and reactance (in ac),the current carried is limited. Typically the conductors are rated for current ranging from 100 A to less than 1000 A. in order to transmit a given power, larger voltages are needed for higher powers.

Electrical power networks, today are quite complex and very large in size. They are spread over wide areas. In India every state has its own power network. States are grouped into regions and there are five regional grids, Viz., north, south, east, west and north-east interconnecting the states and the entire country.

Typical transmission voltage in the country are 220 kV, 400 kV and 750 (765) kV ac and ±200 kV D.C. to ±500 kV D.C. The subtransmission and primary distribution voltages are 132 kV, 110 kV, 66 kV, 33 kV. etc.

1.1 SUPPLY SYSTEMS

The electrical transmission system in India is 3-phase ac system of 50 Hz and as such the distribution systems receive power from a 3-phase system only. But depending on power requirement and ratings, the loads can be single phase or 3-phase. As such in most cases, a 3-phase 4-wire system with neutral wire is adopted so that it can cater to both single phase as well as 3-phase loads (shown in Fig 1.2)

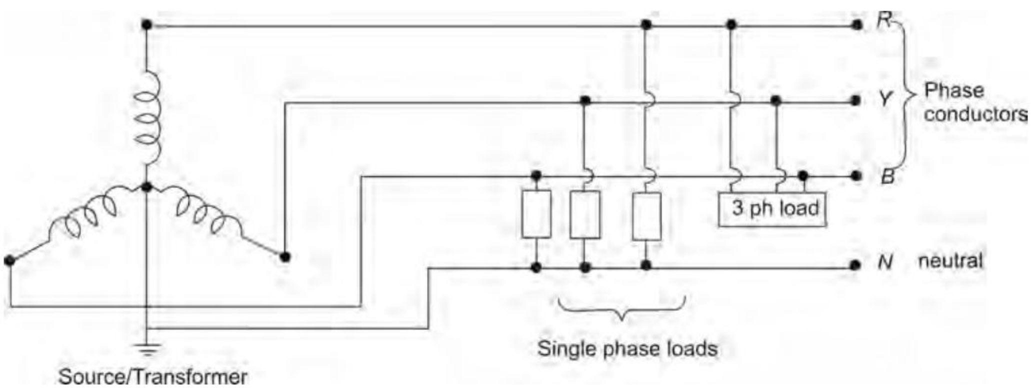


Fig. 1.2 *3-Phase four-wire distribution system*

Any supply system adopted should have minimum losses, good efficiency easyness for adoption and less maintainance. Hence a review of the different systems and their relative advantages is presented for comparison. In all the cases, the power transmitted, length of the line taken and maximum voltage to the ground are the same.

1.1.1 Distribution Supply Systems

1. *2-wire dc System*

Voltage between the conductors = 2 V_m, i.e., midpoint earthed

$$\text{Current } I_1 = \frac{P}{2V}, P = \text{Power transmitted}$$

$$\therefore \quad \text{line losses} = 2I_1^2 R = \frac{P^2 R}{2V_m^2} \quad \text{.... (1.1)}$$

where R = conductor resistance

2. *Single-phase ac*

Maximum voltage = V_m

$$V_{rms} = \frac{V_m}{\sqrt{2}}$$

$$\text{Power factor} = \cos\theta$$

$$\text{Current } I_2 = \frac{P}{V_{rms}\cos\theta} = \frac{\sqrt{2}P}{V^2\cos\theta}$$

$$\text{Line losses} = 2I_2^2 R_3 = \frac{4P^2 R_2}{V^2 \cos_2\theta} \quad \text{.... (1.2)}$$

3. *Single-phase ac: Midpoint grounded*

Maximum voltage = 2 V_m

$$V_{rms} = \frac{2V_m}{\sqrt{2}}$$

$$\text{Power factor} = \cos\theta$$

$$\text{Current} = I_3 = \frac{P}{2V_{rms}\cos\theta} = \frac{P}{\sqrt{2}V_m\cos\theta}$$

$$\text{Line losses} = 2I_3^2 R_3 = \frac{P^2 R_2}{2V_m^2\cos^2\theta} \quad \text{.... (1.3)}$$

4. *3-phase system ac: Neutral at earth potential (zero)*

$$\text{Phase voltage} = \frac{V_m}{\sqrt{2}}$$

$$\text{Line voltage} = \frac{3V_m}{\sqrt{2}}$$

$$\text{Current } I_4 = \frac{P}{\sqrt{3}\dfrac{\sqrt{3}V_m}{\sqrt{2}}\cos\theta} = \frac{\sqrt{2}P}{3V_m\cos\theta}$$

$$\text{Line losses } = 3I_4^2 R_4 = 3\left(\frac{\sqrt{2}P}{3V_m\cos\theta}\right)^2 \cdot R_4 = \frac{2P^2 R_4}{3V_m^2\cos^2\theta} \qquad \text{.... (1.4)}$$

Assuming equal line losses in all the three cases

$$\frac{P^2 R_1}{2V^2} = \frac{4P^2 R_2}{V_m^2\cos^2\theta} = \frac{P^2 R_3}{2V_m^2\cos^2\theta} = \frac{2P^2 R_4}{3V_m^2\cos^2\theta} \qquad \text{.... (1.5)}$$

i.e.,
$$R_1 = \frac{8R_2}{\cos^2\theta} = \frac{R_3}{\cos^2\theta} = \frac{4R_4}{3\cos^2\theta} \qquad \text{.... (1.6)}$$

Area of cross section of conductor is inversely proportional to the resistance.

Hence, the conductor cross sections are in the ratio

$$a_1 : a_2 : a_3 : a_4 = 1 : \frac{8}{\cos^2\theta} : \frac{1}{\cos^2\theta} : \frac{4}{3\cos^2\theta} \qquad \text{.... (1.7)}$$

Volume of conductor required (in case of 3 ph it is three and for other it is two conductors)

$$v_1 : v_2 : v_3 : v_4 = 1 : \frac{8}{\cos^2\theta} : \frac{1}{\cos^2\theta} : \frac{2}{\cos^2\theta}$$

It is obvious that 2 wire dc system is superior and hence it is now used for HVDC transmission for long distances. To cater for different categories of loads 3ph 3-wire or 4 wire system ac is adopted. Three-phase 3-wire system is used for transmission and primary distribution where as 4 wire system is used for LT applications, 400 V 3Ph/230 V single phase).

The single-phase system with midpoint earthed is nowadays used for rural distribution and agricultural loads, etc., tapped from 3-phase 11kV distribution through $\dfrac{\frac{11}{\sqrt{3}}kV}{230-0-230V}$ transformer having power rating from 10 kVA to 25 kVA. The 11 kV side is single wire with ground return.

In case of electrical transport systems such as for tram or electric buses in cities and urban areas usually single-phase single-wire distribution is used. Typical supply voltages maybe 500 V to 1500 V dc single-wire with ground return (tram-cars) and 2 wire dc system for electric buses or cars. Electric traction nowadays adopts 3000 V dc for short distance and 25 kV ac single wire for long distances.

1.2 THE DISTRIBUTION SYSTEMS

For large consumers, the polyphase (3Ph) is essential for motor and other loads. Hence it is a 3 wire system and is usually nearly balanced. Most of the loads greater than 10 kVA will be supplied through 3 ph. 3-wire system. For 10 to 100 kVA it may be 400 V, 3 Ph. system and for larger loads, 3.3 kV, 6.6 kV or 11 kV. Nowadays mostly 11 kV system is adopted and 3.3 kV, 6.6 kV systems are out of use.

But small consumers require single phase system. These are primarily domestic loads, small commercial concerns, lighting loads and rural agricultural loads. The supply system adopted is 3-phase 4-wire system (400–415V) for 3ph with 230–240 V single phase, connected between any phase and neutral as shown in Fig. 1.2.

1.3 ORGANISATION AND CONTENTS OF THE BOOK

This book is mainly intended to deal with the power distribution aspects of electrical energy. Power distribution engineering is a vast and special topic and is not given much importance in electrical engineering. The consumer is the most important person and he should be provided with 'UNINTERRUPTED' and 'CONTINUOUS' power supply, all the 24 hours in a day, 365 days in a year. This requires careful understanding of the supply systems, the voltage drop and power loss problems, faults and protection aspects, power control and alternate supply networks, tariff and metering, economics and planning. Expansion for future requirements should also be clear and known to the distribution engineers and planners.

The contents of this book are arranged as follows. Chapter 2 deals with load characteristics modeling and distribution planning. Chapter 3 explains overhead lines and cables, Chapter 4, primary and secondary distribution systems, Chapter 5, substation equipment and design Chapter 7, reactive power compensation and application of capacitors. Chapter 8 is on substation equipment and location. Chapter 9 deals with faults and over voltages, Chatper 10 on protection, Chapter 11 is on metering and tariffs and Chapter 12 is on voltage control and distribution automation and planning.

The book is intended to give a comprehensive idea of electrical distribution to both students as well as for practicing engineers. Review questions, multiple choice, other short questions and examples are given at the end of each chapter. The references for further reading are given at the end of the book.

Summary

The electrical transmission and distribution network and its arrangement and practices are outlined in this chapter. Different conductor arrangements for dc and ac power supplies are given.

Keywords

Transmission and subtransmission
Primary and secondary distribution
Supply systems
dc systems
ac single and 3-phase system

Review Questions

(1) What is the difference between transmission and distribution system?

(2) What are the different types of electrical loads? Give examples.

(3) What are the different types of supply systems that are adopted for transmission of electric power? Give comparison

(4) Mention the standard voltages and systems adopted in India for distribution systems. Why is the 3Ph. 4 wire system preferred?

(5) What is the advantage of adopting high-voltage $\left(\frac{11}{\sqrt{3}} kV\right)$ single-phase distribution system for rural and agricultural loads?

(6) Why is distribution system not adopted

Multiple Choice Questions

1. The common voltage adopted for low voltage electrical distribution is
   (a) 220 V dc (b) 230 V ac 1 Ph
   (c) 400 V 3 Ph 3-wire (d) 400 V3Ph 4-wire
2. For large power loads, distribution voltage is
   (a) 500 V dc (b) 400 V 3 Ph ac
   (c) 11 kV 3-Ph 3-wire ac. (d) 11 kV 3-Ph 4wire ac.
3. The most efficient transmission system for economic adoptability is
   (a) dc 2 wire (b) dc 3 wire
   (c) single-phase ac (d) 3 Ph ac
4. Single-phase ac with mid point earthing is used for
   (a) bulk load distribution (b) domestic loads
   (c) rural and agricultural loads (d) industrial loads
5. The usual voltage level adopted for high-voltage distribution network in India is
   (a) 132 kV (b) 11 kV
   (c) 16 kV (d) 400 V

6. In ac systems, the ground or earth is connected to
   (a) neutral (b) one of the phases
   (c) mid point (d) none of the above
7. For tram cars and other electrical buses, the electrical supply used is
   (a) 230 V or 400 V single phase ac
   (b) 500V to 1500V dc single wire or two wire
   (c) 25 kV, single-phase single wire with ground return
   (d) none of the above.
8. In railways and other long distance transport system, the voltage used is
   (a) 25 kV, single phase ac (b) 25 kV, 3 Ph ac
   (c) 500 to 1500 V dc (d) none of the above.

Fill in the blanks

9. 400 V, 3 Ph distribution is ______________distribution?
10. Low voltage single phase distribution is used for ______________.
11. The disadvantage of using dc 2-wire or 3-wire distribution system is ______________.
12. The aim of good and efficient distribution system is ______________.

Answers

1. d	2. c	3. d	4. c
5. b	6. a	7. b	8. a

9. low voltage 10. Rural loads and agricultural single phase loads
11. Large power and 3-Ph loads cannot be catered
12. Energy efficient, uninterrupted supply system.

Two

Devices that take or consume electrical power are known as "LOADS". The nature, duration, variations of loads or electric power, its characteristics and how they are modeled for analysis purpose is explained in this chapter along with suitable examples. Definitions of a few technical terms are also given.

Load Characteristics and Load Modelling

Introduction

Electrical energy consumers and utilization organizations like industries etc., require energy for different purposes and their requirements will be at different times. In order to estimate the total requirement of power demand and energy, a few qualities and characteristics relating to the requirements are to be defined.

2.1 DEFINITIONS

Load Electrical power needed in kW or kVA

Demand The power requirement (in kVA or kW) at the load averaged over a specified interval (15 min or 30 min). Sometimes it is given in amperes at a specified voltage level.

Demand Intervals The time interval specified for demand (D_t), usually 15 min or 30 min. This is obtained from daily demand curves or load duration curves.

Maximum Demand The maximum load (or the greatest if a unit or group of units) that occurred in a period of time as specified. This can be daily, weekly, seasonal or on annual basis (for billing purpose in India it is monthly and in kVA).

Demand Factor The ratio of maximum demand to the total load connected to the system

Connected Load The sum total of the continuous rating of all the apparatus, equipment, etc., Connected to the system.

Utilization Factor The ratio of maximum demand to the rated capacity of the system.

Load Factor The ratio of average load in given interval of time to the peak during that interval.

Annual Load Factor The ratio of total energy supplied in an year to annual peek load multiplied by 8760.

Diversity Factor (D_f) The ratio of sum of the individual maximum demands of various sub-divisions of the system to the maximum demand of the entire or complete system.

Coincident Maximum Demand (D_g) Any demand that occurs simultaneously with any other demand and also the sum of any set of coincident demands.

Coincidence factor (C_f) This is usually referred to a group of consumers or loads. It is defined as the ratio of coincident maximum demand D_g to sum total of maximum demands of individual or group of loads.

Generally, it is taken as the reciprocal of the diversity factor.

Load Diversity The difference between the sum of peaks of two or more individual loads and the peak of combined load.

$$\text{Load diversity} = \Sigma D_i - D_g \tag{2.1}$$

$$D_i = \text{individual maximum demand}$$

$$D_g = \text{coincident maximum demand}$$

Contribution Factor This is a factor that is usually referred in distribution systems regarding the importance of weighted effect of a particular load.

If C_1, C_2 … C_n are the contribution factors of each of the n individual loads and D_1, D_2, D_3 .... D_n are their maximum demands.

D_g = coincident maximum demand is taken as

$$D_g = C_1D_1 + C_2D_2 + \text{............}C_nD_n = \sum_{i=1}^{n} C_iD_i \quad \text{.... (2.2)}$$

$$\text{Hence } c_f = \text{coincidence factor is } = \frac{\sum C_iD_i}{\sum D_i} \quad \text{.... (2.3)}$$

The contribution factor $C_i = C_f$ when all the demands equally affect or influence the maximum demand.

Loss Factors This is the ratio of average power loss in the system to power loss during peak load period and referred to the variable power losses, i.e., copper losses or power loss in conductors or windings but not to no load losses in transformers, etc.

2.2 LOADS AND LOAD CHARACTERISTICS

A load or power requirement (also kVA) of a consumer varies widely. But in general the consumers can be grouped into a few categories as their needs and demands are the same.

A broad classification of loads are

(i) Domestic and residential loads
(ii) Only lighting loads (such as for street lights etc.)

(iii) Commercial loads (shops, business establishments, hospitals)
(iv) Industrial loads
(v) Agricultural loads and other rural loads

All these loads will have peak demands at different times and for different durations. Industrial and commercial loads may have two peak load periods. Agricultural loads are seasonal and vary very differently.

Lighting loads such as street lighting etc. may have almost zero demand during day time and constant load during 10 p.m. to 6 a.m. and a slightly higher demand between 6p.m. to 10 p.m.

Another classification of electrical loads is the billing categories used by the electrical distribution authorities or State electricity boards. This includes categories such as residential and domestic, industrial, commercial, rural, HT consumers and others. A better approach to the classification of loads is to divide them into individual load components. The components of a particular load are individually defined and modeled. All the components put together form the composite load and can be defined as a 'LOAD WINDOW' as per IEEE definition. See Section 2.6.

System Power Factor In ac systems, kVA demand is more appropriate than kW and load power factor is of importance. Typical p.f of residential, commercial and Industrial loads are as follows.

Fluorescent lamps : 0.6
Arc lamps and neon signs : 0.4 to 0.7
Fans and small motors : 0.5 to 0.8
Electronic gadgets : 0.6 to 0.8
Domestic appliance (like washing-machines, vacuum cleaners etc.) : 0.6 to 0.7
F.H.p. motors (1 kW or less) : 0.4 to 0.75
Water pumps (Large size $\geq$ 5 h.p) : 0.65 to 0.8
Chemical industries : 0.70 to 0.85

2.2.1 Domestic and Residential Loads

The important part in the distribution system is domestic and residential loads as they are highly variable and erotic. These consist of lighting loads, domestic appliances such as water heaters, washing machines, grinders and mixes, TV and electronic gadgets etc. The duration of these loads will be few minutes to few hours in a day. The power factor of these loads in less and may vary between 0.5 to 0.7. In residential flats and bigger buildings, the diversity between each residence will be less typically between 1.1 to 1.15. The load factor for domestic loads will be usually 0.5 to 0.6.

2.2.2 Industrial Loads

Industrial loads are of greater importance in distribution systems with demand factor 0.7 to 0.8 and load factor 0.6 to 0.7. For heavy industries demand factor may be 0.9 and load factor 0.7 to 0.8

Typical power range for various loads

Cottage and small-scale industries: 3 to 20 kW.

Medium industries (like rice mills, oil mills, workshops, etc.) : 25 to 100 kW

Large industries connected to distribution feeders (33 kV and below): 100 to 500 kW.

2.2.3 Water supply and Agricultural Loads

Most of the panchayats, small and medium municipalities have protected water system which use pumping stations. They normally operate in off peak time and use water pumps ranging from 10 h.p to 50 h.p or more, depending on the population and area.

2.2.4 Agricultural and Irrigation Loads

Most of the rural irrigation in India depends on ground water pumping or lifting water from tanks or nearby canals. In most cases design and pump selection is very poor with efficiencies of the order of 25%. Single phase motors are used (up to 10 h.p.) for ground water level 15 m in depth or less with discharge of about 20 l/sec while multi stage submersible pumps with discharge of 800 to 1000 l/m may require motors of 15 to 20 h.p.

2.2.5 Sensitive and Important Loads

With computer applications in every area, computer loads and computer controlled process loads are often non-linear and sensitive. They require close tolerance limits for voltage and frequency (voltage limit ± 5% and frequency ± 0.5 Hz with unbalance and wave form distortion less than 3%. This requires special attention while providing the distribution of electric power.

2.3 LOAD CURVES AND LOAD-DURATION CURVES

The consumption of electrical power or energy by any utility varies from time to time in a day as well as during a week, month, season or year. For example in summer fans, AC units, coolers etc. are used but not during winter or cold season. Industries working during day time will consume only lighting load during night (10 pm to 6 am). Hence knowledge of variation of loads and their nature is essential for distribution planning. The load characteristics are usually presented as load curves and load duration curves.

2.3.1 Load Curves and Load-Duration Curves

(a) Load Curves The load (power requirement) of any concern or unit is tabulated as the amount of power required or consumed during a certain period in a day, week or a given season. Typical load data for suburban area is given in table 2.1. The same data is also presented as a graph between duration (time) and the demand or load during that period (Fig. 2.1)

(b) Load-Duration Curves This is a graph obtained from load curve showing the load in (kw) and duration over which it occurs in descending order of load magnitudes.

Table 2.1a: Load data on a typical feeder

Duration type of load (kW)	*0 to 6 AM*	*7 AM*	*8 AM*	*9 AM*	*10 to 1 PM*	*2 to 5 PM*	*6 PM*	*7 to 9 PM*	*10 PM*	*11 PM*	*0 HRS*
Lighting	100	-	-	-	-	-	50	100	100	100	100
Domestic	200	300	400	400	500	500	600	1000	800	600	200
Commercial	250	300	500	700	1000	1200	800	400	250	250	250

Table 2.1b Load duration computation for data of Table 2.1a

Type of load	Magnitude	Duration
Lighting	100	11
	50	1
	0	12
Domestic	1000	3
	800	4
	600	8
	500	16
	400	18
	300	19
	200	24
Commercial	1200	2
	800	3
	600	5
	500	12
	400	14
	300	15
	200	24

Explanation for Table 2.1b: Procedure for obtaining load-duration data from load (demand) data

(i) Lighting load of 100 kW exist for 7 p.m. to 00 hrs to 6 a.m., i.e., for 11 hours (6 p.m. to 7 p.m., hence total duration of 50 kW is 11 + 1 = 12 hrs. '0' load exists for rest of the time, i.e., 12 hrs.

(ii) *Domestic load* A load of 1000 kW exists from 7 p.m. to 9 p.m. and up to 10 p.m. Hence, total load of 1000 kW exists from 7 p.m. to 10 p.m. and total duration is 3 hours.

Load of 800 kW exists for 1 hr, i.e, 10 p.m to 11 p.m and total duration is 3 + 1 = 4 hours.

Load of 600 kW exists from 6 p.m. to 9 p.m. and 11 p.m. to 00 hours, i.e., 3 + 1 = 4 hours. Hence, total duration for 600 kW = 4 + 4 = 8 hours.

A load of 500 kW exists from 10 to 1 p.m. to 6 p.m. hence duration is 8 hours. Total duration for 500 kW load is 8 + 8 = 16 hours.

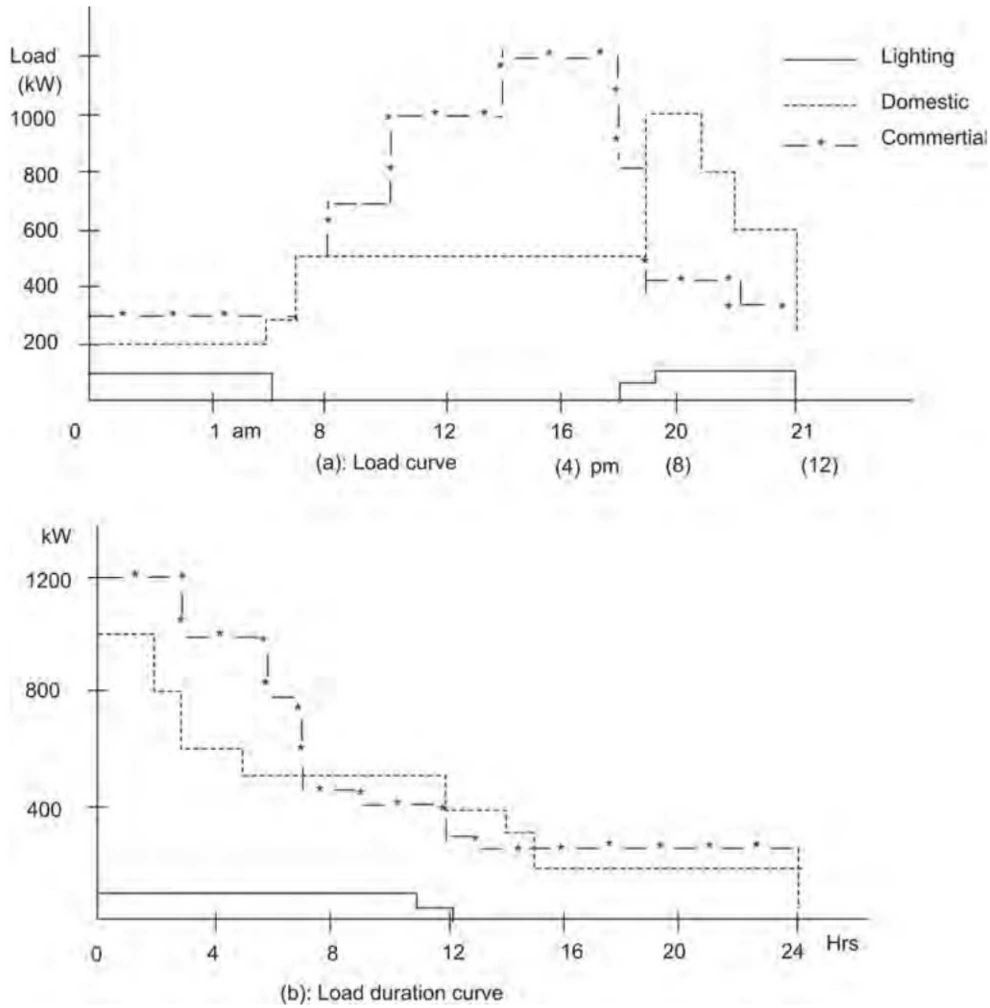


Fig. 2.1 *Load and load duration curves for data given in Table 2.1*

A 400-kW load exists from 8 a.m. to 10 a.m., i.e., 2 hrs total duration for the 400-kW load is 16 + 2 = 18 hours.

A 300-kW load exists from 7 a.m. to 8 a.m., i.e., 1 hour. Hence, total duration is 18 + 1 = 19 hours.

A 200-kW load exists for the rest of the time, i.e., 24 hours.

In a similar manner, duration for commercial load is computed.

The load curves of different loads on a week day for loads mentioned in Section 2.2 are given in Fig. 2.2. It may be observed that they are two load peaks (the maximum load that occurs during that day) for industrial and commercial loads. The load curves are given taking maximum or peak load as 100 % and the loads as percentage of the peak load.

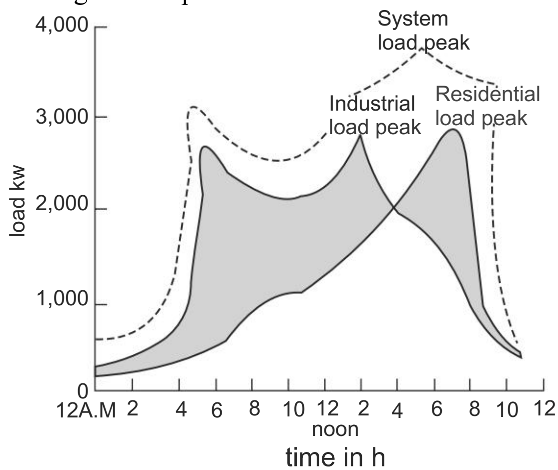


Fig. 2.2 *Typical load curve for two different loads*

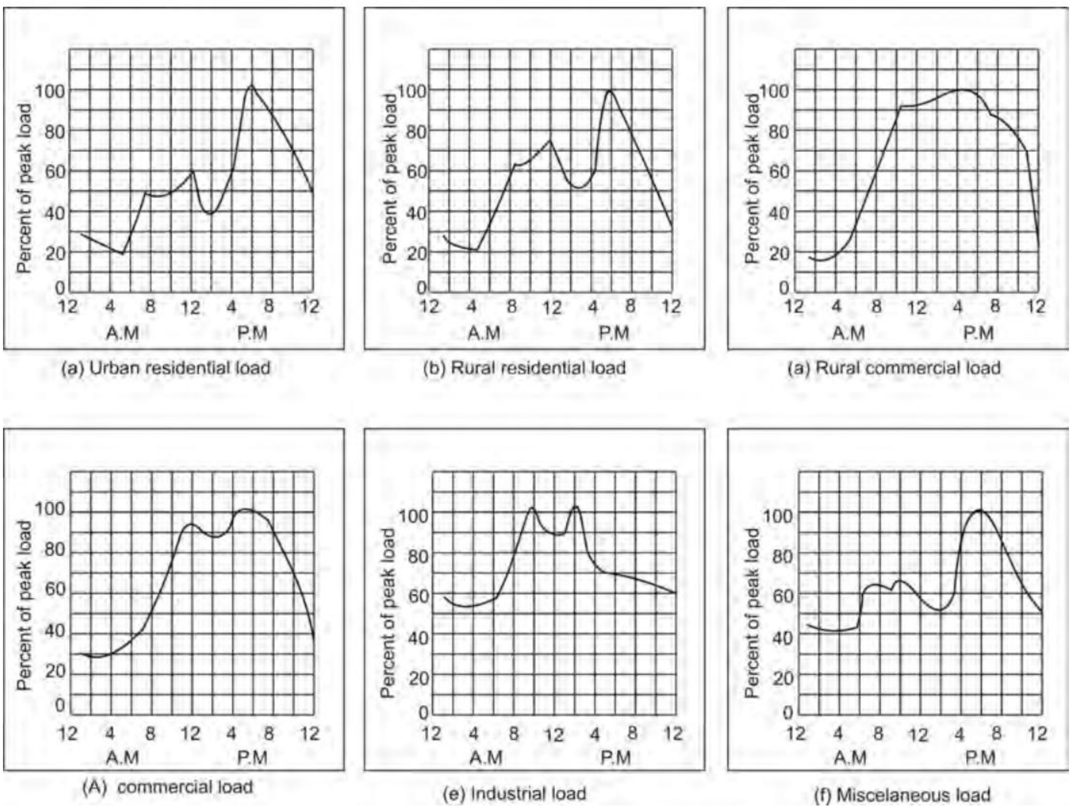
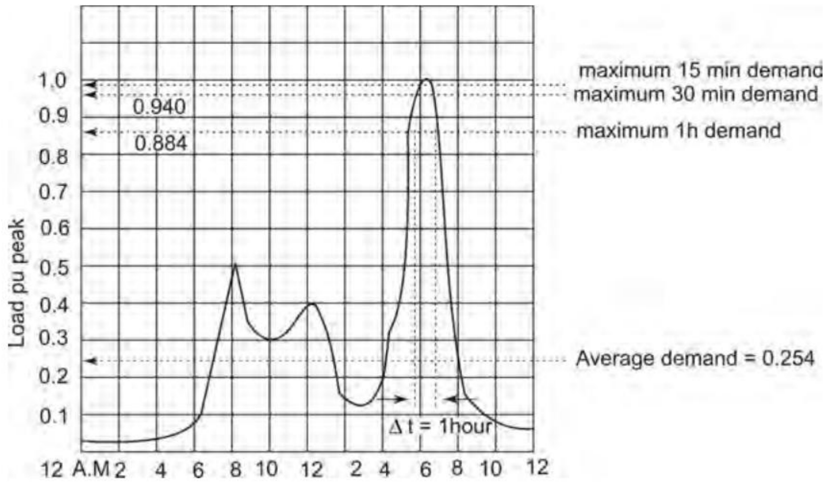


Fig. 2.3 *Typical load curve for different loads mentioned in Section 2.2*

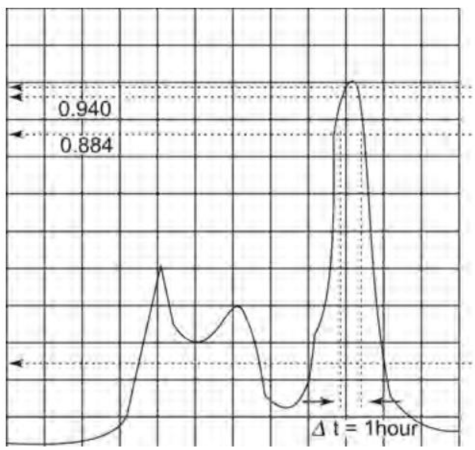
2.3.2 Load-Duration Curves

Typical load (or demand) curves for different kinds of load mentioned in section 2.3 are shown in Fig. 2.3

Typical daily demand curve and load-duration curve shown in Fig. 2.4 (a) are (b) on unit basis. Peak load is taken as 1.0 unit.



(a) *Daily demand curve (load curve)*



(b) *Load duration curve for daily demand shown in Fig.2.4 (a)*

Fig. 2.4 *Typical daily demand (load) curve and corresponding load duration curve*

The load data on a 11-kV feeder during a day is given in Table 2.2 and the load-duration table corresponding to the load data given in Table 2.2, is given in Table 2.3.The load curve and load duration curves for the above data are depicted in Fig 2.5 Using the data given in tables 2.2 and 2.3 different factors mentioned earlier are computed in example 2.1 to 2.6

Table 2.2 Load data on a typical feeder

Time Hour/ load kW.	Street light	Residential	Commertial	Industrial	Agricultural
0.00 – 6.00 AM	80	200	320	100	600
6.00 – 8.00 AM	-	700	400	100	400
8.00 – 9.00 AM	-	800	400	300	-
9.00 – 10.00 AM	-	600	400	400	-
10.00 – 5.00 PM	-	500	700	400	-
5.00 – 6.00 PM	-	600	900	400	-
6.00 – 7.00 PM	80	800	1200	320	-
7.00 – 8.00 PM	80	1000	1200	320	-
8.00 – 9.00 PM	80	1000	1200	220	-
9.00 – 10.00 PM	80	800	1050	170	-
10.00 – 12.00 PM	80	500	320	100	400

(The data refers to a typical 11 kV line)

Power cut imposed from 8 a.m. to 10 p.m. on agricultural loads. Load (kW) is rounded of to the nearest 10s of kW.

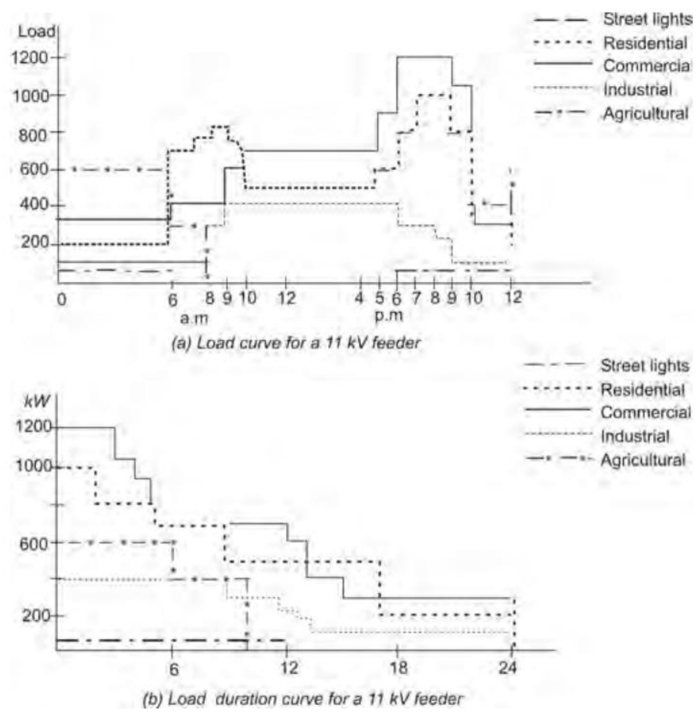


Fig. 2.5 *Load curves and load duration curves for data given in table 2.3*

Table 2.3 Load duration table for different loads of Table 2.2

Types of load	Magnitude (kW)	Duration (hours)
Street light	80	12
	0	12
Residential	1000	2
	800	4
	700	6
	600	8
	500	17
	200	24
Commercial	1200	3
	1050	4
	900	5
	700	12
	600	13
	400	16
	320	24
Industrial	400	9
	320	11
	300	12
	220	13
	170	14
	100	24
Agricultural	600	6
	400	10
	0	24

Example 2.1 *What are the peak (maximum) demands of individual load, system maximum demand and contribution factors? Given that system peak is 1700 kW between 2 p.m. to 5 p.m.*

Solution MD of lighting load: 80kW (7pm to 6am)

MD of domestic load: 1000 kW (7pm to 9pm)

MD of commercial load: 1200 kW (2 pm to 5 pm)

System maximum demand: 1700 kW (2 to5 pm)

Example 2.2 *what is the contribution factor for each of the loads? System peak occurs at 2 pm to 5 pm.*

Solution Lighting load $C_i = \dfrac{0}{80} = 0$

Commercial load $C_i = \dfrac{1200}{1200} = 1.0$

Residential load $C_i = \dfrac{500}{1000} = 0.5$

Example 2.3 *What is the diversity factor and coincidence factor for the above loads?*

Solution Diversity factor $= \dfrac{\sum D_i}{\sum C_i D_i} = \dfrac{100 + 1200 + 1000}{1700} = \dfrac{2300}{1700} = 1.352$

Diversified MD $= \dfrac{100 + 1000 + 1200}{1.352} = 1700$

($\Sigma\, C_i D_i = 0 \times 100 + 1.0 \times 1200 + 0.5 \times 1000 = 1700$). This is same as system peak in this case)

Coincidence factor $C_f = \dfrac{1}{1.352} = 0.74$

Example 2.4 *For the feeder given in Table 2.3 at a peak load of 1500 kW, the power loss recorded is 75 kW. If the annual loss factor is 0.2, what is (a) annual average power loss, and (b) total energy loss per year. ?*

Solution Annual power loss = peak load power loss × loss factor

$= 75 \times 0.2 = 15$ kW

energy loss per year = 15 × 8760 = 1,31,400 *units*

(Note: one year = 365 × 24 = 8760 *hours*)

Example 2.5 *In the above example (Example 2.4).the system peak load is 3 MVA and power loss in 2% of peak load. What is the total loss and annual energy loss?*

Solution Power loss in feeder $= \dfrac{2}{100} \times 3000 = 60 \text{ kW}$

energy loss per year = 60 × 8760 = 5,25,600 *units*

Example 2.6 *The load curves of two different categories of loads and system peak load are as follows. Determine the diversity factor and coincidence factor for the system.*

Peak load for industrial load 2000 kW

Peak load for Residential load =2000 kW

System peak load D_g = kW

Solution Diversity factor $D_f = \dfrac{\sum D_i}{D_g} = \dfrac{2000+2000}{3000} = \dfrac{4}{3} = 1.333$

Load diversity $\sum D_i - D_g$ = 4000 – 3000 = 1000 kW

Coincidence factor $= \dfrac{1}{D_f} = \dfrac{1}{1.333} = \dfrac{3}{4} = 0.75$

2.4 RELATION BETWEEN LOAD AND LOSS FACTOR: A SIMPLIFIED APPROACH

In general, load changes occur continuously for any type of load and the load pattern on any feeder or distributor can be idealized and simplified approach for load on a feeder can be taken as shown in Fig. 2.6.

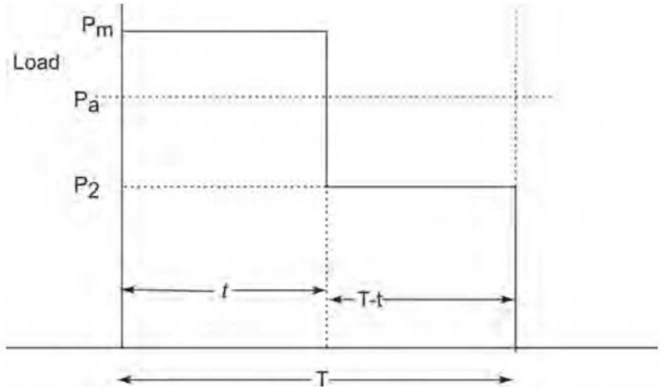


Fig. 2.6 *Idealised load pattern*

Let a peak load P_m exist for duration of 't' and p_2 be the off peak load during any interval 'T' considered. Let P_a be the average load during the period 'T'.

$$P_a = \frac{P_m \times t + P_2(T-t)}{T} \qquad \text{.... (2.4)}$$

But load factor $= \dfrac{P_{aV}}{P_{peak}} = \dfrac{P_a}{P_m}$

For the duration 'T' considered

$$\text{Load factor } = \frac{P_m \times t + P_2(T-t)}{P_m \times T}$$

$$= \frac{t}{T} + \frac{P_2}{P_m}\frac{(T-t)}{T} \qquad \text{.... (2.5)}$$

and loss factor $= \dfrac{(Power\ loss(avg)\ in\ given\ time\ period)}{powoer\ loss(max.\ loss) \times the\ total\ duration}$

This can be extended to the whole duration of 24 hours by considering P_1, P_2 .... P_k as the loads occurring over a duration of $t_{1,} t_2$........t_k with P_m as the peak load. If P_{LS} is average power loss and P_{Lm} power loss corresponding to peak load P_m.

$$\text{Loss factor } = \frac{P_{LS}}{P_{lm}} = \frac{P_{LS}.t + P_m(T-t)}{P_{lm} \times T} \qquad \text{...(2.6)}$$

Since losses are proportional to $I^2 \times P^2$

($\because$ voltage is constant)

$$\text{Loss factor } = \frac{t}{T} + \left(\frac{P_{avg}}{P_m}\right)^2 \left(\frac{T-t}{T}\right) \qquad \text{... (2.7)}$$

(a) This is = t / T if off peak load i.e $P_2 \times 0$,(same as load factor)

(b) For short time peak $t << T$ loss factor $\approx \left(\frac{P_{aVg}}{P_m}\right) = (load\ factor)^2$ (2.8)

(c) In general for variable industrial loads loss factor, is taken as

= 0.3(load factor) + 0.7 (load factor)^2 ... (2.9)

Example 2.7 *Find the annual load factor and average demand, given that peak load is 3.5 MW and energy supplied is 10 million units (10^7 kwh). Peak demand was recorded during April – June.*

Solution Average demand $= \frac{10^7\,\text{kWh}}{8760} = 1141\,\text{kW}$

Peak load = 3500 kW

Annual load factor $= \frac{1141}{3500} = 0.326$

Example 2.8 *A feeder supplies 2 MW to an area. The total losses at peak load are 100 kW and units supplied to that area during an year are 5.61 million. Calculate the loss factor.*

Solution Load factor $= \frac{5.61 \times 10^6}{200 \times 8760} = 0.32$ (unit supplied/ peak load × 8760)

Loss factor = 0.3 (*load factor*) + 0.7 (*load factor*)^2

$= 0.3 \times 0.32 + 0.7 \times (0.32)^2 = 0.168$

Average power loss = 0.168 × (100 kW) = 16.8 kW

The above examples illustrate how the average power loss and loss factor can be estimated from the peak load occurring and units supplied. The estimates give gross idea regarding power losses and hence the revenue lost in a distribution system. The loss factor should be as low as possible so that the energy efficiency will be high. In general, loss factor will be such that

(load factor)^2 < (loss factor) < (load factor)

Figure 2.7 shows how loss factor varies with load factor with different functional relations assumed.

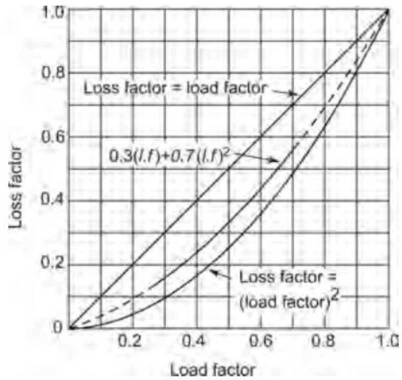


Fig. 2.7 *Variation of loss factor with load factor*

2.5 LOAD GROWTH AND DIVERSIFIED DEMANDS

As the residential or commercial areas grow with increased population and new areas area added, it will be necessary to account for the new loads added and also to take in to account diversity between similar loads and non coincidence between peaks of different types of loads added. This will optimize the additional capacity to be added. For the purpose variation in the peaks of different kinds of loads is taken. To illustrate this, an example of urban domestic and residential loads are considered. Actual connected loads are

(i) Lighting and fans
(ii) Refrigerator
(iii) Home Ac/Home heating
(iv) Domestic appliances such as mixes, wet grinders, etc.
(v) TVs, music systems, and other Electronic gadgets
(vi) Other appliances such as washing machines, electric, driers, etc.

A study reveals that the time of variation of load factor for these loads during a day is as follows.

Table 2.4 Load factor for domestic loads

Duration / L.F	Lighting & fans	Refrigerators	Home AC & Heaters	Domestic apliances	Electronic gadgets Radio, TV etc.
0 – 6 AM	0.1 to 0.2	0.75 to 0.85	0.3 to 0.4	0.1	0.3
6 – 8 AM	0.35 to 0.4	0.85	0.35 to 0.45	0.5 to 0.6	0.6 to 0.8
9 – 12 Noon	0.3	0.85 to 0.9	0.6 to 0.8	0.6 to 0.8	0.7 to 0.9
12 – 4 PM	0.25 to 0.3	0.9	0.8 to 0.95	0.3 to 0.5	0.6 to 0.8
4 – 6 PM	0.7 to 0.9	0.9	0.9 to 1.0	0.6 to 0.7	0.5 to 0.6
6 – 8 PM	1.0	1.0	0.8 to 0.9	1.0	0.5 to 0.6
8 – 10 PM	0.85 to 0.95	1.0	0.6 to 0.8	0.85 to 0.9	0.7 to 0.9
10 – 12 PM	0.4 to 0.7	0.95 to 0.95	0.4 to 0.6	0.4 to 0.5	0.9

From Table 2.4, it can be inferred that there is a lot of variation for certain types of loads such a lighting and fans, domestic appliances, home ac & heating etc. In order to have an optimum supply system, a diversified maximum demand depending on the customers and their connected loads have to be taken.

The steps suggested are the following:

(i) Determine the total number of appliances by multiplying the total member of customers per unit saturation i.e., the customers that use that particular load or appliance at the same time

(ii) Determine the diversified demand per customer from the house variation factors (load factors) from the available data like Table 2.4.

(iii) Determine the maximum demand using steps (ii) and (i).

(iv) Determine the contribution factor for each type of load.

The procedure is illustrated with the following example.

Example 2.9 *Let there be 500 residential flats connected to a feeder line, with 10 flats connected to distribution transformer (11 kV/415 V 3Ph).Load survey indicated that the maximum diversified demand per customer is as follows.*

Load (kW)	Appliance	Coincide factor
1.5 kW/flat	For washing machine and drier	0.8
0.2 kW/flat	Refrigerator	0.65
0.9 kW/flat	Lighting and fans	0.9
0.5 kW/flat	Electronic gadgets	0.7
0.6 kW/flat	Other appliances & loads	0.5

Applying the load factor and diversity between maximum demands among the loads, the average diversified maximum demands for the above load are

$$= 1.5 \times 08 + 02 \times 0.65 + 0.9 \times 0.9 + 0.5 \times 0.7 + 0.6 \times 0.5$$

$$1.2 + 0.13 + 0.81 + 0.35 + 0.30 = 2.79$$

For the 500 flats, the power requirement is $2.79 \times 500 = 1395$ kW

Since 10 flats are connected to each transformer

Transformer rating $= \dfrac{1395}{50} \approx 28$ kVA will be required

Usually 25 kVA transformer with 10% overload capacity will be sufficient.

Total number of transformers required = 500/10 = 50.

Total kVA rating is 50 × 25 = 1250 kVA

NOTE: If all the maximum demands are numerically added the power requirement would have been (1.5 + 0.2 + 0.9 + 0.5 + 0.6) × 500 = 1850kW, 35% more than the pervious value.

2.6 LOAD MODELING

It has been mentioned in Section 2.2 that a common classification for the loads of different types will be useful for load modelling. The load components of different loads as a whole constitute a total composite load and is usually modelled taking into the following factors. The model takes into consideration the type of application, viz, static application which incorporate any voltage dependent nature of the loads. They include the following:

(a) (i) Power flow—Distribution system power flow and transmission power flow studies

(ii) Voltage stability studies

(b) Dynamic application, i.e,

(i) Transient stability

(ii) Dynamic stability and the other type of analysis basis on both voltage and frequency dependent loads

The other type analysis based on both voltage and frequency dependant the load.

The static load modelling usually takes the substation load into sub components as percentage of total demand and duration. This is schematically shown as a "Load window" given in Fig. 2.8. The load window shown here is for typical residential and commercial loads in residential localities.

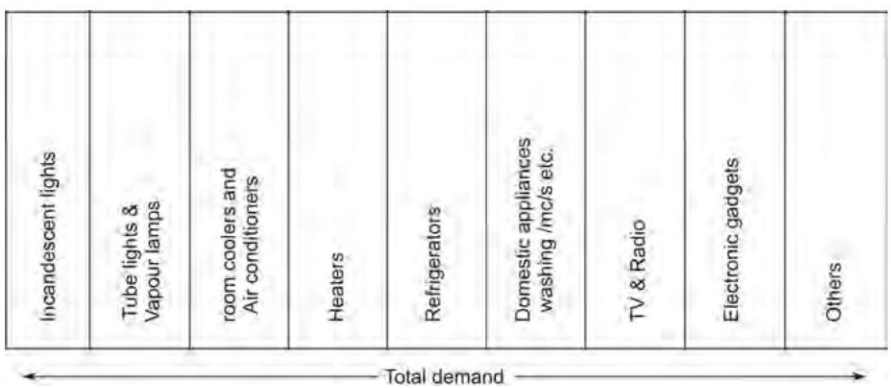


Fig. 2.8 *Typical load window for distribution system load*

Construction of load window is based on the load data available like (i) maximum demand of a certain component of load (example: air conditioners) (ii) the duration over which it is spread (iii) its diversity (iv) its component part in the total load as a percentage (v) its operation like full load, part load, and p.f at which it operates. To this, frequency dependent nature of the load can be added. In such cases the load 'S' is split into two components 'P'(active power) and 'Q' reactive power and the load is considered as

as $P = P(V) + [1+ D_p \Delta f]$ … 2.10

$Q = Q(V)[1 + D_Q \Delta f]$ …2.11

where $P(V)$ and $Q(V)$ depend on the voltage of the distribution system, Δf is the frequency change that occurs and D_P and D_Q, the factors that correct the loads for frequency deviation. Correction factors for certain loads like heaters, air conditioners etc, for ambient temperature change is also needed. This is necessary only where "Transient or Dynamic" load modelling is needed. Typical variation * of real power (P) and reactive power Q of a room air conditioner rated for 230 V is given $P = 1.0 + 0.494\Delta V + 2.021(\Delta V)^2$ and $Q = 0.497 + 2.445\Delta V + 8.604(\Delta V)^2$ where ΔV is per unit derivation of voltage. Typical composition of load window for there different categories of loads is illustrated in table 2.5

*(see Ref. 18. for further information)

Table 2.5 Composition of load window (Lw). For three different types of loads

Types of load	L_w 1 (%)	L_w 2 (%)	L_w 3 (%)
3ph central ac systems	25	10	40
Window type ac	05	20	-
Refrigerators	05	10	5
Incandescent lamps	10	10	-
Tube lights and other vapour lamps	20	35	30
Heaters, etc.	15	10	-
Others (including electronic gadgets)	20	05	5
Motor loads (pumps, industrials motors)	-	-	20

It may be noted that for static load modeling in distribution system, all loads are voltage dependent. For example, if a water heater is rated for 2kW at 230 V, it will draw a power of 1.7 kW at 210 V and 2.12 kW at 240. Also the heater is a nonlinear resistor and the power drawn depends on the effective resistance and heat dissipation. As such the representation of different loads for load modeling is quite difficult.

Example 2.10 *In a load model study it is required to estimate the change in load of typical industrial motors with variation of voltage and frequency. Taking the total nominal rating of the motors as 415 V, 50 Hz, 3Ph, 100 kW at p.f = 0.85, estimate the new rating at*

(i) $V = 440 V, f = 50.5$ Hz

(ii) $V = 380$ $V, f = 49.0$ Hz. *Use the power law as*

$P = 1.0 + 0.15\,\Delta V + 2(\Delta V)^2$, $D_P = 1.6$

$Q = 0.657 + 2.35\,\Delta V + 68.6\,(\Delta V)^2$, $D_Q = -0.65$

Solution $P = P(V)(1 + D_{1,} \Delta f)$

$$Q = Q(V)(1 + D_Q \Delta f)$$

(i) $\Delta V = \dfrac{25}{440} = 0.0568; \Delta f = \dfrac{0.5}{50} = 0.01$

(ii) $\Delta V = \dfrac{-20}{440} = -0.04545; \Delta f = \dfrac{-1}{50} = -0.02$

Q at rated voltage and frequency $= \dfrac{100}{0.85} \times 0.5268 \approx 62 RkVA$ $(\sin\phi = 0.5268)$

(i) New $P = 100\ \{1 + 0.15 \times 0.0568 + 2 \times (.0568)^2\}\{1 + 1.6 \times 0.01\}$
$= 103.12$ kW

New $Q = 62\ \{0.657 + 2.35 \times 0.0568 + 6.6 \times (0.0568)^2\} \times \{1 - 0.65 \times 0.01\}$
$= 49.93$

New KVA = 114.97, p.f = 0.900

(ii) New $P = 100\ \{1 - 0.15 \times 0.04545 + 2 \times (0.4545)^2\} \times \{1 - 1.6 \times 0.02\}$
$= 96.53$

New $Q = 62\{0.657 - 2.35 \times 0.04545 + 6.6 \times (0.04545)\} \times [1 \times 0.65 \times 00.1]$
$= 35.18$
New kVA = 102.74, p.f = 0.940

2.6.1 Load Models for 3-Phase,3-wire and 4-wire systems

The loads that occur in distribution network are generally

(a) three-phase balanced loads connected between the three line,
(b) single-phase loads connected between the phase wires and neutral; They form the unbalanced loads,
(c) Single-phase loads connected between any two lines, which is generally rare, and
(d) other loads such as combination loads, 2-phase loads, etc.

The modelling that is usually done is to take them as

(i) Constant current loads
(ii) Constant impedance loads
(iii) Constant power (kVA) load—in this modelling both real power and reactive power is taken as constant

(iv) Any combination of the above—usually in load-flow analysis, constant power per phase and either phase to neutral or line-to-line voltage is defined and used for computation.

2.7 LOAD GROWTH AND FORECASTING

Population growth and energy requirement do not grow linearly but follow non linear power law or exponential growth. The usual function that fits is

$y = ka^x$, where y is the new value after a growth period 'x', k is the initial value of y i.e, when $x = 0$ and 'a' the rate at which y increases logarithemically.

Power growth, i.e., increase in load demand after a period x with and annual growth rate of 'g' is usually expressed as

$$P_n = P_0(1 + g)^n \qquad \text{....(2.12)}$$

P_0 = initial power demand

g = growth rate

n = period

This is also known as compound interest law (here $1 + g = a$ of the previous equation, $y = ka^x$)

Future demands are normally estimated knowing the growth rate factor 'g'.

Example 2.11 *A rural area has a power demand of 500 kW and it was found that the growth rate is 6%. What will be the demand after 5 years.*

Solution Here P_o = 500 kW, g = 0.06 and n = 5 years

$\therefore$ P after 5 years = $500\,(1 + 0.06)^5$ = 669kW

2.7.1 Load Forecasting

Based on certain conditions and trends existing and assuming that they continue, load forecasting is a method by which future increase in loads are predicted. There is a great need for accurate forecasting of loads over a given period to meet with the power and energy requirements of the future and money to be spent. In our country there is a lot of pressure due to limited financial and energy resources and hence electrical load fore-casting is vital.

The models adopted for load fore casting are statistical models based on Markov process, Time Series analysis and Sampling techniques. The method used is regression analysis.

2.7.2 Regression Analysis

The mathematical modelling is done by taking the previous growth over a period and the future trend is extra polated. This is done by either fitting a linear or non linear curve for the growth to get least overall error or fitting a sequence of discontinuous non linear curves from the pervious data extra polating the results. The factors that are taken into account are (i) basic trends,(ii) seasonal variations, and (iii) random and cyclic variations depending on weather conditions.

The trends are fitted into either

(i) Linear increase as $P = a + bt$
(ii) Exponential or compound interest law

$$P_n = P_o(1 + g)^n \quad \text{or}$$

(iii) other power laws like
  (a) $P = Ax^b$ (exponential growth)
  (b) $P = A + Bx + Cx^2$ (quadratic law)

may also be used.

These trends and estimates are checked with typical correlations from available records and actual values.

To conclude, load forecasting and energy forecasting for future years is difficult but necessary process in order to plan for future power and energy requirements.

Summary

In this chapter different types of electric loads, their clarification and characteristics are discussed. Models adopted for load analysis, load growth and forecasting are presented.

Keywords

Loads
Loads characteristics
Loads curves
Loads duration curves
Load factor
Loss factor
Load modelling
Load forecasting

Review Questions

1. Explain what is meant by
   (a) load factor (b) diversity factor (c) contribution factor

   Discuss the characteristics of different loads.
2. What is load curve and load duration curve? Explain their importance in distribution networks
3. What is loss factor? How is it related to load factor? Explain its significance.
4. Explain how load growth is estimated. How is diversified maximum demand computed? Illustrate with an example.

5. Explain briefly classification of loads. How is load modelling done in distribution networks?
6. Explain how load growth in distribution system can be determined and estimated?
7. Explain the characteristics of different loads and loads models
8. How does the load kVA, kW and reactive kVA change with
   (a) Variation of supply voltage from nominal value?
   (b) Variation of frequency from nominal value?
9. Explain why deviation of (a) voltage (b) frequency be taken into consideration for estimating the load on the distribution system. Give the experical relation for change in 'P' and 'Q' with the above variations.

Problems

10. Using Table 2.3 and taking only residential and commercial loads, determine the following factors, if the system peak occurs between 3pm and 6pm and is 1700 kW.
    (i) Contribution factor
    (ii) Load factor
    (iii) Coincidence factor
    (iv) Diversity factor

11. Using the data given in Table 2.3 and considering only commercial, agricultural and residential loads determine
    (a) load factor
    (b) load diversity
    (c) coincident max. demand

12. Two 1.5, MVA,11 kV feeders supply the load given in Table 2.2 and the load is equally distributed. The peak load recorded or each feeder is 1.6 MW and the peak power loss is 200 kW. Its annual loss factor is 0.22. What is the energy loss per year?
13. In Example 2.6, the system peak load is 2.5 MVA and the power loss is 5% of the peak load. What is the total power loss and annual energy loss?
14. A distribution concern has the following load:

Type of load	Max.demand(kW)	Diversity of the group	Demand factor
Domestic	1500	1.2	0.8
Commertial	200	1.1	0.8
Industrial	10,000	1.25	0.9

    If the overall diversity factor is 1.5, determine the maximum demand and connected load of the each of the above loads.

15. A certain urban area has a load of 1 MVA and a growth rate of 8%. Estimate the load after (a) 5 years and (b)10 years using
    (i) exponential or compound interest law
    (ii) quadratic law if $A = 1.0$, $B = 0.08$, $C = 0.1$

Multiple Choice Questions

1. Demand interval in usually

   (1) 1min (2) 5 min (3) 30 min (d) 3hours

2. Demand factor is the ratio of

   (a) maximum demand to connected load
   (b) total load to maximum demand
   (c) maximum demand to rated capacity
   (d) none of the above

3. Load-duration curve is between

   (a) load and time of occurrence
   (b) load and time duration over which it occurs
   (c) units consumed and duration in day
   (d) power supplied and time

4. the empirical relation used between load factor. ($l.f$) and loss factor is, loss factor =

   (a) $0.7(l\,.\,f) + 0.3(l\,.\,f)^2$ (b) $0.3 + (l\,.\,f)$
   (c) $0.3(\,l\,.\,f) + 0.7(l\,.\,f.)^2$ (d) $0.7[(l\,.\,f) + (l\,.\,f)^2]$

5. The coincidence factor for lighting loads in domestic/residential loads is about

   (a) 0.1 (b) 0.5
   (c) 1.0 (d) 0.9

6. Utilization factor is the ratio of

   (a) Maximum demand to total load connected
   (b) Maximum demand to rated capacity of the system
   (c) Any demand occurring in a day to maximum demand
   (d) Total load to maximum demand

7. Power factor of domestic appliances like fans, washing machines, mixes, etc. is in the range

   (a) 0.75 to 0.85 (b) 0.4 to 0.75
   (c) 0.4 to 0.8 (d) 0.6 to 0.75

8. Sensitive and important loads which require close tolerance for supply voltage and its frequency are

   (a) computer loads and microprocessor- controlled process industry
   (b) agricultural loads
   (c) water supply and pump loads
   (d) none of the above

(9) Load forecasting is done using

   (a) power law (b) regression analysis
   (c) time series analysis (d) power law and regression analysis

(10) For typical urban loads, peak demand can occur
   (a) once in a day   (b) twice in a day
   (c) more than twice in a day   (d) cannot be predicted.

Fill in the Blanks

11. Load growth follows ______________ law
12. A feeder supplying 1 MW load to an area has peak load losses of 65 kW and supplies 2.704 million units in a year. The load factor is ______________.
13. A load in an area has a load factor 0.6. The approximate loss factor may be ______________.
14. Load diversity is the difference between ______________ and______________.
15. The time interval taken for estimation of maximum demand for billing is ______________.
16. Usual power factor of fluorescent lamps is ______________.
17. Small industrial motors work at p.f. of ______________.
18. Domestic loads have p.f. of ______________.
19. Coincidence factor is defined as ______________.
20. Heavy industrial loads have demand factor ______________.

    An air-conditioner motor is rated 5kW at 400 V, 3 ph 50 Hz and p.f = 0.85, what will be the power drawn and new rating if

21. Voltage is 380 V
22. frequency is 49 Hz
23. Voltage is 380 V and frequency 49 Hz
24. KVA rating and new p.f.

    [Hint: Use the equation given in Section 2.6, page 25]

P: $[1.0 + 0.494\Delta V + 2.02(\Delta V)^2]P$

Q: $[0.5 + 2.445\Delta V + 8.604(\Delta V)^2]$Q where P,Q given P, Q new values with Dp = 1.5 $D_Q = -6$]

Answers

(1). c	(2).a	(3).b	(4).c	(5).d
(6). b	(7).d	(8).a	(9).d	(10) b.

11. Power law or compound interest law
12. 0.4   13. 0.432   14. sum of the peak demands of individual loads and coincident maximum demand   15. 15 min (in AP state) or 30 min
16. 0.5 to 0.6   17. 0.4 to 0.75   18. 0.6 to 0.7   19. See definition
20. 0.9   21. 4.89 kW   22. 4.85 kW   23. 4.743
24. Q of motor at rated voltage and frequency

3.1 kVAR new Q = 1.20707, KVA = 4.897, p.f = 0.96

Three

Power transmission is done either through overhead lines or cables. The electrical parameters, characteristics of lines and cables, insulators and hardware required for overhead lines is discussed alongwith typical illustrations.

Overhead Lines And Cables

Introduction

Electric power is transmitted from the source or substation to the user through base conductors supported by insulators on poles or over head lines. These will be either copper or aluminium conductors. Now a days only aluminium alloy conductors (A A C) or ACSR conductors are only used. The size of the conductor is based on

(i) current-carrying capacity,

(ii) mechanical strength required depending on the span used, and

(iii) voltage drop or line regulation and power loss.

Further, the choice of the type and conductor size also depends on mechanical considerations like

(a) ambient temperature,

(b) wind speed,

(c) ice loading in case of cold countries, and

(d) other mechanical aspects like maximum allowable tension, working tension, sag, clearances, span, etc.

Most of the conductors chosen for distribution lines will have current rating between 100 to 500 A. Typical conductors cross section as per I.S are given in Table 3.1.

Table 3.1 *Conductor data for overhead lines (ACSR and AAC)*

Type	Conductor area (mm^2)	Approximate diameter (mm)	Resistance at 20°C (Ω)	Max load (breaking) (kN)	Current carrying capacity (A)
ACSR 7/2.11	20	6.33	1.40	7.61	105
ACSR 7/3.55	50	10.05	0.55	18.25	193
ACSR7/4.09	80	12.27	0.371	27.00	250
ACSR 7/4.72	100	14.15	0.280	34.40	300
ACSR3 7/2.59	150	18.13	0.180	67.30	400
AAC 7/2.2	22	6.00	1.54	6.45	95
AAC 7/3.15	55	9.45	0.62	16.03	189
AAC 7/3.81	80	11.43	0.425	23.4	225
AAC 7/4.26	100	12.78	0.340	29.6	295
AAC 7/3.15	148	15.75	0.23	43.5	375

Choice of the overhead line conductor and its application depends on the line length, voltage of operation, clearance, and voltage drop and power losses in the conductor. Further the number of joints, turnouts and jumpers needed also play an important role in the choice.

3.1 LINE PARAMETERS

Resistance The voltage drop in the overhead line is a result of the resistance and inductance. The charging current of line, even through small for 11 and 33 kV lines is due to the capacitance. The resistance of the line conductor at any temperature 'T' is given by

$R_T = R_{20^\circ}[1+0.0003(T+20)]$ for AAC conductors (R_{20} is resistance per Km at 20ºC). ....(3.1)

Skin effect When a conductor carries steady current, the current is distributed uniformly over the whole conductor cross section. With alternating currents, due to the variation of magnetic field from centre of conductor to the surface, the current distribution is not uniform and current density increases from the centre towards the surface. This results in increased power loss for the given current. The effect is similar to an increase in resistance. At power frequencies, for a 2.5 cm conductor, the increase in resistance may be 8 to 10%. As such, stranded conductors are used instead of solid conductors.

The overall increase in resistance due to both temperature and skin effect may be of the order of 20 to 50% as compared to dc.

Inductance The inductance of a 2 wire single phase line is

$0.4 \text{ In } D/r'$, mH/km ....(3.2)

$= 0.92\,1 \log D/r'$, mH/km

and that of a 3 phase, 3 wire symmetrically spaced line per phase is

$= 0.2 \ln D/r'$, mH/km .... (3.3)

$= 0.461 \log D/r'$, mH/km

Capacitance The capacitance of a two-wire single phase line is

$$= \frac{0.0121}{\log D/r}\,\mu\text{F/km} \quad ...(3.4)$$

and that of a three-phase line per phase is

$= 0.0242/\log D/r'$ F / km ...(3.5)

where D is the spacing, r the radius of the conductor and r' = geometrical mean radius

$= \exp(-0.25)r = 0.7788r$

If the conductors are not equally spaced but have a spacing of D_1, D_2, D_3, then 'D' known as geometrical mean distance given by

$$D = \sqrt[3]{D_1 D_2 D_3} \quad ....(3.6)$$

for regular and uniform transposition of the lines. Normally, all distribution lines are taken to be short lines only and their independence per conductor or phase is taken as $(r + j\omega L)$ where $\omega = 2\pi f = 100\pi$ for 50Hz, neglecting capacitance effect.

The independence of lines per phase are available as charts or tables for different spacing adopted.

Line-charging Current This is given by $I_c = V\omega C$/phase, where 'V' is the voltage per phase 'ω' is the angular frequency and 'C' is the capacitance per phase. The charging current of a typical 33 kV line may be 0.5 to 0.8 A/km and 30 to 50 kVAR/km will be charging kVA. Hence capacitance and charging current are neglected for lines up to and including 33 kV.

The amount of power ttransmitted by typical distribution lines may be as follows :

11 kV, 3 ph 3 wire	up to 15 km	3 to 5 MVA
22 kV, 3 ph 3 wire	up to 25 km	5 to 10 MVA
33kV, 3 ph 3 wire	up to 35 km	10 to 25 MVA

3.2 OVERHEAD LINES, INSULATORS AND SUPPORTS

Overhead lines are intended for power transmission by bare conductors (or insulated conductors) supported on insulators and mounted on cross arms connected to the poles. Poles can be steel joists or prestressed concrete poles (the latter are preferred nowadays). Wooden poles were used earlier but have been discontinued now. The poles will be 6 to 10 m high and will be buried in ground with concrete foundation up to depth of 1/3 of its total length. The conductors are supported on insulators (called pin insulators) made of porcelain, toughened glass, etc. Where ever line is terminated or changes its direction strain (or tension) insulators are used. A few insulators are shown in Fig.3.1 and line configurations in Fig. 3.2. Since porcelain insulators are brittle, break easily and are heavy, polymeric and silicone rubber insulators are introduced and are replacing the porcelain insulators.

3.2.1 Silicone and Polymeric Insulators for Overhead Lines

Insulation contamination is a common problem on overhead lines. Wet atmospheric conditions result in water filming on the insulator surfaces and causes the leakage current to develop. Further, dust pollutants like carbon, cement, coal dust, chemicals like fertilizers at industrial areas, mine sites, etc., cause deposits on the insulator surfaces under both wet and dry condition and increase the leakage currents resulting in failure of insulators. This is the worst situation with the conventional porcelain insulators.

The recent development in the past 20 years in to replace the porcelain insulators with silicone rubber (RTV and HTV) insulators and polymeric insulators. Because of its high hydrophobicity (repelling nature to moisture) it inherently resists water filming on its surface. Hence the leakage currents are reduced and surface contamination is much less. There is a great amount of saving in maintenance costs as no washing of insulators in needed frequently.

The benefits obtained by using polymeric or silicone rubber insulators (RTV and HTV) are

(i) improvement of reliability by minimising interruptions and outages due to flashovers, vandalism, pole fires, etc.
(ii) elimination or reduction of maintenance such as frequent washing, etc.
(iii) energy efficiency, as leakage currents are very less
(iv) improved power quality due to reduced RI and TVI (Radio and TV Interference)

(v) less installation costs since insulators are very light (a 11kV insulator weights only 10 to 15% of a porcelain insulator)
(vi) more service life

The constructional features of the composite type silicone rubber or polymeric insulators are as follows :

The insulators are manufactured with electrical-grade corrosion-resistant epoxy core rod which will take the mechanical load. The sheds are made out of silicone rubber. The material is highly filled with 'ATH' to resist tracking and silicone base polymer to provide the hydrophobicity. The sheds are fitted to the rod through high temperature injection molding process. Distribution insulators are rated to 70 kN and are tested. A variety of end fittings are designed and a range of end fittings are available to provide flexible coupling that integrate into line design.

Nowadays line post insulators, strain insulators as well as guy insulators are widely used up to 69 kV and in India also porcelain insulators are gradually replaced with silicone and polymeric insulators

Typical polymeric and silicone rubber insulators are shown in Fig. 3.1 'c' 'd' and 'e'

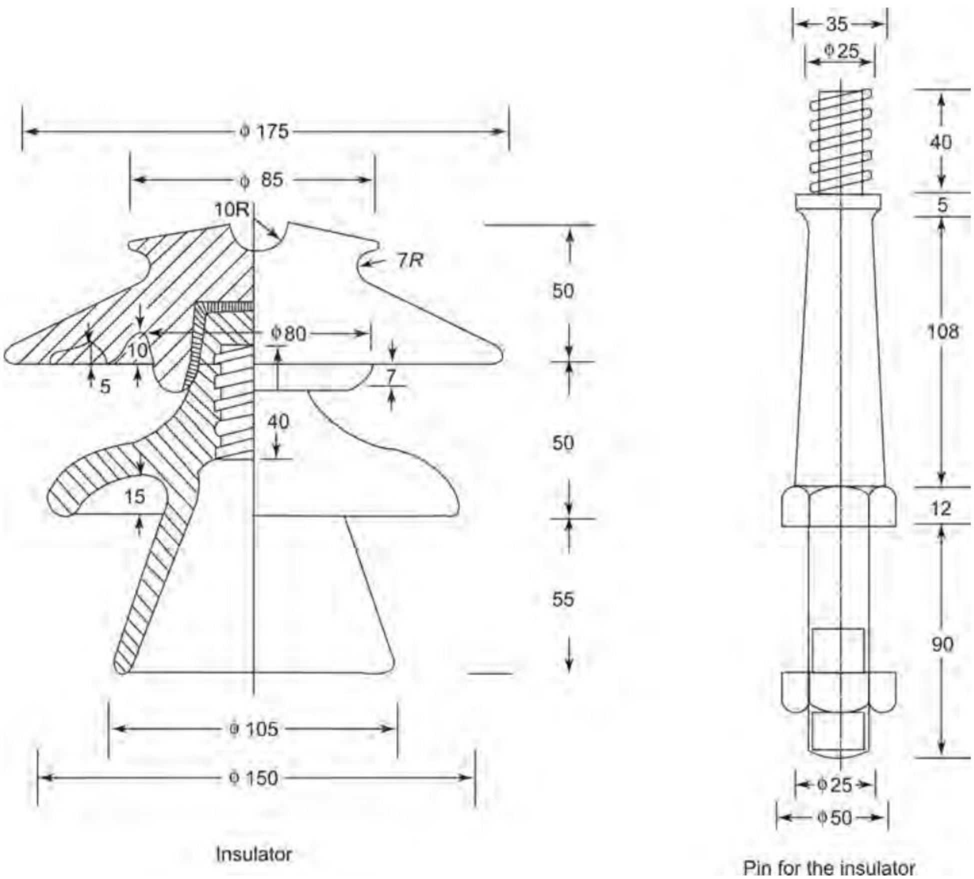
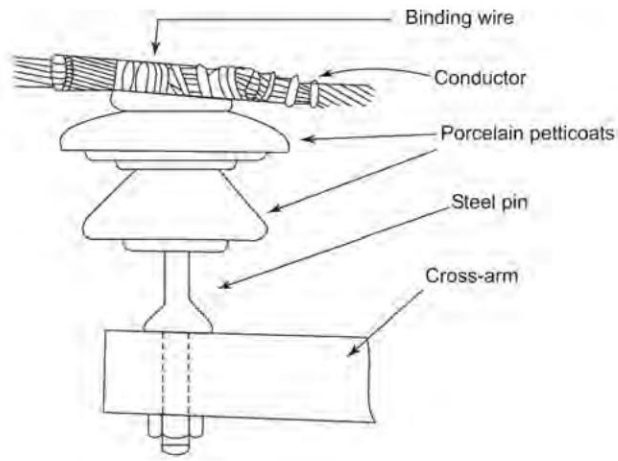
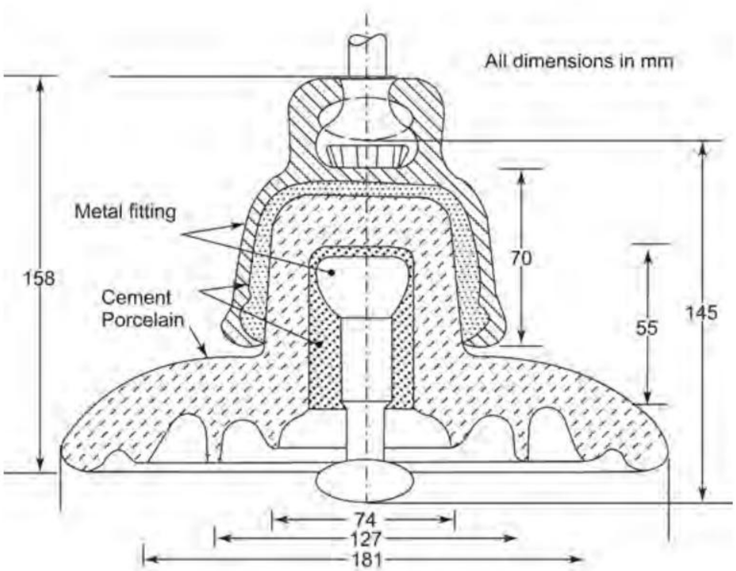


Fig. 3.1(a) *11-kV pin insulator with pin shown separately (porcelain insulators)*



(a) Pin insulator installed on cross arm



10″ *Disk insulator (cross section) (porcelain)*

Fig. 3.1 (b)

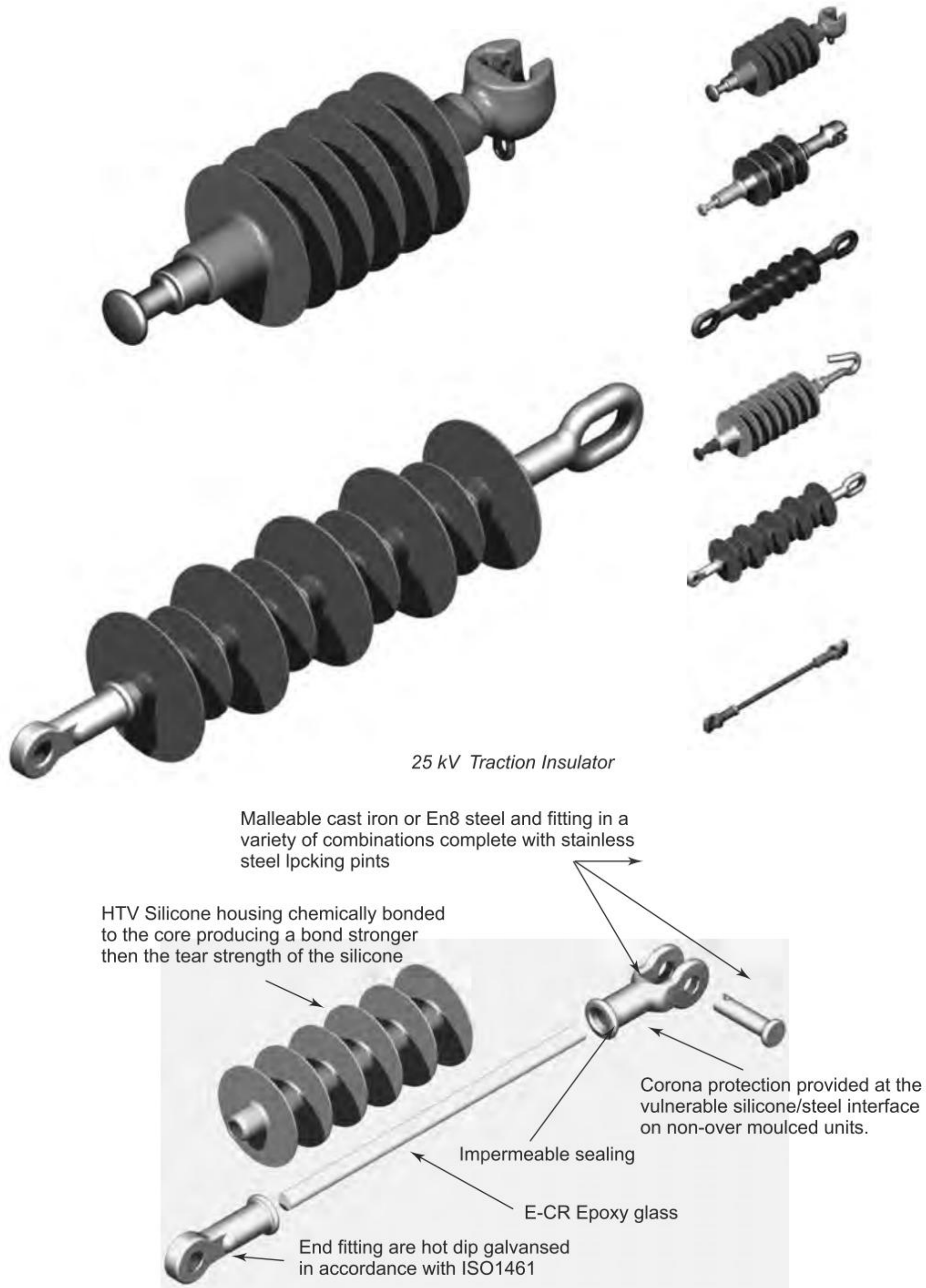


Fig. 3.1 (c) *Longrod insulators (polymeric and silicone rubber)*

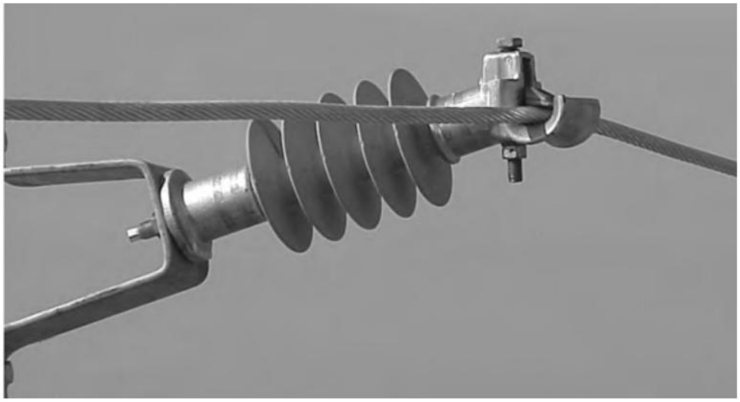


Fig. 3.1 (d) *Polymeric insulator holding line conductor*

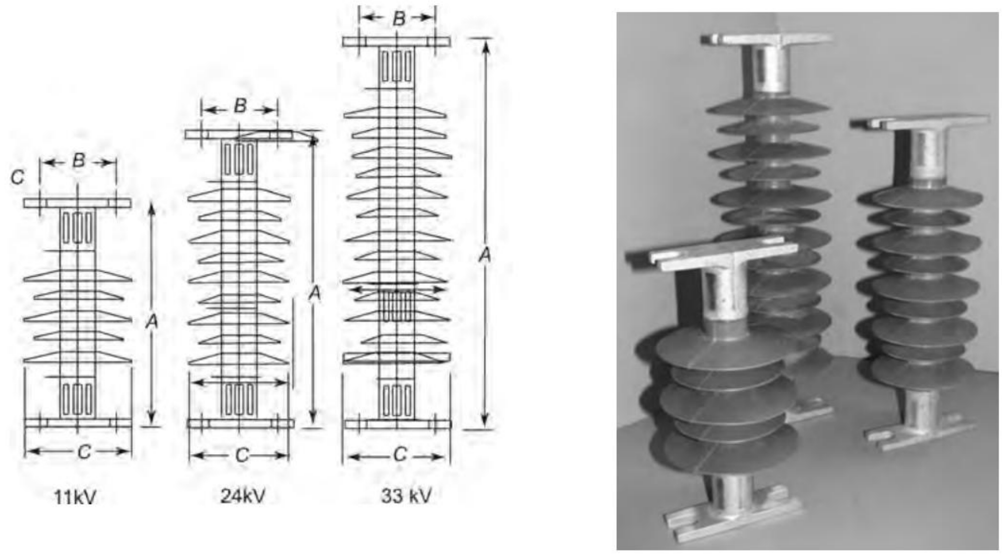


Fig. 3.1 (e) *Air break isolating switch insulators*

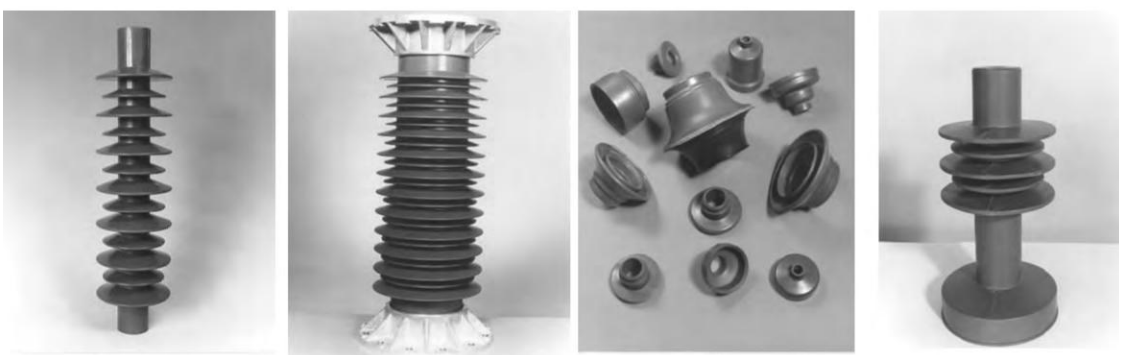
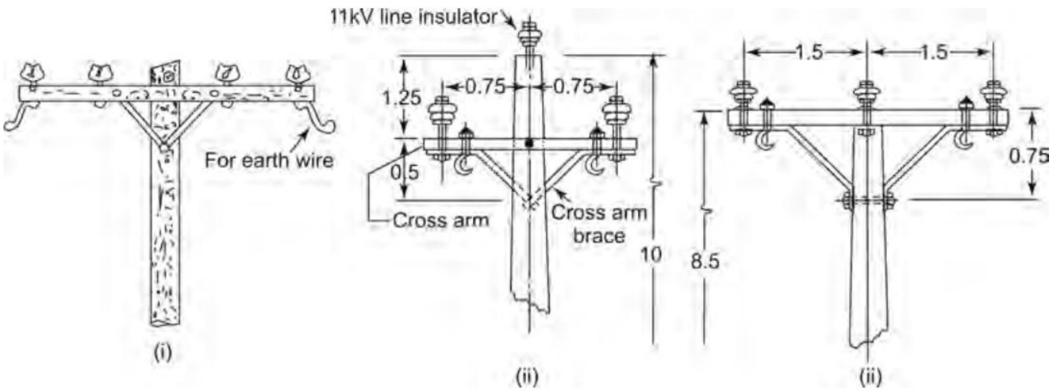


Fig. 3.1 (f) *Other miscellaneous insulators*



(Denominations shown in meters approximately)

Fig. 3.2 (a) *(i) 3-ph, 4-wire distribution arrangement (L.V. 400V)*
(ii) 11-kV, 3-ph single circuit triangular formation
(iii) 11-kV, 3-ph single circuit horizantal formation

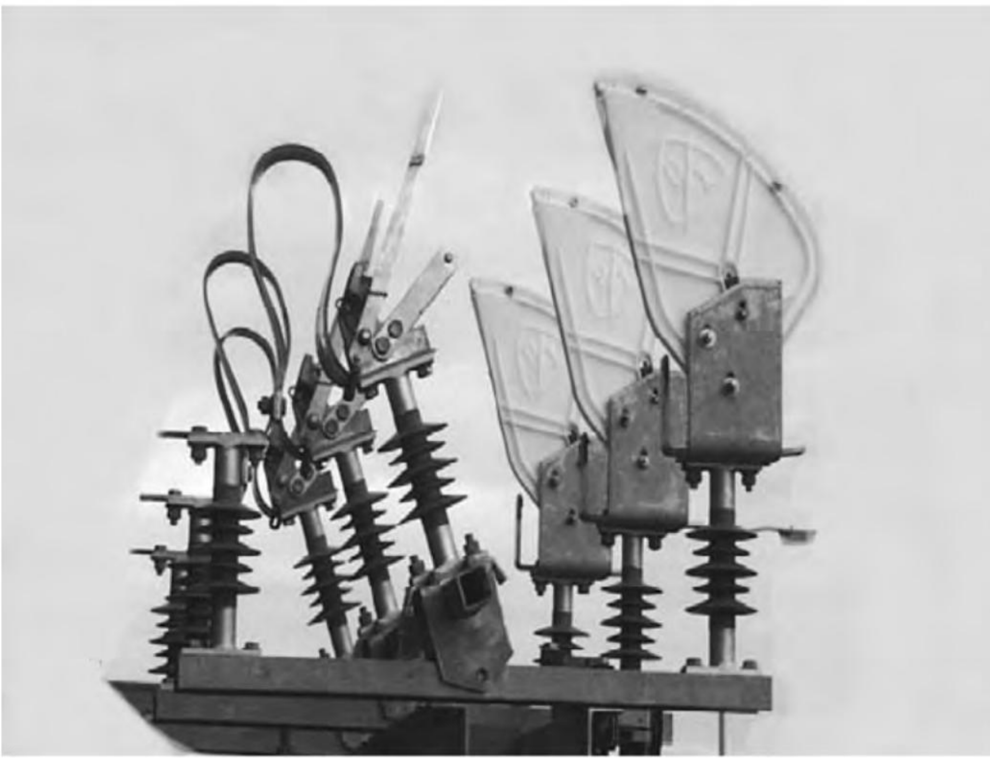


Fig. 3.2 (b) *: Air-break isolator switch using EPDM and silicone insulators*

3.3 CABLES

In busy areas, cities and places where sufficient space is not available for power transmission, insulated wires (or cables) are used. Cables are costlier, the over all cost of cable transmission can be 5 to 6 times or more compared to overhead lines for the same distance. The power cables can be either single core or two core and are used for single-phase, 2-wire system. 3 core, 3½ or 4 core are meant for 3-phase 3-wire and 4-wire systems. The cables are designed for 1100 V/660 V operation or less for low voltage operation (used for 400/440 V supply). High voltage cables are meant for 3.3 kV to 33 kV or more. Cable conductor will be with alloy copper or aluminium conductor. Now a days cable insulation in generally PVC, XLPE or paper insulated upto 11 kV and XLPE and paper-oil insulated cables for above 11 kV. Cable conductors are sector, segmented or oval shaped stranded conductors. Round conductor configuration in used for cross section up to 15 mm^2, while segmented and oval shapes are preferred for larger cross sectional areas. Usually lead sheet or armour is provided as protection against mechanical stresses and moisture ingress.

Conductor resistance is the same as with bare conductor expect that the *dc* resistance is multiplied by a factor to correct for skin effect, proximity effect and temperature rise. R_{ac} the *ac* resistance for 50 Hz and operating temperature of 80°C (may be 2.2 times that of *dc* resistance at 20°C.

Capacitance Single-core cables and 3-core cables with screened circular conductors have the capacitance

$$C = \frac{0.0246\varepsilon_r}{\log \dfrac{r_1}{r_c}} \text{ nF/km/ph}$$

where ε_r = dielectric constant r = radius of conductor and r_c radius of screen or shield. For other types of conductors, the measured value is given by the manufacturer.

Inductance $$L = 0.460 \log \frac{D_m}{r'} \text{ mH/ph/km}$$

where D_m = geometric mean distance

r = geometrical mean radius

Even though conductor current ratings are given by the manufactures, the actual current rating in determined by

(i) ambient temperature

(ii) depth at which it is buried

(iii) thermal conductance of the soil, duct, ground surface, etc.

Usually cables are buried at a depth of 0.75 to 1.25 m below the ground depending voltage of operation and the conductor temperature will not be more than 75° to 85°C (i.e) allowing not more than 30°C over an ambient maximum temperature of 45°C.

Typical cable along with cross sections are given in Fig. 3.3 a and b.

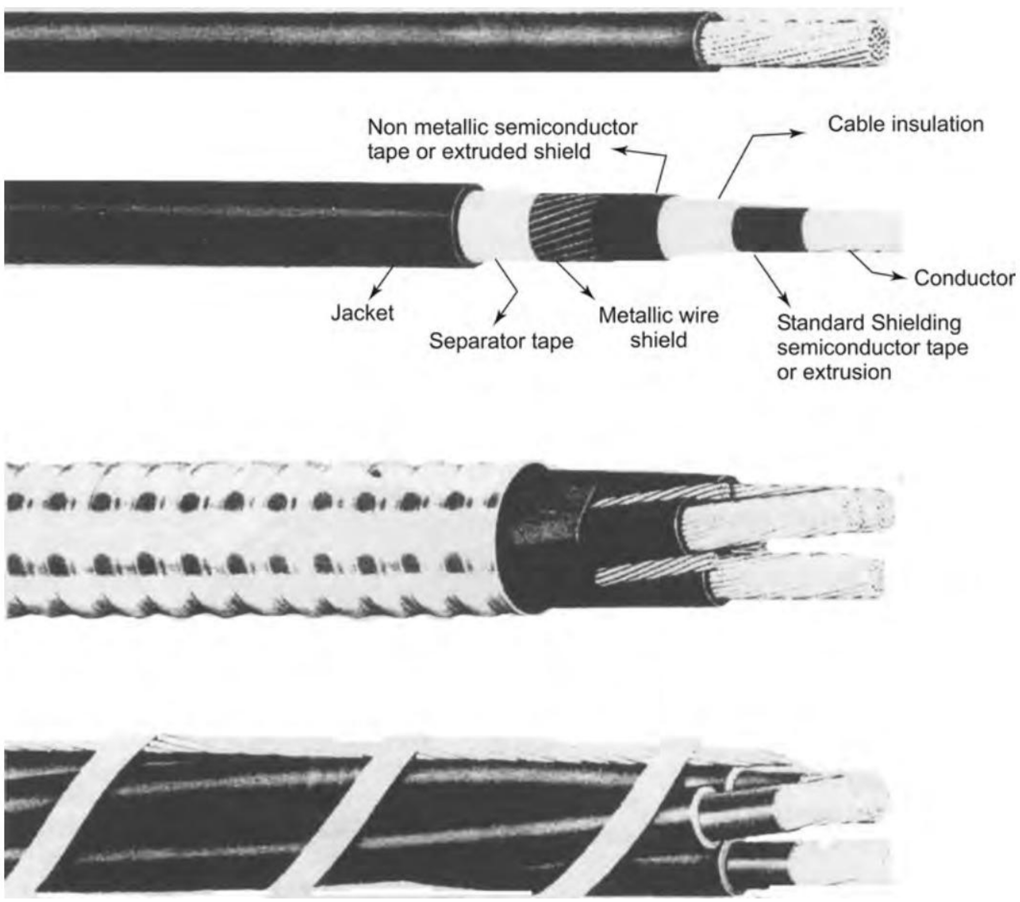
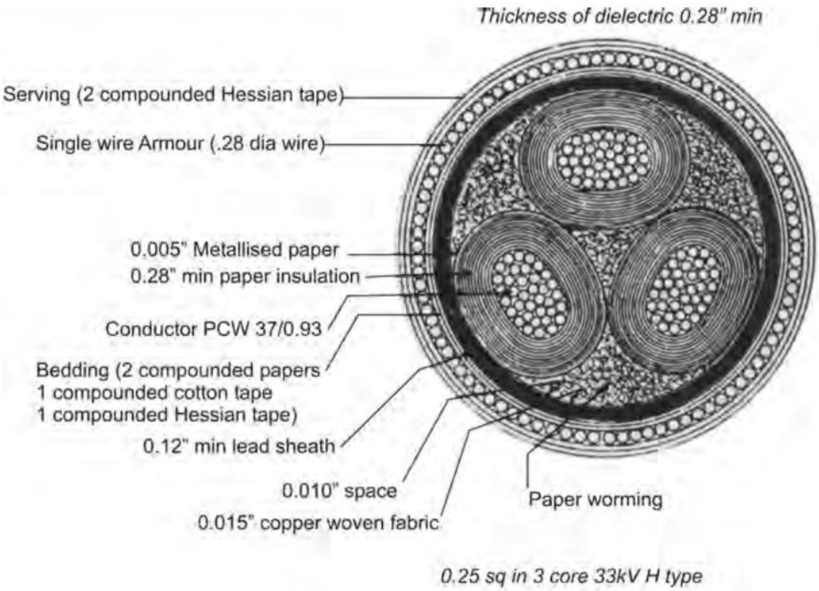


Fig. 3.3(a) *Shield cables: single and three core*



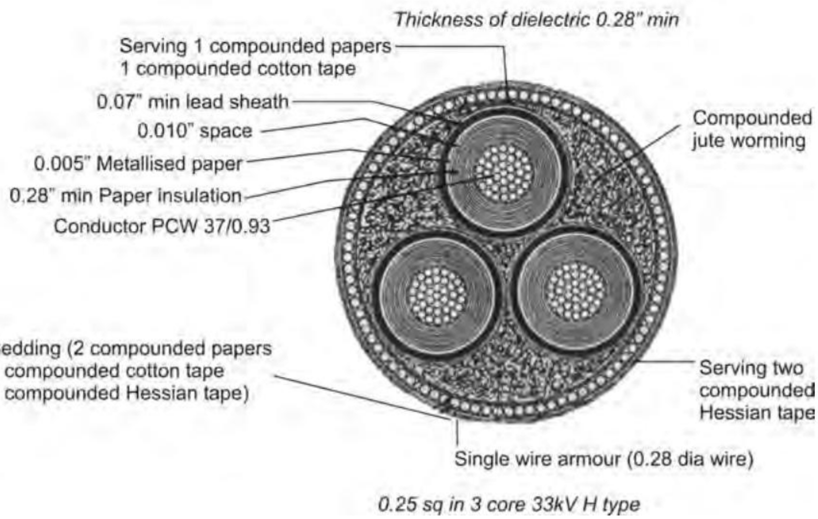


Fig. 3.3(b) *Cross section of typical H type and S.L. cables*

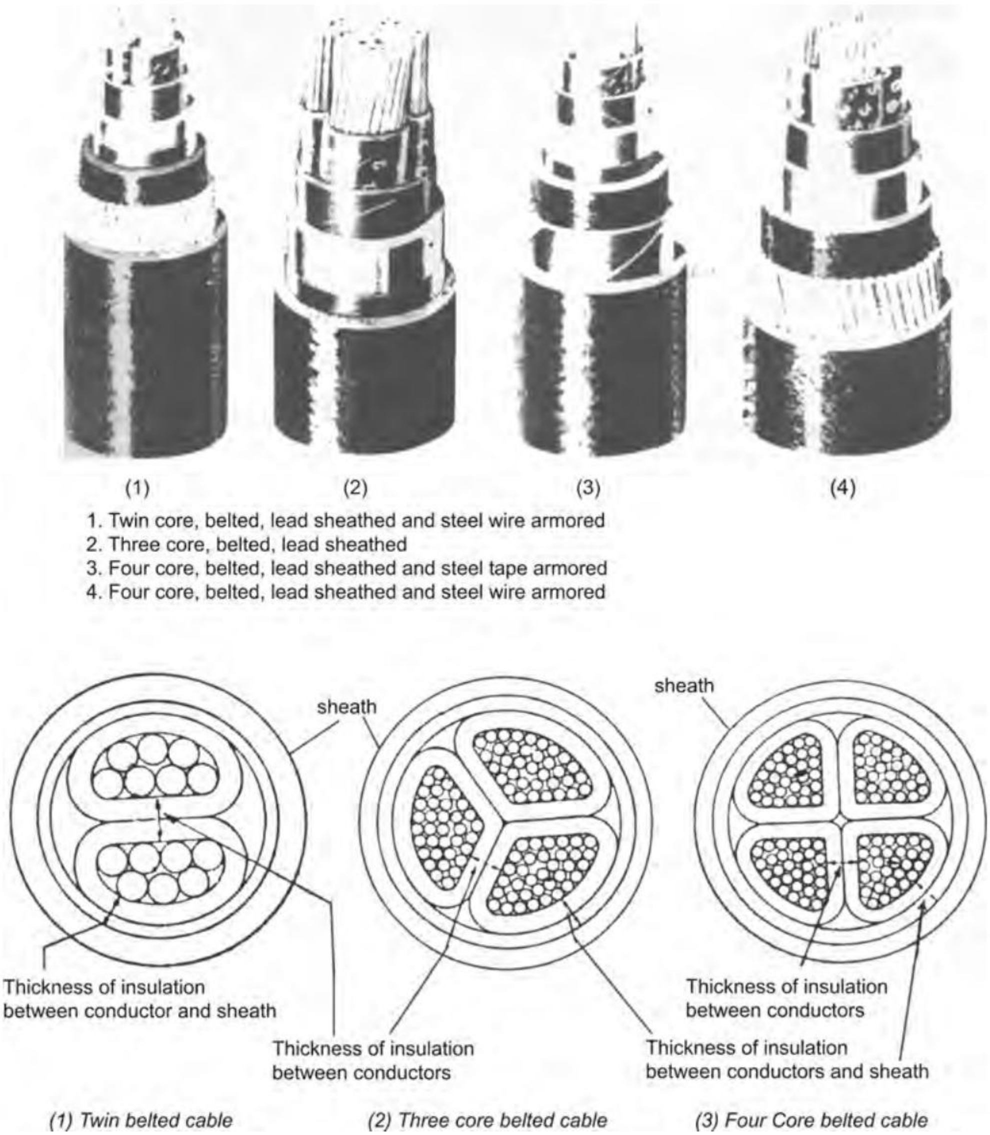


Fig. 3.3(c) *Low voltage cables*

3.4 INSULATION RESISTANCE

Electrical insulation and insulation resistance is most important aspect for both overhead transmission as well as for insulated cables. This is the resistance per phase to the ground and should be usually in mega ohms, so that leakage currents will be in micro amperes only. The leakage currents will be (i) the volume current that flows through the insulation due to conductance, dielectric absorption and capacitance and (ii) the surface leakage currents due to the surface condition of the cable and any other deposits like moisture dust etc. present on the surface. Insulation resistance is affected by (i) temperature, (ii) moisture, (iii) surface conditions, and (iv) aging and curing. Typical values of insulation resistance may be not less than 10 MΩ for 400/440 V, 250 MΩ for 11 kV and 400 to 500 MΩ for 33 kV rated equipment or apparatus.

3.5 VOLTAGE DROP AND POWER LOSS IN CONDUCTIONS

The most important aspect of the distribution system is voltage drop and power losses. These should be as minimum as possible. For distances up to 30-km line length, both cables and over head lines are approximated only with the series impedance as shown in Fig.3.4.

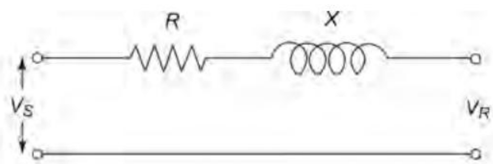


Fig. 3.4 *Line representation with series impedance Z = R + jX*

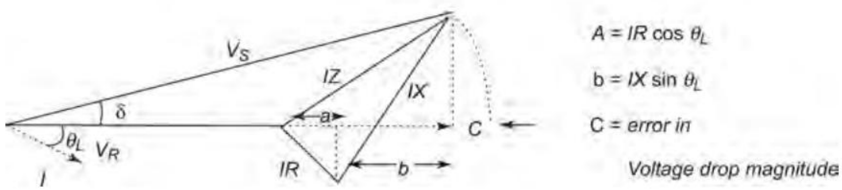


Fig. 3.4(a) *Phasor diagram*

The voltage drop in the line conductor/ph is given by IZ where $Z = R + jX = Z\underline{|\theta}$

For a lagging load of I at $p.f = \cos\theta_L$,

the voltage drop is $(I\underline{|-\theta_L}).(Z\underline{|\theta_C})$

$$= IZ(\theta_C - \theta_L) = I(\cos\theta_L - j\sin\theta_L)(R + jX)$$

$$= I(R\cos\theta_L + X\sin\theta_L) + j(R\sin\theta_L - X\cos\theta_L)$$

Usually I $(R\sin\theta_L - X\cos\theta_L)$ will be small hence voltage drop is

$$\approx I(R\cos\theta_L + X\sin\theta_L) \quad \text{.... (3.8)}$$

and receiving end voltage is

$$V_R = V_S - I(R\cos\theta_2 + X\sin\theta_L)$$

or $$V_s = V_R + I(R\cos\theta_L + X\sin\theta_L)$$

The phasor diagram is given in Fig. 3.4a. It may be noted that the error in magnitude by neglecting $I(R\sin\theta_L - X\cos\theta_L)$ 'c' , will be usually less than 3% in practical cases.

Power Loss The power loss per conductor is given by I^2R and for a Three phase line it will be $3I^2R$. In case of Three-phase, 4-wire system, the power loss will be $I_1^2R + I_2^2R + I_3^2R + I_n^2R_n$ where I_1, I_2, I_3 and I_n are the 3 phase and neutral currents and R and R_n are the resistances of phase conductor and neutral. A detailed discussion on voltage drop and power loss calculation is given in the next chapter (chapter 6). In actual distribution system these calculations are simplified and presented in a different manner.

Example 3.1 *A single-phase 230-V, 50-Hz line for street light purposes in run using 7/2.11 conductor over a length of 3.2 km. The conductor spacing is 0.6m. Determine the resistance, inductance and impedance of line per km.*
The resistance per conductor/km is 1.4Ω at 20°C.

Solution Taking the temperature rise of the conductor to be 50ºC.

Resistance per conductor per km = $R_{70°}$ = 1.4[1 + 0.00403 × 50]

= 1.4 × [1 + 0.201] = 1.6814 Ω / km / conductor

For 3.2-km length and 2 conductors

$$R = (1.6814) \times 2 \times 3.2 = 10.76\ \Omega$$

Inductance/km $$L = 0.4\ \text{In}\ D/r' = 0.4\ \text{In}\frac{60}{(0.7788 \times 0.633)} = 1.92\,mH$$

Inductance for 3.2 km = 1.92 × 3.2 = 6.15 mH

reactance at 50 Hz = 6.15 × 10^{-3} × 314 = 1.932 Ω

Hence impedance of the line is (10.76 + j1.932) Ω

And impedance of the line per km is 3.362 + j0.603 Ω/km

Example 3.2 *In the above problem (Example 3.1) if the average current is 10 A, at 0.8 p.f lag what in the power loss ?*

Solution Total power loss = I^2R = 10^2 × 10.76 = 1.076 kW

Voltage drop $\approx I\,(R\cos\theta + X\sin\theta)$

= 10 (3.362 × 0.8 + 0.59 × 0.6)

= 10 (2.9 + 3.54) = 64.4V

Note: The conductor used is not a good choice as power loss and voltage drop for an avarage current of 10A is too high.

Example 3.3 *A single phase $\frac{11}{\sqrt{3}} kV$ line feeds an agricultural load of 10 kW at 0.7 p.f through a conductor 7/2. 11 over a distance of 7 km. If the sending end voltage is 6300 V, what will be voltage at the load end ? Take the impedance of the line as in Example 3.1.*
Line impedance per km 3.36 + j0.603Ω

Solution Load current $= \dfrac{10,000}{0.7 \times 6300} = 2.26\text{A}$

Total impedance of line $(3.36 + j0.603) \times 7 = 23.5 + j4.221$

Voltage drop $I(R\cos\phi + X\sin\phi)$

$$= 2.26(23.52 \times 0.7 + 4.221 \times 0.714) = 37.28 + 3.01 \approx 40.3\text{V}$$

Voltage at receiving end $= 6300 - 40.3$

$= 6259.7\text{V}$

% voltage drop $= \dfrac{40.3}{6300} \times 100 = 0.64\%$

Summary

The electrical characteristics of overhead lines and cables (viz.), the resistance, inductance and capacitance of single-phase and three-phase lines are given. Different types of insulators used in overhead lines and line configurations along with line hardware is discussed. Performance of overhead lines (i.e.) the regulation, voltage drop and power losses is explained with suitable examples

Keywords

Overhead lines
Line parameters
Cables
Voltage drop
Insulators
Power loss

Review Questions

1. What are the merits and disadvantages of overhead power lines over cables?
2. What are electrical and other parameters of the lines that influence the distribution line performance?
3. Briefly discuss the use of underground cables for power distribution. What are the common types of cables used and their conductor and insulation and configuration.
4. Compare overhead line and underground cable distribution system.
5. How is the capacitance of a 3-phase 3-core sheathed cable calculated or estimated?

Problems

6. Find the inductance and capacitance of a two-wire line with conductor diameter 1 cm and spaced 0.9 m apart. The total length of the line is 12 km.
7. A 3-phase, 3-wire line has conductors of diameter 1.9 cm and the spacing between the conductor 1.5 m, 1 m and 1 m in a triangular form. Determine the inductance and capacitance per phase per km.
8. A single-core lead shealted cable has a conductor of 10-mm diameter with insulating material of 20-mm thickness and $\in_r = 3.5$. Calculate the inductance and capacitance per unit length (1 m and 1 Km).
9. A single-phase transmission line has a resistance 0.22 Ω and inductive reactance 0.3Ω. The line has a sending end voltage of 11,500 V when transmitting a power of 1 MVA at 0.85 p.f. logging . Find the receiving and voltage drop.
10. A 3-ph line has a line inpedance of $0.6 + j0.6\ \Omega$ and has a load of 900 KVA. If the receiving end voltage is to be 3,300 V, find the sending end voltage for load *p.f.* (a) 0.8 lag, and (b) 0.707 lag.

Multiple Choice Questions

1. For low voltage 400-V/230 distribution, the overhead line will have

   (a) 3 conductors (b) 4 conductors
   (c) 5 conductors (d) 6 conductors

2. 11-*kV*, 3-phase line can carry power of (MVA)

   (a) 3 to 5 (b) less than one
   (c) 10 (d) 25

3. Overhead lines for distribution system up to 33 kV will usually have current ratings of

   (a) less than 100 A (b) 500 A or more
   (c) 100 to 500 A (d) any rating up to 1000 A

4. PVC cables are generally used for voltage rating of

   (a) less than 1100 V (b) 33 kV and above
   (c) 11 kV to 33 kV (d) less than 10,000 V

5. For distribution lines, line reactance will be usually

   (a) far greater than resistance (b) almost equal to resistance
   (c) less than resistance (d) all the three above

6. Charging current for distribution lines is not considered because

   (a) line capacitance is very small (b) line capacitance in very large
   (c) leakage current will be too high (d) none of the above

Fill in the Blanks

7. For voltages above 11 kV, the cables insulation used in ______________.
8. The insulation resistance for 11 kV system will be about ______________.
9. Disk insulators are used as ______________.

10. The choice of conductor for overhead lines, mostly depends on __________ and __________.
11. The capacitance of a cable per unit length per phase is ______________ than that of a over head line of same rating.
12. In overhead distribution line conductor, choice on voltage-drop consideration is more important than power loss TRUE/FALSE
13. Polymeric and silicone rubber insulators are preferred because ______________
14. Insulating material used in cable of 11 kV rating and above is ______________
15. Voltage drop in power lines should be less than ______________ % for good performance

Answers

1. b	2. a	3. c	4. d	5. c	6. a

7. PVC or XLPE 8. 250 MΩ
9. Suspension or strain (tension) insulators
10. Current carrying capacity, mechanical considerations
11. More
12. TRUE
13. Light weight and better pollution performance
14. XLPE or impregnated paper
15. 5%.

Four

Distribution lines (feeders) and substations, their planning, location and installation is dealt with in this chapter. Feeder loading, feeder regulation and its importance in distribution systems is discussed.

Distribution Feeders

Introduction

Distribution system consists of supplying power to consumers, depending or their power requirements from the sub-transmission systems. Bulk power substations are located at a convenient point on the transmission systems to tap power and transport it to the utility concerns which may be large industries, townships, commercial organizations or rural & agricultural loads. A transmission substation may be a large unit of 100 MVA (MW) or more. Power is taken from such substation and fed to the loads through

(i) Sub-transmission systems (132 kV, 110 kV, 66 kV, or 33 kV)
(ii) Primary distribution feeders (11,22 or 33 kV)
(iii) Secondary distribution systems (11 or 6.6 kV)
(iv) Low-voltage distribution (400/415 V 3-ph 230/240-V single phase)

The sub-transmission and distribution systems also include substations like 33 kV/11 kV, 11 kV/415 – 400) V etc. All the above systems considered are 3-phase, 3-wire or 4-wire systems. Distribution substations will have transformers, switch gear, metering and measuring equipment, alternate feeder loops for supply in case the main feeder is out of service.

The distribution system study consists of locating of substations at load centers, planning and design of the feeders such that minimum length of lines is involved and to have lowest possible line voltage drop and line losses. At the same time it is important to see that the distribution feeders are located along a road side for easy maintenance and repair.

There are certain special distribution systems for certain applications. Electric traction in India is now 25-kV single phase with phase conductor running over the rail track and the rails are the return conductors. The traction substation are 220 kV or 132 kV or 110 kV/25 kV single phase. The primary is connected between two line conductors of the 3-ph transmission system, while the secondary is 25-kV single phase with one terminal earthed and connected between overhead lines and the rail conductors. Traction substations usually have ratings 25 to 65 MVA and spaced along the rail track at about 30 to 40 km distance.

4.1 PRIMARY AND SECONDARY DISTRIBUTION

Single line diagram of a typical sub-transmission and distributors is given in Fig.4.1.

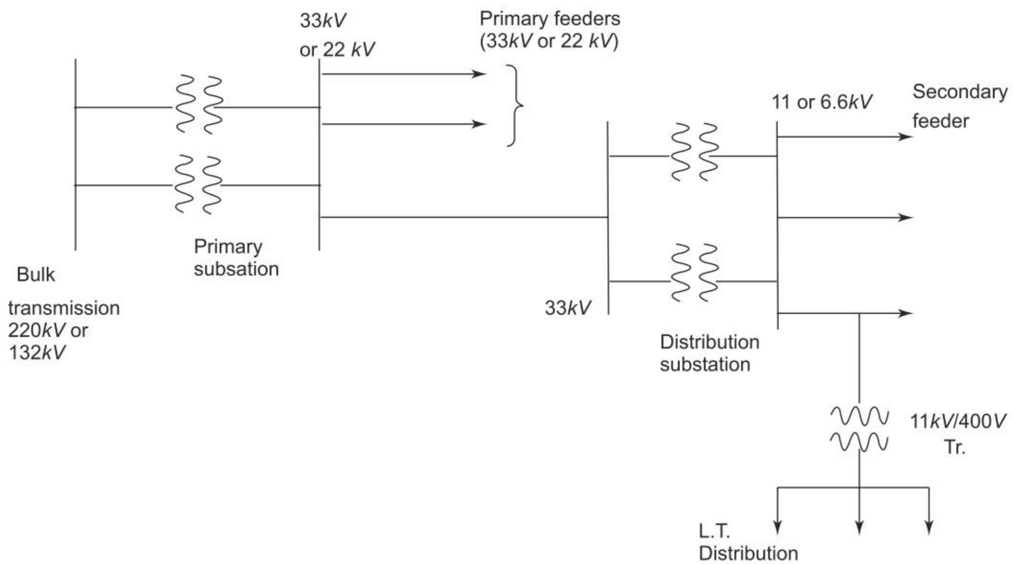


Fig. 4.1 *Typical sub-transmission and distributions systems*

The distribution system at the transmission substation which may be 220/132 kV to 33 kV or 22 kV. The substations are rated up to 1000 MVA or more and are located at the out skirts of a city or at a central remote point in a district. At present, in most parts of India, each of the district in almost every state has a loading of 500 MVA or more and cities with 1000 to 1500 MVA and above. As such there are quite a few transmission substations for every 50 km in busy areas.

4.2 DISTRIBUTION SUBSTATION LOCATION AND PLANNING

The primary task in planning distribution system is to determine the ratings of the feeder and hence the substation. The ideal way of locating a substation is to have it at the centre of a assumed circle and have all the loads/feeders directly connected to it along radial line as shown in Fig.4.2.

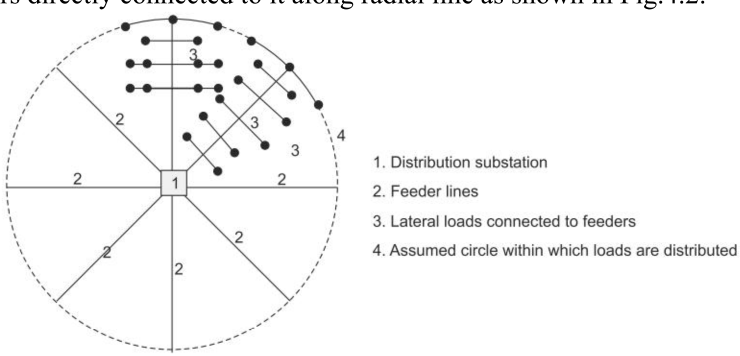


Fig. 4.2 *Ideal distribution of circular area*

But the above arrangement is not possible. In most cases, the location of substation and feeder arrangement is done such that

(i) it satisfies the voltage regulation requirements at the farthest load point
(ii) it is closer to the load centre of the area to be served and the load kVA multiplied by the distance is as minimum as possible
(iii) it has proper access for the incoming and outgoing feeders and also expansion is possible when future loads are to be added
(iv) in case of a supply feeder failure, alternate supply arrangement is possible and customers affected are a minimum
(v) the land location, right of way for the feeders and approach roads to the substation etc. are legal and are not opposed by municipal or local administration laws

The expansion or additional capacity requirements are met by either

(a) keeping the service area of given substation constant and increasing its capacity and size,

or

(b) keeping the substation capacity constant and going for new substation.

The first alternative is feasible and possible when enough place and incoming feeder capacity is available (say up to 100% or so) while the second alternative is the usual method adopted.

The size and choice of the substation for a given area depends on

(i) load density, (i.e.), kW or kVA per square km. of area under service
(ii) the number and type of consumers
(iii) future load growth

The feeder design and analysis is done based on the voltage regulation and power loss.

4.3 FEEDER LOADING AND VOLTAGE-DROP CONSIDERATIONS

Distribution lines are normally considered to be short lines with resistance and inductance of the line only considered. In Chapter 3, Section 3.5 (Figure 3.3) the equivalent circuit, the voltage drop and relation between sending end voltage (V_s) receiving end voltage (V_r) are given. The phase angle difference between V_S and V_R will be of the order of 5° or less for lagging power factor loads of 0.8 and above. In order to have a simplified expression for regulation, the % voltage drop (VD) in terms of per unit voltage is preferred.

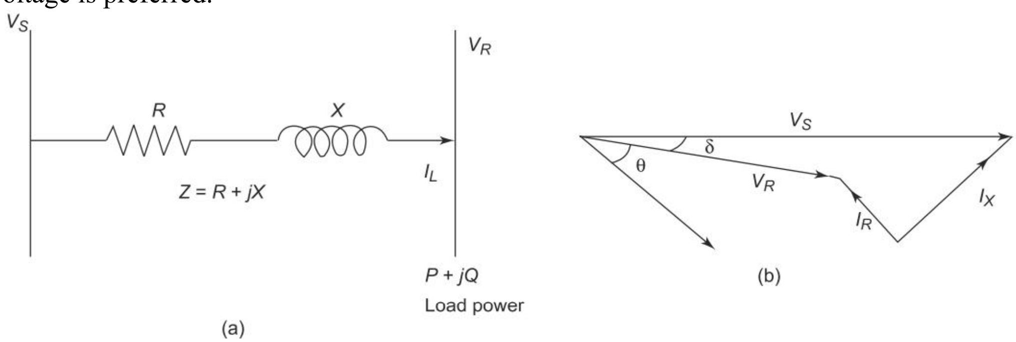


Fig. 4.3 *Short line and its phasor diagram*

The simplified diagram per phase of a a.c feeder with a load $P + jQ$ (power P and reactive power Q along with load current I_L and line impedance Z is shown in Fig. 4.3.

Let the line length be 'l' and impedance per unit length $z = r + jx$ ohms/km.

$\therefore$ Total impedance $Z = z.l$

Let receiving end voltage $= V_R \angle 0°$

Let sending end voltage $= V_S \angle \delta$

Let load current $= I_L = I \angle -\theta$ (lagging load)

$$\text{The percent regulation of the line is} = \frac{V_S - V_R}{V_R} \times 100 \qquad \text{....(4.1)}$$

Since the phase angle between V_S and V_R is usually small, the numerical difference between V_S and V_r is taken as the voltage drop

$$V_S \angle \delta = V_R \angle 0 + I_L Z$$

Referring to the phasor diagram

$$V_S = V_S(\cos\delta + j\sin\delta)$$

$$= V_R + I_L(\cos\theta - j\sin\theta)(R + jX) \qquad \text{.....(4.3)}$$

Since δ is small,

$V_S \approx V_S \cos\delta$ and $V_S \sin\delta$ is negligible

$$\therefore \quad V_S = V_R + I(R\cos\theta + jX\sin\theta)$$

$$\text{Per unit voltage } (VD) = \frac{V_S - V_R}{V_R} = \frac{I(R\cos\theta + X\sin\theta)}{V_R} \qquad \text{....(4.4)}$$

where VD = the per unit voltage regulation or per unit voltage drop and percentage voltage drop is (VD) × 100.

For leading power factors VD can be negative. Usually (VD) is not referred to the actual receiving end voltage and is rather expressed with respect to system base voltage V_b.

$$\text{as such } V_D = (V_S - V_R)/V_b \qquad \text{...(4.4a)}$$

Example 4.1 *In an 11-kV, 3-ph system, the sending end voltage is* $= \frac{11,500}{\sqrt{3}} V/\text{phase}$ *and the receiving end voltage is* $= \frac{10,500}{\sqrt{3}} V/\text{phase}$. *Find the regulation.*

Solution

$$\text{The voltage drop is as } \frac{11,500}{\sqrt{3}} - \frac{10,500}{\sqrt{3}} = \frac{1000}{\sqrt{3}}$$

$$\text{The regulation is} = \frac{\dfrac{11{,}500}{\sqrt{3}} - \dfrac{10{,}500}{\sqrt{3}}}{\dfrac{11{,}000}{\sqrt{3}}} = \frac{1000}{11{,}000} = 0.0909 \text{ or } 9.09\%$$

$$\left(\frac{11{,}000}{\sqrt{3}} \textit{ is system normal voltage per phase}\right)$$

and not

$$\frac{\left(\dfrac{11{,}500}{\sqrt{3}} - \dfrac{10{,}500}{\sqrt{3}}\right)}{\left(\dfrac{10500}{\sqrt{3}}\right)} = \frac{1000}{10500} = 0.0951 \text{ (or) } 9.51\%$$

Note: It is a different convention used in distribution systems as the customer is more interested in the drop or derivation from the rated or nominal system voltage and not on actual drops

4.3.1 Voltage Drop in Terms of Active and Reactive Power on Feeder Lines

The complex power at receiving end is $P_R + jQ_R = V_R I_L^*$

I_L^* is conjugate of the load current I_L

$$\therefore \quad I_L = \frac{P_R - jQ_R}{V_R} \qquad .....(4.5)$$

Sending-end voltage $V_S = V_R + I_L Z$

$$V_S = V_R + \left(\frac{P_R - jQ_R}{V_R}\right)(R + jX)$$

$$V_S = V_R + \frac{RP_R + XQ_R}{V_R} - \frac{jXP_R - RQ_R}{V_R}$$

Since '*j*' part is negligible

$$V_S = V_R + \frac{RP_R + XQ_R}{V_R} \qquad ....(4.6)$$

$$\therefore \quad V_S - V_R = \frac{RP_R + XQ_R}{V_R}$$

$$(VD)\, unit = \frac{V_S - V_R}{V_b} = \frac{RP_R + XQ_R}{V_R V_b} \qquad .....(4.7)$$

(V_b = system voltage or base voltage)

complex power $S = P_R + jQ_R$

and $P_R = S\cos\theta$ and $Q_R = S\sin\theta$

$$\therefore \quad (VD)PU = \frac{\left(\dfrac{S\cos\theta}{V_R}\right).R + \left(\dfrac{S\sin\theta}{V_R}\right)X}{V_b} = \frac{S(R\cos\theta + X\sin\theta)}{V_b V_R} \qquad .....(4.9)$$

4.4 VOLTAGE-DROP IN FEEDER LINES WITH DIFFERENT LOADINGS

The load connected to a feeder can be in any manner as shown in Fig.4.4.

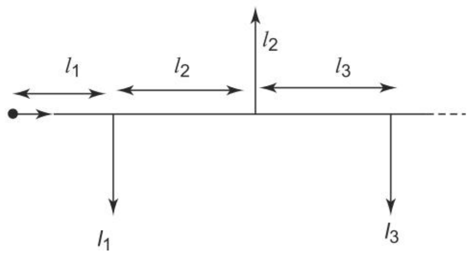


Fig. 4.4 *Feeder line loading*

The load point can be at any distance ℓ_1, ℓ_2, ℓ_3, etc. from the substation feeding point with load current I_1, I_2, I_3, etc.

The voltage-drop computations will be difficult. (This is illustrated in the examples 6.6 and 6.8 given in the Chapter 6.)

Therefore, to make mathematical analysis simple, lines are analysed with four types of 'IDEAL' loads:

(i) load at end of the line
(ii) load uniformly distributed
(iii) uniformly increasing load
(iv) uniformly decreasing load

A line-end load is one when a feeder supplies a single load long distance away from the substation. Uniform loading is one when loads are connected at every pole like street lights, residential houses, etc. Uniformly increasing or decreasing loads are ideal cases of load pattern connected to the feeder lines. An 11-kV feeder supplying an agricultural or rural loads, the load on the feeder either gradually increases or decreases. The schematic loading is shown in Fig. 4.5.

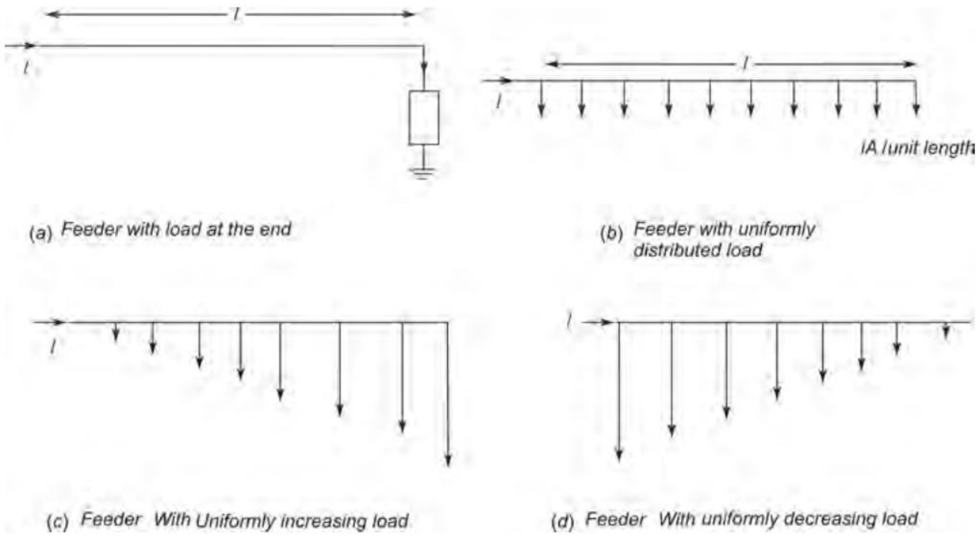


Fig. 4.5 *Different types of ideal loads on feeders*

4.4.1 Feeder with Load at the End

Impedance per unit length $= \text{'}z\text{'}\,\Omega/\text{ph}$

Total impedance $Z = z\ell$

Voltage drop (VD) $= Iz\ell$ .....(4.10)

and the power loss in the line per phase is $= I^2 r\ell$ .....(4.10a)

4.4.2 Feeder with Uniformly Distributed Load of *i* amp/unit Length

Total current $= I = i\ell$

Consider a length 'x' from the beginning of the feeder. The current up to point x is ix

$\therefore$ the voltage drop in a length 'dx' at that point is (ix) (zdx)

$\therefore$ total voltage drop over the entire length 'ℓ' is

$$= \int_0^\ell (ix)\, zdx$$

$$= iz\int_0^\ell xds = iz\frac{\ell^2}{2}$$

The total current in the line is $i\ell = I$

Hence the voltage drop in the line is $Iz\,\ell/2$ ... (4.11)

This the equal to one half of the voltage drop with line loaded at its end.

Hence the load may be considered to be at the mid point of the line

Power Loss in the Line The power loss due to the current in any section 'dx' at a distance x from the sending end is $dP'_r = (ix)^2$ rdx where 'r' resistance of conductor per unit length.

$$\therefore \text{ the total power loss } P_r = \int_0^t dP_r = \int_0^t (ix)^2 rdx$$

$$= i^2 r \int_0^t x^2 dx = \frac{i^2 r \ell^3}{3}$$

But total current $\qquad I = i\ell,\ P_r = \dfrac{I^2(r\ell)}{3} = \dfrac{I^2 R}{3}$

Hence total power loss is 1/3 of the power loss if the load were to be assumed to be concentrated at 1/3 of the distance form sending end for power loss calculations.

Figure 4.6 shows the position of the load for voltage drop calculations with line loaded uniformly.

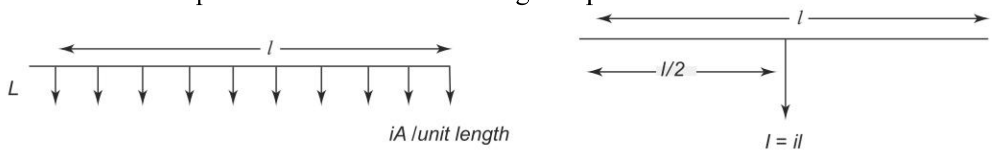


Fig. 4.6 *Line with uniformly distributed and its equivalent concentrated load for voltage drop calculations.*

4.4.3 Line with Uniformly Increasing Load

Line with a uniformly increasing loading from source is shown in Fig. 4.7.

At any point 'x' from the sending end of the line, $\dfrac{dIx}{dx} = -clx$

where I is the sending-end total current. The voltage decreases as the current increases and hence for the voltage drop calculations the rate of loading is considered as negative.

The total current from sending end $I = \int_0^t i_x x dx = i_x \ell^2/2$

Hence the current at any point x has the functional relation $i_x = \dfrac{2Ix^2}{\ell^2}$

The rate at which the current increases 'c' is $2/\ell^2$

Hence total current I_x, (i.e., current up to the point x) is $\int_0^x \dfrac{dI_x}{dx} = I\left[1 - \dfrac{x^2}{\ell^2}\right]$

(Note that at $x = 0$ total current is I and the total current goes on decreasing as distance increases)

The voltage drop in any section dx due to the current I_x is

$$dv = I_x z dx = I\,(1 - x^2/\ell^2) z dx$$

$$\text{The voltage drop (VD) } = \int_0^t dv = \int_0^t I(1 - x^2/\ell^2) z dx$$

$$= I\left[\ell - \frac{\ell^3}{3\ell^2}\right] z = \frac{2}{3} Iz\ell = \frac{2}{3} Iz \qquad \text{....(4.12)}$$

This is equivalent to having a concentrated load from 2/3 distance from sending end.

Power Loss in the Feeder The power loss in any section 'dx' is $I_x^2 rdx$

$$dP_r = I^2\left(1-\frac{x^2}{\ell_2}\right)^2 rdx$$

$\therefore$ total power loss $P_r = \int_0^t I^2\left(1-\frac{x^2}{\ell^2}\right)^2 rdx$

$$= I^2 r\int_0^t\left(1-\frac{2x^2}{\ell^2}+\frac{x^4}{\ell^4}\right)dx = I^2 r\left[x-\frac{2}{3}\frac{x^3}{\ell^2}+\frac{x^5}{5\ell^2}\right]_0^t$$

$$= I^2 r\left[1-\frac{2}{3}\ell+\frac{\ell}{5}\right] = \frac{8}{15}I^2 r\ell \quad \text{.... (4.12a)}$$

The power loss is 8/15 of the power loss with load at the end of the line.

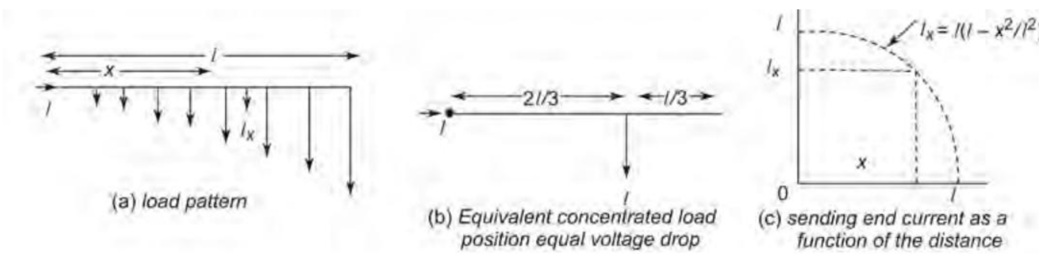


Fig. 4.7 *Line with uniformly increasing load*

4.4.4 Line with Uniformly Decreasing Load from Sending End

Line with a uniformly decreasing loading from the source as shown in Figure 4.8.

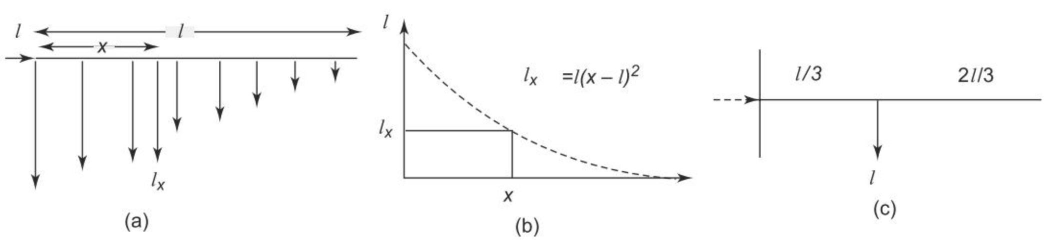


Fig. 4.8 *Line with uniformly decreasing current loading (a) Load pattern (b) Total current as a function of distance (c) Equivalent concentrated load at its location for same voltage drop*

In the case the total current I_x at any point x is given by

$$I_x = \frac{I}{\ell^2}(x-\ell)^2 = I(1-x/\ell)^2$$

$$\therefore \quad \frac{dIx}{dx} = 2I(1-x/\ell)$$

it is negative as in the previous case c ($\because$ $x/\ell < 1$) and the rate at which current loading decreases $c = 2/\ell^2$ as in the previous case.

The voltage drop in any section dx is $dv = I_{'s'}zdx$

$$\text{Voltage drop }(VD) = \int_0^t \frac{Iz}{r^2}(x-\ell)^2 dx = \frac{Iz}{\ell^2}\left.\frac{(x-\ell)^3}{3}\right]_0^\ell = \frac{Iz\ell}{3} \qquad \text{... (4.14)}$$

The voltage drop is 1/3 that of the line with load at the end of the line. The equivalent concentrated load position for equal voltage drop is shown in Fig. 4.8 c.

Power Loss Calculation The power loss with in the section 'dx'

$$dP_r = \left[I\left(1-\frac{x}{\ell}\right)^2\right]^2 rdx$$

$$\text{Total power loss } P_r = I^2 r\int_0^t \left(1-\frac{x}{\ell}\right)^4 dx = I^2 r\frac{\ell}{5} \qquad \text{... (4.14a)}$$

The analysis shown in Section 4.4. gives the effect of different pattern of loading on the voltage drop and power loss.

The loading patterns described earlier in this section are best illustrated by considering a numerical example. Usually, dedicated feeders feeding a load like an industry or concern having its own substation can be considered as one with a load at the line end or a few loads connected to the feeder at a suitable points in between. Loads connected at every pole on a low-voltage distributors in residential colonies or commercial locations are examples of uniformly distributed loads. Loads which are uniformly increasing or decreasing do not normally occur in practice.

Consider a feeder of 10-km length with 200-A load connected at the feeder end. This is equivalent to the load described in Section 4.4.1. Instead, if the feeder is connected to '20' transformers which supply the loads and are uniformly placed through out the length, this loading is equivalent to a uniformly distributed load of 20A/km. For voltage-drop analysis, this can be looked as a point load connected at the middle of the feeder (i.e.) 200-A of load, 5 km away from the feeder starting point.

4.5 VOLTAGE DROP CONSTANT 'K' FOR FEEDERS WITH DIFFERENT TYPES OF LOADINGS

The voltage drop in terms of active and reactive power transmitted is given by

$$(VD)Pu = \frac{RP_R + Q_R X}{V_b V_r} \quad \text{... (eqn 4.7)}$$

Taking the line length as 'ℓ' total 3-phase power as S_3
and impedance per unit length, $z = r + jx$

$$P_r = \frac{S_3}{3}\cos\theta; \quad Q_y = \frac{S_3}{3}\sin\theta$$

$$R = r\ell \quad \text{and} \quad X = x\ell$$

Substituting $(V.D)Pu = \dfrac{(S_3)\ell(r\cos\theta + x\sin\theta)}{3V_R V_b}$ ....(4.13)

If S_3 is expressed in kVA, V_R and V_b is volts

$$(V.D)P.u = \frac{(S_3)\ell(r\cos\theta + x\sin\theta)}{3V_R V_b} \quad \text{...(4.14)}$$

of S_3 is expressed in kVA, V_r and V_b in volts

$$(V.D)Pu = \frac{S_3\ell(r\cos\theta + x\sin\theta)\times 1000}{3V_R V_b} \quad \text{...(4.15)}$$

If S_3 is expressed in MVA, V_r and V_b in kV, $(V.D)P_u$ is same as Equation 4.13

Usually $(V.D)Pu$ is written as $= \ell \times k_1 \times S_3$

$$\text{where} \quad k_1 = \frac{(r\cos\theta + x\sin\theta)}{3V_b V_R} \quad \text{...(4.16)}$$

(voltage expressed in kV and S_3 in MVA)

$$k = k_1 \times 10^{-3} \quad \text{...(4.17)}$$

(voltage expressed in volts and S_3 in kVA)

The constants k_1 or k are functions of line base voltage V_b, conductor size, conductor spacings and load p.f angle 'θ'

$\ell = \ell$ for load at line end

$\ell = \dfrac{\ell}{2}$ for uniformly loaded feeder

$\ell = \dfrac{2\ell}{3}$ *or* $\dfrac{\ell}{3}$ for uniformly increasing and uniformly decreasing loadings.

4.6 FEEDER RATING WITH SQUARE-TYPE DISTRIBUTION SYSTEM

Usually, the town planning will be such that the streets are formed as parallel lanes and the feeders and distributions are run along the side of the roads. For highly dense populated area with residential flats, etc. each building or a group of buildings can have their own transformer. Other wise the transformer is located at a convenient place and L.T lines (Feeders) are run along the streets. The houses are given supply connection from poles of the overhead line. The distribution substation location and capacity is determined by a assuming the load density and the length of the feeder lines and limiting the voltage drop to a set value.

4.6.1 A Square-Shaped Distribution Service Area Considered for Computing Substation Capacity

A typical square shaped service area with a centrally located substation (SS) is shown in Fig. 4.9. To arrive at the % voltage drop (VD) with a load density 'D' kVA/unit area, let a square area $\ell \times \ell$ be fed from substation 'SS' as shown in Fig. 4.9. Let the load density be D kVA/km^2. Total load $S = \ell^2 D$. Let the area be serviced by four feeders one which is shown. The area served by one feeder is $\frac{\ell^2}{4}$ and kVA rating of that feeder is $\frac{S}{4}$. Assuming uniformly increasing load on the feeder as shown in the Figure 4.9. The load is considered to be concentrated at $\frac{2}{3}$ the length (i.e.) $\frac{2}{3}\frac{\ell}{2}$ or at $\frac{\ell}{3}$.

$$\text{Hence } (\%VD) = \left(\frac{2}{3}\right)\left(\frac{\ell}{2}\right)(k)\frac{S}{4} = \frac{2}{3}\left(\frac{l}{2}\right).(kI)\frac{\ell^2}{4}$$

$$= \frac{2}{3}kD\left(\frac{\ell}{2}\right)^3 \qquad \text{...(4.18)}$$

The constant k is already given in equations 4.13 and 4.14.

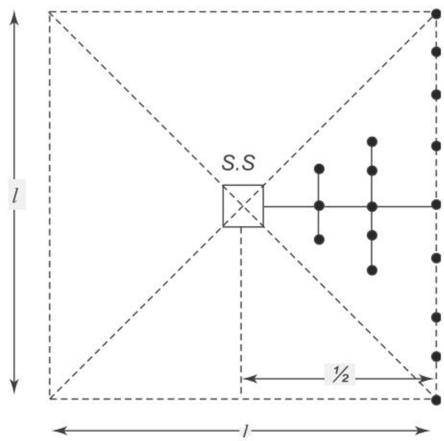


Fig. 4.9 *Square type distribution area with SS located at the centre*

In case we consider the loading to be uniform,

$$(\%\,VD) = \frac{1}{2}\left(\frac{1}{2}\right)(k)\left(\frac{S}{4}\right)$$

$$= \frac{1}{2}\left(\frac{1}{2}\right)(k.D)\left(\frac{\ell^2}{4}\right) = \frac{1}{2}kD\left(\frac{\ell}{2}\right)^3 \qquad \text{....(4.19)}$$

To conclude the (%VD) in the feeder varies as third power of the feeder length which is very important for considering line length.

To have a near approximation to the ideal system indicated in Fig. 4.2, some times a Hexagonal distribution area or in general a polygon shaped area with '*n*' feeders can be considered as shown in Figure 4.10 (a) and (b).

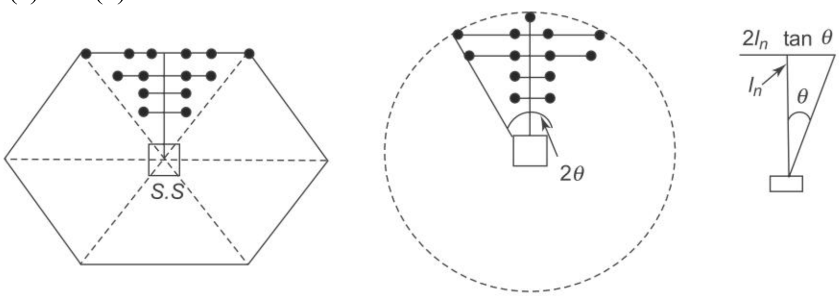


Fig. 4.10 *(a) Hexagonal distribution (b) Polygonal distribution of 'n' sides*

4.6.2 Hexagonal Distribution System—Feeder Ratings

Referring to Figure 4.10a let the feeder length be ℓ_6 so that the side of the hexagon is $\frac{2}{\sqrt{3}}\ell_6$

Area of hexagon is $6 \times \frac{1}{2}\frac{\ell_6}{\sqrt{3}} \times \ell_6 = \sqrt{3}\,\ell_6^2 = 0.577\ell_6^2$

The load served by each feeder with load density D kVA /unit area is 0.577 $D\ell_6^2$

(%VD) with uniformly increasing load is

$$\frac{2}{3}\ell_6 \times k \times D \times \frac{1}{\sqrt{3}} \times \ell_6^2 = 0.385\,k\,D\ell_6^3 \qquad ....(4.20)$$

(%VD) with uniformly distributed load is

$$\frac{1}{2} \times \ell_6 \times kD.\frac{1}{\sqrt{3}}(\ell_6)^2 = 0.289\,kD\ell_6^3 \qquad ...(4.21)$$

4.6.3 '*n*' sided Polygonal Distribution System Feeder

Referring to Fig. 4.10(b) let the feeder length = 'ℓ_n'

The area served by the feeder is = $\ell_n^2 \tan\theta$

(side of polygon is = $2\ell_n$ and area of the triangle is $= \frac{1}{2} \times 2\ell_n \tan\theta \times \ell_n = \ell_n^2 \tan\theta$

with uniformly increasing load

$$\%VD = \frac{2}{3}\ell_n kD\ell_n^2 \tan\theta \left(\theta = \frac{\pi}{n}\right)$$

$$= \frac{2}{3} kD\ell_n^3 \tan\left(\frac{\pi}{n}\right)$$

With uniformly distributed load

$$\%VD = \frac{1}{2} kD\ell_n^3 \tan\left(\frac{\pi}{n}\right)$$

Note: in the case of an ideal circular area divided into n segments and feeder length

ℓ = radius of the circle

Area enclosed in an angular segment 'θ' with n radial feeders = $\frac{\pi}{n}\ell^2$

$$\%\ VD \text{ for uniformly increasing load } = \frac{2}{3}\left(\frac{\pi}{n}\right) kD\ell^3 \left(\tan\frac{\pi}{n} = \frac{\pi}{n} \text{ for } n \text{ large}\right) \quad ...(4.22)$$

$$\text{and } \%\ VD \text{ for uniformly distributed load } = \frac{\pi}{2n} kD\ell^3 \quad ....(4.23)$$

The voltage-drop computations and their effect on the feeder loading and capacity are best illustrated in the following numerical example.

Example 4.2 *An 11-kV, 3-phase distribution line has 37/2.59 ACSR conductor with conductor spacing of 0.8 m in equilateral triangle form. The load supplied is at 0.85 p.f. lagging. Determine the constant k for % VD.*

Solution Resistance of conductor per km = 0.180 Ω/km (Table 3.1)

L = inductance per km = 1.20 ln D/r (Equation 3.2)

D = 0.8 m and r' = 0.92 cm

$$L \equiv 0.2 \ln \frac{0.8}{0.92 \times 10^{-2}} = 0.893\,\text{mH}$$

Inductive reactance 'x' at 50 Hz = 0.280 Ω/km

$$k = \frac{(r\cos\theta + x\sin\theta)1000}{V_R V_b} \qquad \sin\theta = 0.5287,\ \cos\theta = 0.85$$

$$\text{Take} \quad V_R = V_b = \frac{11{,}000}{\sqrt{3}} = \frac{11}{\sqrt{3}}\,\text{kV}$$

The k per unit MVA per km of % VD

$$= \left[\frac{(0.18)(0.85) + (0.28)(0.5267)}{\left(\frac{11}{\sqrt{3}}\right)\left(\frac{11}{\sqrt{3}}\right)} \right] \times \frac{1}{3}$$

$$= \left(\frac{0.3005}{121/2} \right) \times \frac{1}{3} = \frac{0.3005}{121} = 2.483 \times 10^{-3}$$

i.e., $k_1 = 0.248\%$ VD/MVA – km

or $k = 0.248 \times 10^{-3}$ VD/kVA – km

Example 4.3 *The feeder in Example 1 carries a load of 750 KVA, 15 km away from the sending end. What is % VD?*

Solution Taking sending-end voltage = 11-kV, 3-phase

$\% VD = \ell \times k \times S \quad \ell = 15$ km $\quad k = 0.248\% \quad S = 0.75$ MVA

$\% VD = 15 \times 0.248 \times 0.75 = 2.79\%$

Example 4.4 *If the load carried by the feeder in Example 4.2 is 1 MVA and uniformly distributed what is the % VD ?*

Solution For uniformly distributed load, the effective length is ½.

Hence $\quad \%VD = \frac{15}{2} \times 0.248 \times 1.0 = 1.86\%$

Example 4.5 *If the loading in Example 4.2 is uniformly increasing what is the % VD ?*

Solution In this case, the effective length is 2/3 ℓ

Hence $$\%VD = \frac{2}{3} \times 15 \times 0.248 \times 1.0 = 2.48\%$$

[*Note:* In all the above examples the conductor size and spacing is taken to give very less k. In actual practice the line impedance will be generally 3 to 4 times more and % VD comes to be around 10%]

Example 4.6 *An industrial area near a city was found to have a load density 0.5 MVA/*km^2*. The total area was to be located between a rectangular strip of 8* km × *4* km*. Determine suitable number of 33/11* kV *substations, their capacity and feeder length. The loads are served by 11-*kV *feeders.*

Solution Total load = 8 × 4 × 0.5 = 16 MVA

Usually an 11-kV feeder is loaded to maximum of 15 MVA-km

Since the rectangular area has a length of 8 km, each feeder may be loaded to not more than 15/8 ≈ 2 MVA. This requires about 16/2 = 8 feeders.

Normally, 33/11-kV substation will cater 4 to 6 feeders and up to 10 MVA. Selecting 4 feeders on each substation and making each substation of 8 MVA capacity, two substations may be required.

The area is divided into 2 square sections of 4 km × 4 km and each of the substation will be located at its center with feeder length = 2 km.

Hence load per feeder is $$\frac{8\text{ MVA}}{4} = 2\text{ MVA}$$

current on each feeder $$= \frac{2 \times 10^3\text{ kVA}}{\sqrt{3} \times 1\text{ kV}} \approx 105\text{ A}$$

Feeder conductor can be chosen to be 50 mm^2 ACSR conductor 7/3.355 mm., (diameter of it is 10 mm). The resistance is 0.93 Ω/km at 20°C.

Inductance $$L = 0.2 \ln \frac{100}{0.5} = 0.333\ \Omega/\text{km}$$

and resistance at operating temperature may be taken as 1.30Ω for temperature rise, skin effect and joints (40% more)

Hence Z/ph = 1.3 + j 0.333 Ω/km

Hence 'k' for 2 MVA and 0.85 p.f lagging load uniformly distributed over a length of (2 km + 2 km) for each substation is

$$k = \left(\frac{r \cos\theta + x \sin\theta}{V_r V_b} \right) \times \frac{1}{3}$$

$$V_r = V_b = \frac{11}{\sqrt{3}} KV, \quad \cos\theta = 0.85, \quad \sin\theta = 0.5267$$

$$k = \frac{1.3 \times 0.85 + 0.33 \times 9.5267}{\frac{11}{\sqrt{3}} \times \frac{11}{\sqrt{3}}} \times \frac{1}{3} = 0.0106$$

or 1.06 VD% MVA – km

% VD of each feeder with uniform loading with $\ell = 4$ km and $S = 2$ MVA

$$\frac{4}{2} \times 1.06 \times 2 = 4.24\%$$

[*Note:* This problem is a simplified example of an actual load survey done by the author. The data is simplified. The feeder length was about 6 km and % VD was about 11% at peak load time.]

Summary

In this chapter, the main feature of the distribution system i.e., the location of the substation, feeder lines and types of loading that can occur are dealt with. The effect of different loading patterns on the voltage-drop, hence regulation and power loss is discussed. Ideal cases of the distributor patterns are presented.

Keywords

Primary and secondary distribution

Substation location and planning

Feeder loading

Voltage-drop

Power loss

Voltage-drop constant

Review Questions

1. What is a distribution system ? How is it subdivided to cater the needs of the customers ?
2. Discuss the arrangement of primary and secondary distribution systems ?
3. What is the importance of % voltage drop (% VD) in feeder lines ? What are the factors that affect % VD.
4. Discuss how an ideal substation with feeders can be arranged ? How is it analyzed for % VD.
5. What are the different 'IDEAL' types of loadings on a feeder ?
6. Compare the % VD of the feeders with square-type service area and hexagonal-type service area.
7. How do you analyze the distribution substation areas shaped as (i) square, (ii) hexagonal, and (iii) n sided polygon ?

8. How do you choose the primary feeder arrangement from reliability point of view ? Discuss the arrangements with suitable diagrams
9. Derive the equation for load power factor for which voltage drop is minimum in terms of line parameters (resistance and reactance).
10. What is the advantage of square-type distributor and service area and how is the substation capacity arrived at ?

Problems

11. A 230 V single phase feeder has resistance and reactance per km = $1.5 + j0.6\Omega$. What is the load it can supply with % $VD = 5.0$ when
    (i) load is uniformly distributed
    (ii) located at the feeder end
    (iii) uniformly decreasing load. Take feeder length = 1.5 km.
12. In question (10) the feeder is a 3-ph, 3-wire line with balanced load 400 V supply. Find the load for different conditions given.
13. A 3-ph, 11-kV line uses a /3.15 mm AAC conductor (Ref Table 3.1). The conductor spacing is horizontal with 1.1 m spacing. The loading is uniformly distributed with 800 kVA. Find the maximum length to which feeder can be used if % VD is to be less than 6%.
14. What will be the maximum length of the feeder for a hexagonal distributor with $k = 0.4\%$ VD/km-MVA with a load density 500 kVA/km^2 with
    (i) uniformly distributed load
    (ii) load at the end of the feeder.
15. A colony in an urbon area is being developed with a load density of 0.3 MVA/Sq.km. The area may be taken as a rectangle of 0.5 km × 2.2 km. with two end roads and one middle road length wise and 10 cross roads connecting the three main roads. Determine the suitable number of 11,000/415 kV substations their location and the corresponding feeder lengths.

Multiple Choice Questions

1. The ideal type of area that can selected with SS at its centre is
   (a) square (b) hexagonal
   (c) circular (d) polygon
2. % k for the 11-kV feeder line will be of the order of (k given as % VD/MVA-km)
   (a) 1.0 (b) 0.001
   (c) 1 to 10 (d) 0.1 to 1.0
3. 'k' is a function of
   (a) supply voltage
   (b) supply voltage and line parameters and load p.f
   (c) supply voltage and load p.f
   (d) line parameters and load p.f

4. A 400-V 3-ph 4-wire LT distribution line with uniform load can carry a load of
   (a) 50 to 200 kVA (b) 500 kVA
   (c) less than 50 KVA (d) no limit
5. The single phase HT distribution for agricultural and rural loads is
   (a) 230 V (b) $11/\sqrt{3}$ kV
   (c) 3.3 kV (d) $33/\sqrt{3}$ kV
6. For which type of the following loads is voltage-drop minimum ?
   (a) Load at the end of the feeder (b) Uniformly distributed load
   (c) Uniformly increasing load (d) Uniformly decreasing load
7. With a line having an uniformly increasing load, the location of equivalent concentrated load for same voltage-drop is at
   (a) middle of the line (b) at the end of the line
   (c) at 2/3 distance from sending end (d) at 1/3 distance from sending end
8. For same power loss, the location of the equivalent concentrated load in a line with uniformly distributed load is at the
   (a) middle of the line (b) 1/3 distance from sending end
   (c) 2/3 distance from sending end (d) 8/15 distance from sending end
9. Example of a nearly equivalent uniformly distributed load on feeders is
   (a) street light loading on a single-phase line
   (b) domestic load on a 3-ph line
   (c) electric traction or tramcar load
   (d) motor load connected in a workshop or factory
10. For % voltage-drop expression which of the following voltage is used ?
   (a) Sending end voltage (b) Receiving end voltage
   (c) System nominal voltage (d) Any one of the above

Fill in the Blanks

11. With uniform loading on a feeder the equivalent concentrated load will be at _______________.
12. With uniformly decreasing load on the feeder the equivalent concentrated will be at _______________ for voltage regulation calculations
13. For uniformly increasing load on a feeder the equivalent concentrated load will be at _______________ for voltage regulation calculations
14. A substation capacity in decided by considering _______________.
15. The voltage-drop VD in terms of load current P.F and line parameters is _______________.
16. For voltage-drop constant 'k' is expressed in terms of _______________.
17. VD in terms of active power P, reactive power Q and line parameters is _______________.
18. A service area for the feeder is _______________.

19. The distribution feeder line voltage is increased from 6.6 kV to 11 kV without changing conductor. The MVA capacity of the line increases by________
20. The % VD is calculated for 3-phase systems taking ____________

Answers

1. c	2. d	3. b	4. a	5. b
6. d	7. c	8. b	9. a	10. c

11. Half the length ($\ell/2$) from sending end or at middle of the line
12. $\ell/3$ from the sending end
13. $2\ell/3$ from the sending end
14. Load density, line voltage, and % VD of the feeder lines and number of feeders
15. $VD = \dfrac{I(R\cos\theta + X\sin\theta)}{V_b}$; V_b = Nominal phase voltage
16. 'S', V_R, V_S and line parameters r and x
17. $VD(pu) = \dfrac{PR + QX}{V_r V_b}$; V_b = Nominal phase voltage
18. The 'ideal' area to which a substation supplies the power normally through the feeders.
19. $\left(\dfrac{11}{6.6}\right)^2 = 2.67$
20. Phase quantities and per phase line parameters.

Five

Primary and secondary electrical distribution networks, ring and radial feeder system and their design aspects are presented.

Primary and Secondary Distribution Networks

Introduction

In the previous chapter voltage drop computation per phase for a 3-phase ac feeders is discussed. In this chapter the voltage drop and power loss calculation on feeder lines for actual operating conditions and hence the design procedure is presented. The distribution system in generally divided into two parts, the primary and secondary systems. Primary distribution is one that carries large power from the sub transmission system and will directly feed bulk loads (1 MVA or more) and voltage levels can be 11 to 66 kV depending on the distances involved and power fed. Primary distribution also supplies to the secondary distribution systems. The power supplied through high voltage lines will be 1 to 10 MVA or more by each of the feeder at 22 or 33 kV.

5.1 PRIMARY DISTRIBUTION SYSTEM

The primary distribution system starts from transmission substation 132/33 or 22 kV to the local distribution substation such as 33 or 22 kV / 11 or 6.6 kV substations. It includes the 33 kV feeders lines, their layout, metering and protection. The 33 or 22/11 or 6.6 kV substation and the entire substation equipment. These feeders are usually designed to form either a loop or individual radial lines but will have an alternate supply feeder in case of failure or emergency. Typical arrangement is shown in Fig. 5.1 as a single line diagram.

A similar arrangement is adopted at 33/11 or 6.6 kV substations and for 11 or 6.6 kV feeders also. Unlike in American practice, all the 33 kV and 11 kV systems and feeders are 3-phase 3-wire only. The busy and congested localities are served by under ground cable system where as most of the service is through overhead lines only. Recently in cities cables hung on poles are adopted to save space and clearance but are costly compared to bare wire system.

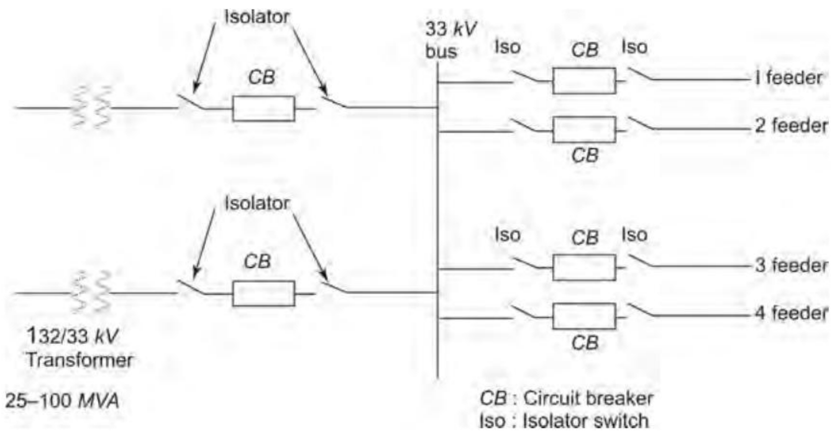


Fig. 5.1 *33 kV bus and feeder arrangement at a transmission substation*

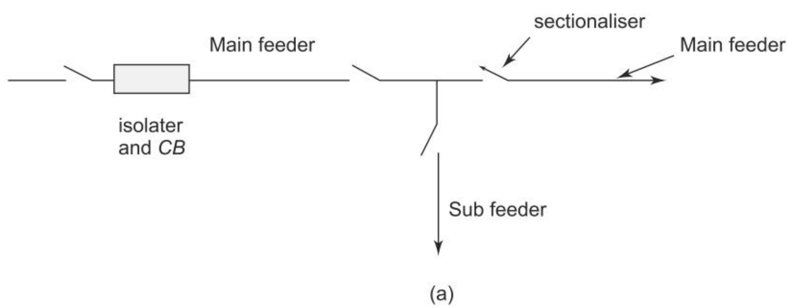


Fig. 5.2a *Feeder with sectional isolators*

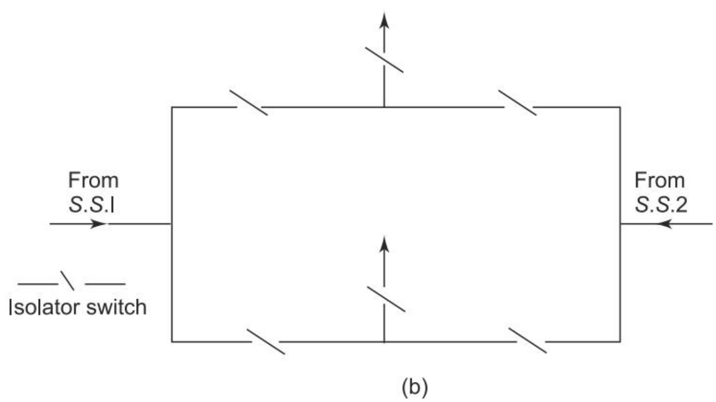


Fig. 5.2b *Typical ring feeder with isolators*

The factors that affect the selection and layout of the primary feeders are

(i) type of area to be serviced and load density
(ii) nature of load and the rate at which it may increase over a period
(iii) alternate provisions for continuity of power supply and spare capacity needed
(iv) quality and continuity of supply
(v) type of circuit (overhead or cable) and cost involved
(vi) the feeder length and route involved

In American and European systems important loads are fed directly through a separate feeder. Also the feeder that connects substation and local sub feeders, is designed with special considerations and are called EXPRESS FEEDERS. Such feeders do not exist in India and Asian countries and all feeder are designed with considerations mentioned above. In some cases very important loads such as Defence organizations, research labs, important industries etc., are directly fed from substations without any tappings. The feeder system is generally radial with branching through sectionalizers. But ring main feeder fed from more than one station is also common to provide reliable and alternate supply to important loads or areas. Single line diagram of typical radial and ring main system are given in Figure 5.2 a. In case of loop or ring feeders, disconnect switches and sectionalizers are used so that the feeding substations do not get overloaded due to unequal division of loads in each section. Line diagrams of typical ring feeders are given in Figure 5.3 a and b.

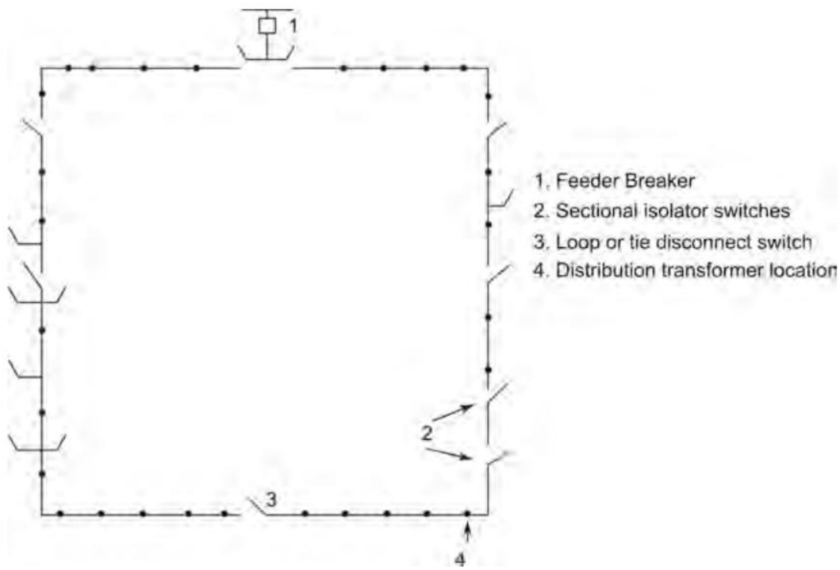


Fig. 5.3 (a) *Typical ring feeder*

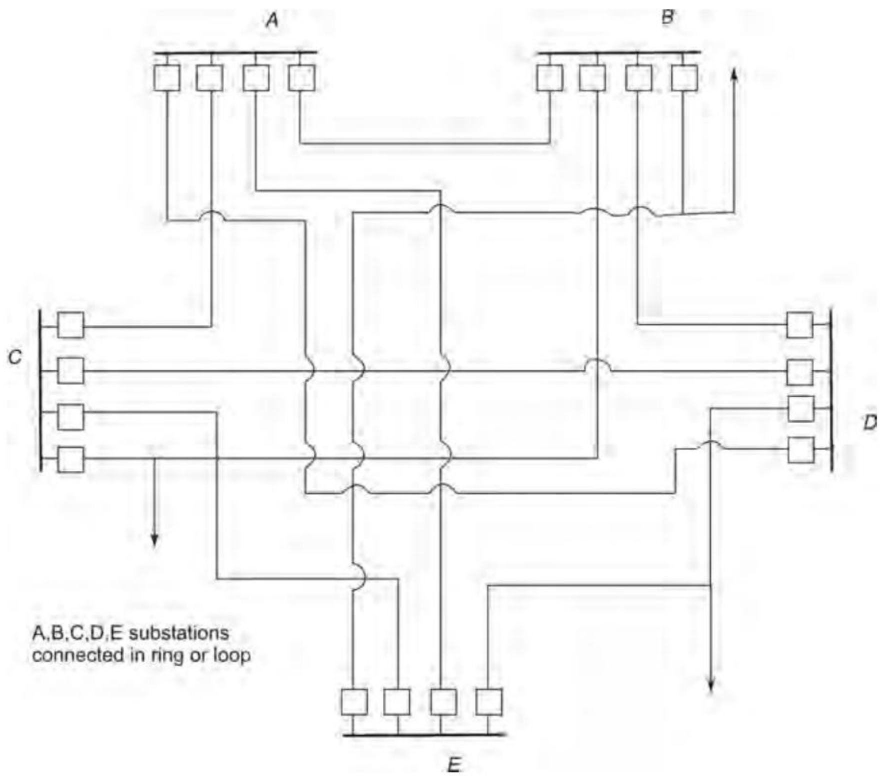


Fig. 5.3 (b) *Primary ring feeder*

5.2 PRIMARY FEEDER VOLTAGE LEVELS AND LOADING

Primary feeder voltage levels and operation is the main factor that affects the design erection cost, maintenance and effective delivery of load to the consumers.

5.2.1 Choice of Voltage Level

The factors that decide the voltage level are

(i) length and loading
(ii) number of sub transmission and distribution lines that feed the given area
(iii) number of distribution substations, their location and ratings
(iv) route plan, number of poles, sections and way clearance (like tree cutting), etc.
(v) number of customers and their importance

The primary voltage levels for distribution feeders in India are 33, 22, 11 and 6.6 kV in different states where as in Europe 34.5 kV, 15 kV (13.2 kV) are used and 33 kV in India is equivalent of 34.5 kV and 11 kV is the equivalent of 15 kV (13.2 kV) of European system). Normally in India all primary feeders are 3-phase, 3-wire. Elsewhere the 4-wire system is used and single phase power is tapped. The power carried by the system is proportional to square of the voltage. In case a 11 kV feeder is upgraded to 33 kV the power transmitted will almost becomes 9 times for a given voltage drop. Loading is directly proportional to the voltage level and the thumb rule followed for increasing the feeder voltage level is

$$\left(\frac{\text{voltage (new level)}}{\text{voltage (existing level)}}\right)^2 = V \text{ square factor } [(V^2) \text{ factor}].$$

and is equal to (load ratio) × (distance ratio) .....(5.1)

$$\text{where distance ratio} = \frac{\text{new distance}}{\text{existing distance}} \quad \text{....(5.2)}$$

$$\text{and load ratio} = \frac{\text{increased or new loading}}{\text{existing loading}} \quad \text{...(5.3)}$$

5.2.2 Feeder Loading

Feeder loading is defined as the maximum load that occurs during peak time taking into account all the possible simultaneous maximum demands. This depends on

(i) nature and density of feeder loads connected
(ii) growth rate and reserve capacity needed
(iii) continuity, reliability and quality of service assured
(iv) feeder voltage levels and regulation requirements
(v) location and capacity of the system
(vi) type, cost of construction and operating cost factors
(vii) the alternate supply provisions made

The number of feeder that serve a given area depends on load density, voltage level chosen, substation capacity, load locations conductors size that can be adopted, voltage drop and power loss considerations. The feeder lines that interconnect two sub-stations in a given area are sometimes called as “TIE LINES”.

5.3 SECONDARY DISTRIBUTION SYSTEMS

Secondary distribution is one that feeds the electrical energy to the consumers depending on the area, number of consumers and their load requirements. It can be either a HV distribution like 11 kV, 6.6. kV or 3.3 kV systems (mostly 11 kV or 6.6 kV is used in India) or LV distribution system (400 – 415 3-phase)/(230 – 240 V single phase system). As already discussed the LV consumer loads are highly different and varying, the devices connected will have all possible and conceivable combinations. The distribution system should provides for the needs of the customer maintaining the specified voltage level. Hence the secondary system should take into account both short range and long range problems, possible expansion and future needs and demands. Further the secondary distribution is to be such that it has

(i) most economic size and combination of line networks, distribution transformers (substations) and service drops (connections)
(ii) minimum circuit length, voltage drop and power losses
(iii) easy route location and maintenance, simple configuration and trouble free working
(iv) provide possibility for easy transformer load management (TLM)

5.3.1 Secondary Voltage Levels

Secondary distribution levels are standard in most countries. The European and Asian practice is 400 – 415 V, 3 phase / 230 V – 240 V single-phase. The corresponding low voltage (LT) supply systems in US and other countries are 120 V – 0 – 120 V (240 volts with centre tapping for single and 208 V 3 phase), 480 V, 3 phase / 277 V single-phase, 2.3 kV or 4.16 kV, 3 phase system etc. The choice of the voltage depends on the loads and usually the current in the drop out connection is limited to about 50 A or less for economic conductor size. The other factor that decides the voltage is the appliance voltage ratings. Most of the electrical goods in out country as well as in Asian countries, nowadays are adopted to be either 230 – 240 V for single-phase and 400 – 440 V for 3 phase. The consumers nowadays, due to short age of power and frequent power interruptions have their own generators or battery inverter power supplies.

The secondary distribution practices adopted are the following:

(i) each individual consumer is provided with separate service connection.
(ii) A group of consumers like domestic supply, commercial loads, small industries are supplied form a transformer substation with radial feeder lines.
(iii) Large consumer with loads of 25 kVA or more (for example, flats in cities, medium size commercial complexes, hospitals, etc.) are provided with their own transformer and distribution SS and directly connected to high voltage distribution.
(iv) Sometimes secondary networks are interconnected with common secondary mains called 'secondary banking'. This network may be fed from more than one primary distribution network. A secondary distribution grid may be formed when continuous uninterrupted supply is needed. Usually this is done inside large industrial concerns etc.

The secondary mains should provide for

(i) division of normal load properly among feeders and distribution transformers.
(ii) in case of faults, division of fault current properly among the network components
(iii) good voltage regulation and proper voltage at the consumer point
(iv) switching off and isolation of faults (short circuits) at any point without interrupting service mains and supply

Typical distribution network with both high voltage and low voltage mains is shown in Fig. 5.4. Secondary distribution with '**secondary banking**' is shown in Fig. 5.5. When secondary banking or paralleling of secondary distribution network is used transformer application factor (TAF) is to be considered carefully.

$$\text{TAF is defined as} = \frac{\text{total capacity of network transformers}}{\text{total secondary network load}}$$

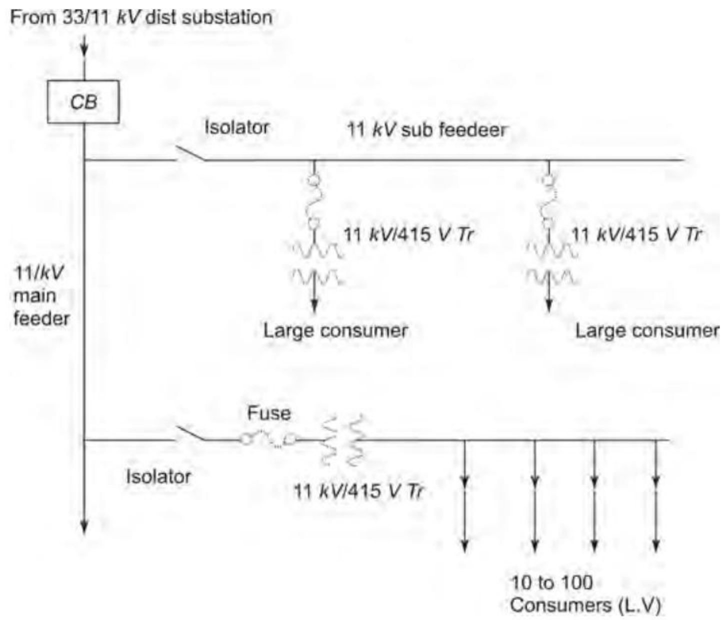


Fig. 5.4 *Typical HV and LT distribution network*

This will be about 2.0 to 2.2 for 2 and 3 feeders and about 1.5 for 4, 5 or more feeders. The contingency and service reliability will be decided by this factor.

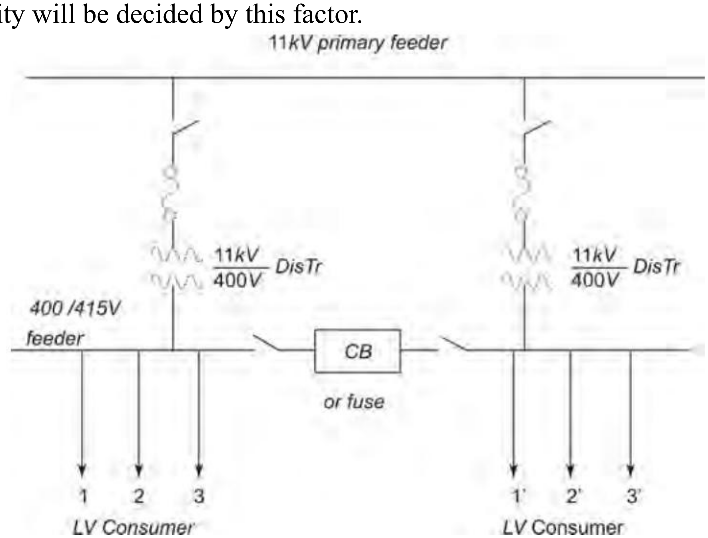


Fig. 5.5 *Distribution system with secondary banking*

The advantages of secondary banking are the following:

(i) Due to parallel operation of the distribution transformers reliability and continuity of supply is more.

(ii) Voltage regulation is better and voltage dip or drop is less when sudden loads like motor starting, etc., occurs.
(iii) In case of load growth, and future expansion more transformers can be added or the transformers can be replaced by larger units.

The disadvantages and difficulties in secondary banking are the following :

(i) overloading of one transformer may occur in case the other one goes out of service.

(ii) Coordination of secondary side fuses and protective devices is difficult.

(iii) Restoration of service to consumers on normal side takes more time in case fault occurs on one of the units.

5.4 DISTRIBUTION FEEDERS

Scheme for Distribution System Development Usually, the growth in any area either by population wise or industrial development wise takes place depending on the environmental and geographical location. For electrical power supply planning the area can be divided into square or rectangular blocks with the substation located at its centre if possible and feeders radiating in all directions. Since this is not always possible, the substation can be at one corner of the area and feeder lines can go along the sides or parallel to the sides, i.e., roads and layout. Typical layouts with existing loads and future developments are shown in Figure 5.6 a and b.

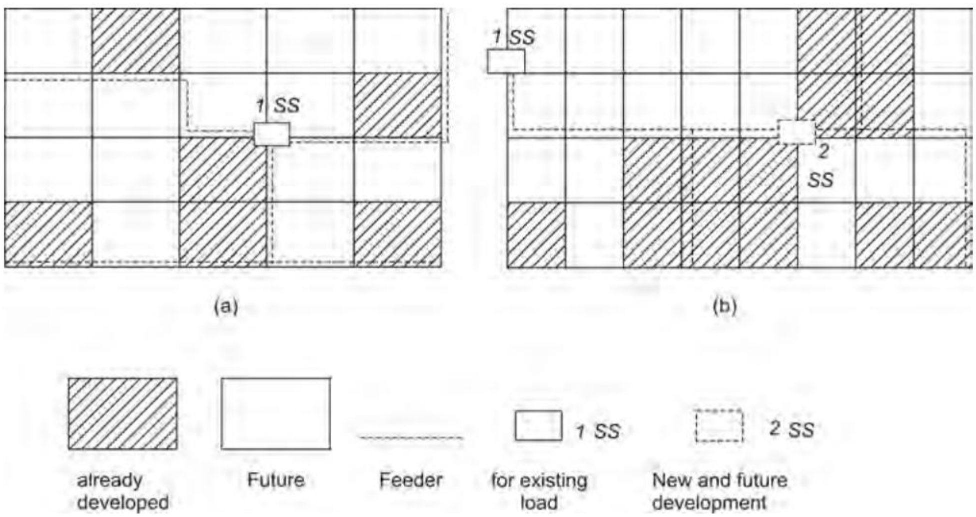


Fig. 5.6 *Rectangular distribution areas with feeding SS*

5.4.1 Simple Schemes

Usually most of the distribution networks will have both primary and secondary feeders and the system should take into account the regulation and voltage drop from the substation to the consumer end. To illustrate the situation two alternate schemes of distribution are shown in the following example.

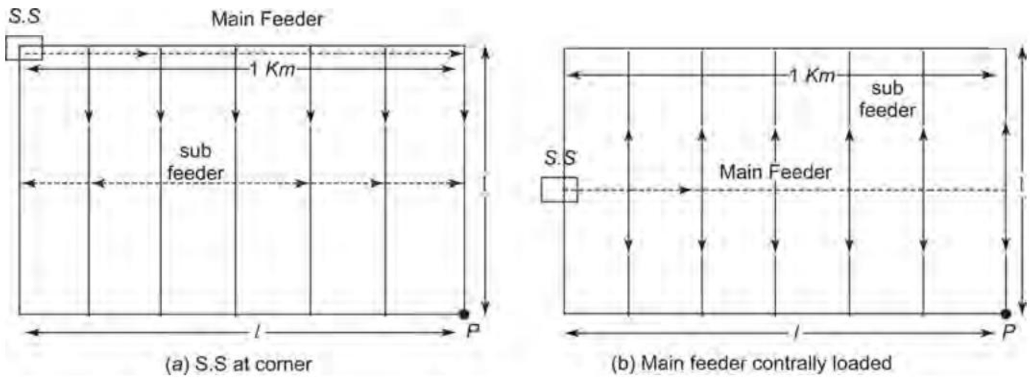


Fig. 5.7 *Square area fed with alternative schemes*

In the first scheme (Fig. 5.7a) the feeder is to be located to one end of the square area with SS at one corner of the area. Sub feeders will run along the streets tapped from the main feeder. This is usually adopted in semi urban and rural areas locating the SS at one end of the town or village. Fig. 5.7b gives a better location for the SS and feeders. The following example gives a comparison for both schemes.

Example 5.1 *Let the load density be 300 kVA/km^2.*

Let the main feeder has installed with conductor constant $k = k_m = 0.01$ % and subfeeders with conductor $k = k_i = 0.045$%. Consider a length of $\ell = 2$ km, load factor = 0.6 and diversity factor 1.2. Work out the distribution scheme.

Solution Load density in the area will be $\dfrac{0.6 \times 300}{1.2} = 150$ kVA/km^2.

Total load is = 150 × 2 × 2 = 600 kVA

(Let the total number of sub feeders = 6 (as shown in the Fig. 5.7). (Load on each sub feeder

$$S_l = \frac{600}{6} = 100)$$

$$\% \, VD \text{ for scheme 'a' will be} = \frac{1}{2} k_m \, S_m + \frac{1}{2} K_l S_l$$

$$= \frac{2}{2} \times 0.01 \times 600 + \frac{2}{2} \times 0.045 \times 100 = 6 + 4.5 = 10.5\%$$

% VD for scheme 'b' will be

$$S_l = \frac{600}{12} = 50 = \frac{2}{2} \times 0.01 \times 600 \, \frac{1}{2} \times 0.045 \times 50 = 6 + 1.125$$

$$= 7.125\%$$

Hence scheme '2' is better,

Note that in scheme 'b' the sub feeders are 12 in number instead of '6' and each of them carry one half load as compared to scheme 'a'. In both cases max. voltage drop occurs at point 'P'

5.5 DESIGN CONSIDERATIONS

Different factors that are to be taken into account for effective and efficient distribution network are the following :

(i) The total network area and load density
(ii) The number of primary feeders and its circuit distance
(iii) The number of outages, and time duration, per year
(iv) The number of planned or scheduled outages (for maintenance power cut etc.) and outage time per year
(v) The alternate or standby arrangement for the important loads in the area
(vi) The secondary and sub-system
(vii) The number of main (primary) substations, the number of transformers to be installed
(viii) The secondary substations and LT system

Further the secondary system or network should look into

(i) Proper division of load among the sub-network and transformers
(ii) The fault levels and protection schemes
(iii) Short circuits, line to ground faults and their clearing without damage to the main network and transformers
(iv) Good voltage regulation
(v) Minimum power loss in the total system

Usually the secondary and low voltage distributing network will have pole or street mounted transformer ranging from 50 to 250 kVA with 3-ph, 4-wire network. When this network is planned care should be taken to see that the distribution transformer utility (or application) factor is high. The application or utility factor is defined as T_u.

$$\text{Transformer utility factor } T_u = \frac{\sum S_T}{\sum S_L} = \frac{\text{Total capacity of transformer in the network}}{\text{Total load on the network}}$$

The design of network is based on minimizing the total annual cost (TAC) on the distribution network.

Total annual cost and operation cost is the sum total of annual installation cost pertaining to

(i) Transformer costs
(ii) Cables and overload lines
(iii) Other line hardware
(iv) Protective system
(v) Cost due to losses in equipment like transformer core loss, line losses, etc.
(vi) Investment cost in fuel, transport, etc.

This is a complex computation and data is usually taken from the existing systems. An optimum solution is usually arrived at by minimizing 'TAC' which is mainly a function of transformer capacity (Capital costs) conductor or cable sizes (costs) of main distributors and the secondary or sub distributors. The other factors that affect the choice and design are the following:

(a) The allowable margin for sudden loads like, motor starting currents without excessive dip in voltage
(b) Limiting the current (capacity) in the lines suitably so that the power drawn from the substation do not exceed at peak loads
(c) The overload capacity and margin on the transformers and substations
(d) The annual energy losses that can be tolerated

The following example gives the calculation of substation capacity.

Example 5.2 *A service area is 10 km × 8 km and has a load density of 300 kVA/km² comprising of domestic, commercial and industrial loads. Design suitable distribution system, given*

(i) the supply can be tapped from an existing 33 kV lines
(ii) the standard system voltages are 33 kV, 11 kV and 6.6 kV
(iii) not more than two 33 kV substations are permissible

Solution Total area covered is $10 \times 8 = 80$ km²

Hence total power requirement $0.300 \times 80 = 24$ MVA. Since the loads are domestic, commercial and small industrial loads, supply system to consumer will be only 400/415, 3-ph /230 – 240 V single-phase. Since only 2 substations are permitted, the length of feeders can be 10 + 8 = 18 km on average.

The maximum demand allowing load factor = 0.7, diversity factor = 1.2

$$S = \frac{20 \times 0.7}{1.2} = 14$$

A 11 kV line can used to carry up to 11 MVA km and hence can be used for longer distance than 6.6 kV. Hence, 11-kV, 3-phase system in chosen for primary distribution and 400 V 3-phase for the LT or sub-distribution.

$$\text{Capacity of each substation} = \frac{14}{2} = 7 \text{ MVA}$$

Allowing for future growth and expansion, 10 MVA capacity, 2 transformers each of 5 MVA can be chosen for each substation with a uniformly distributed load and taking the maximum length of the feeder as 20 km (18 km on average) effective length of each feeder will be $\frac{l}{2} = 10$ km. Feeder line capacity will be $\frac{11}{10} \approx 1.1$ MVA. Hence the current will be

$$I_l = \frac{1.1 \times 10^3}{\sqrt{3} \times 11} = 58 \text{ A}$$

The nearest conductor size for the feeder is ACSR 7/2.11 mm, with effective cross sectional area of 21 mm² over all diameter 6.33 mm and max current 107A at 45°C. Hence the number of feeders from each substation will be $\frac{5\,\text{MVA}}{1.1\text{ MVA}} \approx 5$

The regulation constant 'k' for this conductor with spacing 1 m apart in equilateral triangular form for load p.f of 0.85 is 0.92

$$\text{so that } \% \, VD = \frac{1}{2} \times k \times s = \frac{10}{2} \times 0.92 \times 1.1 = 5.06\%$$

The probable schematic layout of the distribution system in shown in Fig. 5.8 with all feeders radiating from the substation (Scheme 1).

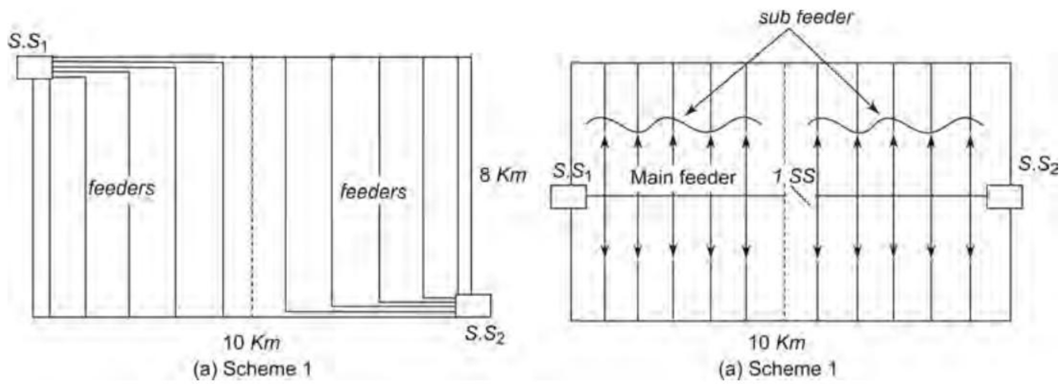


Figure 5.8

Alternately two main feeders each with 5 MVA capacity and feeding 5 sub-feeders of 1 MVA capacity can be chosen. The main feeder current will be $\dfrac{5 \times 10^3}{\sqrt{3} \times 11} \approx 300$ A

The conductor size would be 37/2.59 mm with dia = 1.41 mm, the regulation constant $k = 0.25$ for main feeder and 7/2.11 mm conductor for sub feeders as before.

The regulation constant for the lines with 1 m equilateral triangle configuration with $k = 0.92$ and 0.18% VD/km – MVA

Taking effective length as $l/2 = 2.5$ km for main feeder and $l/4 = 4$ km for sub-feeder

$$\begin{aligned} \% \, VD &= \sum \text{length} \times k \times \text{MVA} \\ &= 2.5 \times 0.18 \times 5 + 4 \times 0.9 \times 1.0 \\ &= 2.25 + 3.68 = 5.93\% \end{aligned}$$

The second scheme gives higher regulation but will be convinient and economical otherwise.

Summary

In this chapter, the power distribution aspects of primary and secondary feeders and feeder design is discussed. Ring and radial feeders, supply voltage levels for the feeders and their choice is presented.

Keywords

Distribution networks
Primary feeders
Secondary feeders
Substations
Location and planning
Voltage levels
Transformer utility factor
Design considerations

Review Questions

1. What are the differences between primary and secondary distribution systems ?
2. How is the voltage level for distribution systems decided ?
3. Give the standard voltage levels adopted for distribution system in India. What are the reasons for the choice. Compare these levels with practice in Europe and US.
4. What are the factors that affect the choice of primary feeders ?
5. Explain the voltage choice and feeder design for secondary distribution system and low voltage (LT) systems.
6. How is the design of distribution system done ? Discuss the factors that contribute for design.
7. What is total annual cost (TAC) in distribution system ? How does it help in effective design of distribution system ?
8. How are the sub-distribution network and LT distribution networks formed ? Illustrate with suitable examples.
9. Draw a line diagram of a radial-type primary feeder. Mention the factors that influence the selection of primary feeders.
10. Mention the factors that are to be considered in selecting ideal substations.
11. Give one line diagram of loop (ring) type primary feeder system and mention the different component parts. What are the considerations for planning loop (ring) feeders ?
12. How is the choice of a primary feeder arrangement made from reliability point of view. Give typical arrangement with a relevant diagram.

Problems

13. A load survey around a town with 10 km^2 area indicated that load density is 150K*VA*/km^2 with a load factor of 0.5 and diversity factor = 1.2. Work out the conductor details and % VD for
    (a) 6.6 kV, 3-phase feeder
    (b) 11 kV, 3-phase feeder
14. In Example 5.2, assuming the town to be 5 km × 2 km, determine the 400-V, 3-phase, 4-wire LT subsystem and corresponding 11 kV/400-V transformer SS. Assume that they are equally, distributed along the length of the 11 kV feeder (Maximum Tr. Capacity 150 kVA only)

15. In Example 5.2, one 11 kV/400 V substation is 100 kVA with 20% overload capacity. The LV line length is 2.5 km divided into two sections. If the line conductors are mounted 0.4 m apart horizontally (4-wire system), determine the proper conductor size, 'k' for the line and % VD at line end.

16. In a service area with load density of 250 kVA/km^2 determine the percentage VD, given

    (i) $k = k_1 = 0.05\%$ (ii) length of feeder 3.5 km

    (iii) load factor = 0.6 (iv) diversity factor 1.25

    Take the total service area to be 8 km^2.

17. In problem 16, if there is a main feeder of 2 km length and sub-feeder for the rest of the length, what will be the % VD? Take $k = k_m = 0.02\%$.

18. An urban residential area has 150 consumers with an average connected load of 2.5 kVA per customer. It is proposed to have a HV distributor of 11 kV with suitable transformers for 415 V supply. Taking the primary (11 kV) feeder to be 3.0 km and the secondary (415 V) feeder to be 2.0 km, estimate the % VD. Load diversity factor = 1.2. Transformers used 4 nos of 100 kVA each. Take k for 11-kV line as 0.02, 415 kV line as 0.045 and for transformer as 3.50%.

19. A cable transmission is used to supply the loads stated in problem 16 at 11-kV supply voltage. Assuming the load has a p.f of 0.85, estimate the voltage drop in the cable. Take $r = 1.15\Omega$ / km and $x_l = 0.45\Omega$ / km, and (i) load as uniformly distributed (ii) load is connected at the end of the feeder.

Multiple Choice Questions

1. 11-kV feeder voltage level is

   (a) LV distribution voltage (b) primary distribution voltage

   (c) sub-transmission voltage (d) none of the above

2. 400-V, LV distribution line will be

   (a) 3-phase, 4-wire or 5-wire (b) 3-phase 3-wire

   (c) 1-phase, 3-wire with central point earthed (d) dc. distribution

3. If the distribution line voltage is changed from 22 kV to 33 kV, the power transmitted can be

   (a) four times (b) two times

   (c) same (d) 2.25 times

4. The approximate MVA capacity of 3-phase, 3-wire power line will be in (km-MVA)

   (a) 2.5 system voltage (b) 0.5 of system voltage

   (c) 1.5 times system voltage (d) 2.25 times system voltage

5. Secondary banking implies

   (a) operating two or more distribution transformers alternately

   (b) operating two or more distribution transformers in parallel with proper protection

   (c) putting the secondary distribution into ring system

   (d) dividing the feeder network into main and sub-feeders

6. Transformer utility factor is
   (a) load on transformer
   (b) ratio of connected load on transformer to transformer capacity
   (c) total load on network / total capacity of transformer
   (d) total capacity of transformers / total load on network
7. Transformer application factor (TAF) is defined as ratio of
   (a) total capacity of transformers in network to total secondary network load
   (b) total network load to total capacity of transformers in the network
   (c) total connected load to total network load
   (d) none of the above
8. Total annual cost (TAC) of distribution system is
   (a) sum total of installation costs of all equipment only
   (b) sum total of all equipment and cost due to losses in equipment and investment cost in fuel etc.
   (c) cost due to losses in power equipment and investment cost in fuel, transport etc. only
   (d) none of the above
9. The disadvantage of secondary banking is
   (a) voltage regulation is poor
   (b) parallel operation of transformers and their load sharing is difficult
   (c) overloading of one transformer can occur and co-ordination of fuses is difficult
   (d) load growth and future expansion is difficult
10. Choice of secondary voltage level depends on
   (a) length and loading of feeder
   (b) number of distribution substations and their location
   (c) number of consumers and their relative imprudence
   (d) all the above

Short Questions

11. Give the line diagram of radial feeder with a sectionaliser
12. What is TAF?
13. What is voltage square factor?
14. Define distance ratio and load ratio for increasing the feeder line capacity
15. What is the main disadvantage of secondary banking?
16. What is an "Express Feeder" in US or European system ?
17. An industrial suburban area has load density of 500 kVA/km^2 spread over 25 km^2. What is the primary distribution voltage level? (Individual loads range from 200 – 500 kVA).

18. What is transformer application factor ?
19. With secondary banking for 2 feeders, what will be the transformer application factor (TAF)?

Answers

1. b	2. a	3. d	4. c	5. b
6. d	7. a	8. b	9. c	10. d

11. Ref Figure 5.1b
12. Total annual cost which includes (i) annual revenue incurred on transformers lines, cables and other hardware + recovering expenditure on energy losses + other maintenance and operating costs (like salaries etc.)
13. (New voltage) / (existing voltage)
14. (Increased line distance) / (existing line distance)
    (Increased load) / (existing load)
15. Over loading transformers put in parallel and isolation of feeders under fault conditions
16. The main feeder that directly connects the substation to load central point
17. Since total load is 12.5 MVA, A 33-kV feeder or 22-kV feeder in preferred. Distribution voltage can be either 11-kV or 6.6 kV with individual consumer to have 11 or 6.6 kV / 400 – 415 V substations at their sites
18. (Total capacity of network transformers) / Total secondary network load
19. 2 to 2.2

Six

This chapter is a continuation of the previous chapter. Voltage drop and power loss in different types of systems, viz., radial and ring or loop systems is presented. Illustrations are presented with respect to dc, single-phase and three-phase ac systems.

Voltage Drop and Power Loss in Distribution Systems

Introduction

In Chapter 4, a discussion has been made on the calculation of voltage drop and power loss in a distribution system. For calculation of line performance, the loading on the feeder is assumed either uniformly distributed or uniformly increasing. In actual systems loading will be uneven and loads also will be unbalanced. Secondly other distribution system such as a single-phase system, 2-wire or 3-wire (midpoint grounded), the dc systems ring feeders, etc., were not analysed. In this section detailed calculations of feeder voltage drops and power losses are presented.

6.1 DC, 2-WIRE DISTRIBUTION SYSTEM

A two-wire Dc system with source connected at one end (Fig. 6.1 a) and sources connected at both ends (Fig. 6.1 b) is illustrated in Fig. 6.1. For single-end fed distribution minimum voltage occurs at the other end while for both end fed feeder, minimum voltage occurs at one of the intermediate load points in between the feeder ends.

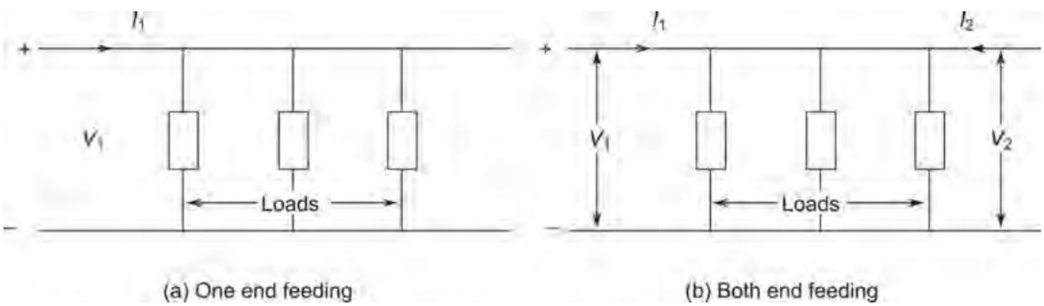


Fig. 6.1 *Dc distribution with one end and both ends fed*

Dc is mainly used for traction and tram car services. The return or negative wire can be the rail or ground.

Example 6.1 *The feeder in Fig. 6.2 is connected to a 250-V DC supply and has a loading as shown. The resistance of the line is 0.20Ω/km. Determine the voltage drop, voltage at the far end and power loss.*

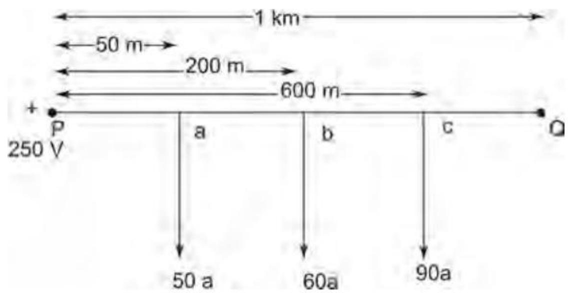


Fig. 6.2

Solution

SECTION	TOTAL CURRENT	DISTANCE	RESISTANCE	VOLTAGE DROP
Pa	50 + 60 + 90 = 200A	50 m	$50 \times 10^{-3} \times 0.2 = 10$ mΩ	$200 \times 10 \times 10^{-3} = 2$V
ab	60 + 90 = 150A	150 m	$150 \times 10^{-3} \times 0.2 = 30$ mΩ	$150 \times 30 \times 10^{-3} = 4.5$V
bc	90	400 m	$400 \times 10^{-3} \times 0.2 = 80$ mΩ	$90 \times 80 \times 10^{-3} = 7.2$V
cQ	0	–	–	0

$\therefore$ total voltage drop = 2 + 4.5 + 7.2 = 13.7 V

Voltage at the other end (Q) = 250 – 13.7 = 236.3 V

Power Losses

SECTION	CURRENT	RESISTANCE R	POWER LOSS = I^2R
Pa	200 A	10 m Ω	$200^2 \times 10 \times 10^{-3} = 400$ Watts
ab	150 A	30 m Ω	$150^2 \times 30 \times 10^{-3} = 675$ Watts
bc	90 A	80 m Ω	$90^2 \times 80 \times 10^{-3} = 648$ Watts
cQ	0 A	–	0
		Total	1.723 kW

$$\% \; VD = \frac{13.7 \times 100}{250} = 5.48\%$$

Total power supplied = 250 × 200 = 50,000 = 50 kW

$$\% \text{ power loss } = \frac{1.723}{50} \times 100 = 3.446\%$$

An alternate method would be considering each load separately

Load	Section	Distance	Resistance	Voltage drop
90 A	Pc	0.600 km	$0.6 \times 0.2 = 0.12\ \Omega$	$0.12 \times 90 = 10.8$ V
60 A	Pb	0.200 km	$0.2 \times 0.2 = 0.04\ \Omega$	$0.04 \times 60 = 2.4$ V
50 A	Pa	0.050 km	$0.05 \times 0.2 = 0.01\ \Omega$	$0.01 \times 50 = 0.5$ V
0	PQ	1 km	0	0 V
			Total (as before)	13.7 V

$\therefore$ voltage at $Q = 250 - 13.7 = 236.3$ V

Power losses cannot be computed by considering each load separately since

$$(\text{Total current})^2 = (I^2) \neq I_1^2 + I_2^2 + I_3^2$$

Example 6.2 *Determine the voltage drop and minimum voltage point if the point Q in Example 6.1 is kept at + 240 V.*

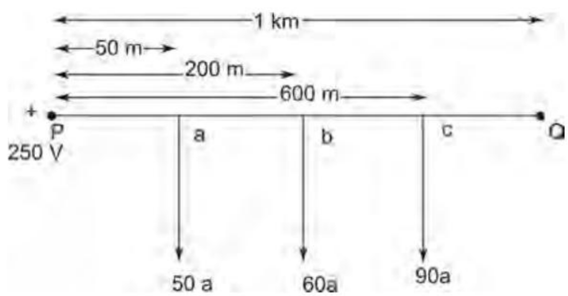


Fig. 6.3

Solution Let I_1 be supplied from P and I_2 from the point Q.

Total load current $I_1 + I_2 = 50 + 60 + 90 = 200$ A ...(1)

Let us assume b to be the minimum potential point.

$\therefore$ (250 – voltage drop Pb) = 240 – voltage drop bQ) ....(2)

Section	Current I	Resistance	Voltage drop
pa	I_1	10 m Ω	$I_1 \times 10 \times 10^{-3} = I_1 \times 10^{-2}$
ab	$(I_1 - 50)$	30 m Ω	$(I_1 - 50) \times 30 \times 10^{-3} = 3I_1 \times 10^{-2} - 1.5$
bc	$(I_2 - 90)$	80 m Ω	$(I_2 - 90) \times 80 \times 10^{-3} = 8I_2 \times 10^{-2} - 8$
cQ	I_2	80 m Ω	$I_2 \times 80 \times 10^{-3} = 8I_2 \times 10^{-2}$

$$= (250) - (I_1 \times 10^{-2} + 3I_1 \times 10^{-2} - 1.5)$$
$$= (240 - (8I_2 \times 10^{-2} + 8I_2 \times 10^{-2} - 8)$$
$$250 - 4I_1 \times 10^{-2} + 1.5 = 240 - 16I_2 \times 10^{-2} + 8$$
$$\text{i.e., } (4I_1 - 16I_1) \times 10^{-2} = 3.5$$
$$= I_1 - 4I_2 = \frac{350}{4} = 87.5A$$

and total current $= I_1 + I_2 = 200$ A

Solving $5I_2 = 112.5$ or $I_2 = 22.5$ A

and $I_1 = 177.5$ A

As assumed minimum voltage does not occur at the point 'b' but at the point c.

The voltage drop in QC $= 22.5 \times 40 \times 10^{-3} = 0.9$ V

and voltage at the point C = 240 – 0.9 = 239.1 V

Note: By feeding from both ends, the voltage drop is reduced and hence also the power loss.

6.1.1 The Ring or Loop System

As mentioned earlier in Chapter 4, a ring or loop distributor is a closed circuit and has more than one feeding points. The main advantage of ring distributor is that the voltage drop is less and hence conductor size can be reduced for a given voltage drop.

Example 6.3 *Let points 'A' and 'B' be connected to 250-V dc supply. The length of the feeders are AD = 50 m, DE = 150 m, EB = 400 m, BC = 100 m and CA = 200 m. The resistance per km = 0.2 Ω. Determine the minimum voltage point.*

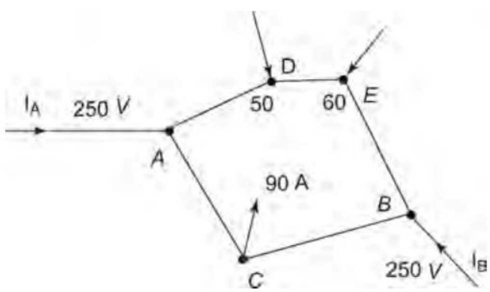


Fig. 6.4

Solution

Let I_A and I_B be the currents fed from A and B.

So that $I_A + I_B = 50 + 60 + 90 = 200$ A ....(i)

Let the current in section $AC = I_1$

And the current in section $BC = I_2$

so that $I_1 + I_2$ = current at $C = 90$ ....(ii)

SECTION ACB	CURRENT	RESISTANCE	VOLTAGE DROP
AC	I_1	$200 \times 0.2 \times 10^{-3} = 40$ m Ω	$40\, I_1 \times 10^{-3}$
BC	I_2	$100 \times 4.2 \times 10^{-3} = 20$ m Ω	$20\, I_2 \times 10^{-3}$

Hence voltage at C = 250 – voltage drop AC

= 250 – voltage drop BC

i.e., $250 - 40I_1 \times 10^{-3} = 250 - 20I_2 \times 10^{-3}$ or $2I_1 = I_2$ ...(iii)

∴ from equations (ii) and (iii) $I_1 = 30\ A$, $I_2 = 60$ A

Considering section $ADEC$

Current in section $AD = I_3$

Current in section $BE = I_4$

So that $I_3 + I_4 = 50 + 60 = 110$ A ...(iv)

As done earlier, equating voltage at E

$I_3 = 49.2$ A

$I_4 = 60.8$ A

Hence current supplied from A is 30 + 60.8 = 90.8 A

current supplied from B is 60 + 49.2 = 109.2 A

Voltage at the point $C = 250 - 40I_1 \times 10^{-3} = 250 - 40 \times 30 \times 10^{-3} = 248.2$ V

Voltage at the point $E = 250 - 80I_4 \times 10^{-3} = 250 - 80 \times 49.2 \times 10^{-3} = 244$ V

Hence the minimum voltage point is E and the maximum voltage drop is 6 V

It may be seen that with ring feeders, voltage drop will be considerably less.

6.2 DC, 3-WIRE SYSTEM

The 3-wire system with positive, negative and zero potential wires are shown in Fig. 6.5. A, ± 250 V D.C. The system can have loads distributed equally between ground and either pole. Large motor loads (rated for 500 V) can be connected between A and B directly. These are used for tram ways, traction purpose etc., and nowadays have very limited application. In industries with large Dc motor drives, application of 3-wire Dc system is seen in a few cases.

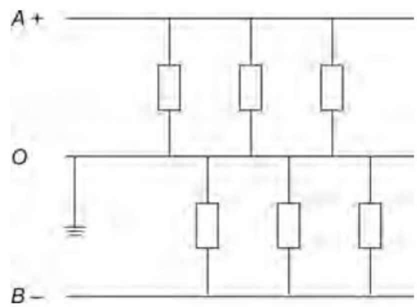


Fig. 6.5 *3-wire D.C. System*

Example 6.4 *A, ± 250 V DC 3-wire feeder feeds four loads as shown in Fig. 6.6. The line wires have resistance 0.2Ω/km and neutral wire (zero potential) 0.4Ω/km. Determine the voltage drop and minimum potential point.*

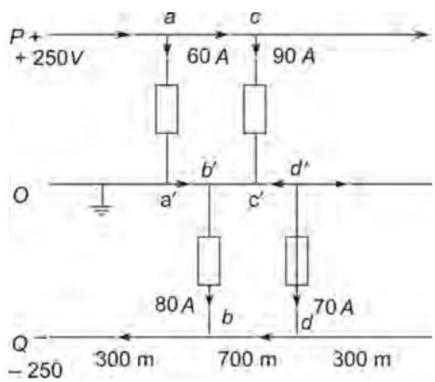


Fig. 6.6

Solution

Section	Current	Length	Resistance	Voltage drop
pa	150 A	0.1 km	0.02 Ω	150 × 0.02 = 3 V
ac	90 A	0.4 km	0.08 Ω	90 × 0.08 = 7.2 V
Qb	150 A	0.3 km	0.06 Ω	– 150 × 0.06 = – 9 V
bd	80 A	0.4 km	0.08 Ω	– 80 × 0.08 = – 6.4 V

The distribution in the neutral section *oa' b' c' d'* is to be determined.

The current from positive wire *P* is 150 A and flowing into the negative wire *Q* = (80 + 70) A. Hence in Section *oa'* no current flows. The current of 60 A coming from *oa'* flows through *a'b'*. Hence the rest of the current (80 – 60 A) = 20 A is from section *cc'* and section *c'd'* will have 70 A. Hence *a'* will be at zero potential.

Section	Current	Length	Resistance	Voltage drop
Oa'	0 A	100 m	0.04	0
$a'b'$	–60 A	200 m	0.08	–60 × 0.08 = –4.8 V
$b'c'$	20 A	200 m	0.08	20 × 0.08 = 1.6 V
$c'd'$	–70 A	200 m	0.08	–70 × 0.08 = –5.6 V

	Potential at different points	Section	Voltage
P	+ 250 = 250	aa	247 –0 = 247 V
a	250 – 3 = 247 V	bb	–241 (–(–3.2) – 237.8 V
c	250 – (3 + 7.2) = 239.8 V	cc	239.8 – (4.8) = 244.6
c ′	0–4.8 V = -4.8 V	dd	–234.6 – (–8.8) = –225.6
b ′	–4.8 + 1.6 V = 3.2		
b	–250 + 9 = –241.0 V		
d^1	–3.2 V – 5.6 V = –8.8 V		
d	–250 + (9 + 6.4) V = –234.6 V		
Q	–250		

The solution presented is a simplified procedure. If the exact solution is to be obtained, loop or nodal analysis may be applied but the difference between exact solution and the one presented will be negligible.

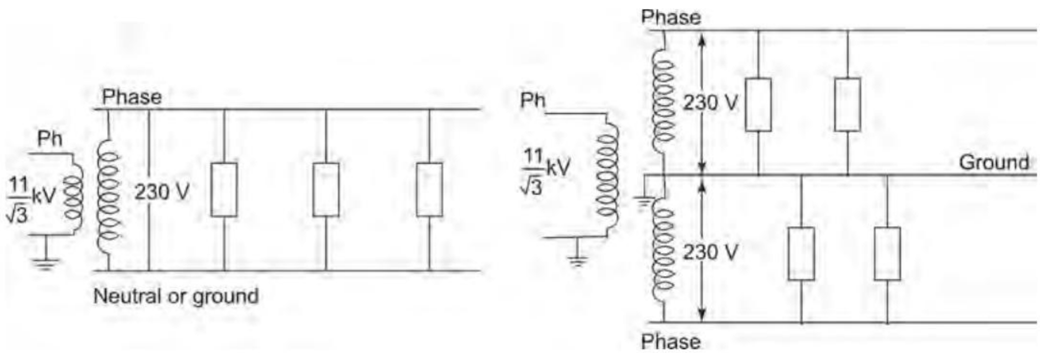
6.3 AC SINGLE-PHASE DISTRIBUTION SYSTEM

The most commonly used single-phase system in India is (230 – 240 V) 50 Hz ac system. It is meant to supply lighting domestic or commercial loads. It is not used as a separate system but is part of 3-phase, 4-wire system. On the other hand, to supply single-phase loads to remote places like agricultural or rural loads, the primary distribution one phase (one conductor) with ground return is used as a single-phase system (11 kV or 6.6 kV/$\sqrt{3}$). There is a lot of saving with respect to conductors, line hardware etc., and can carry power over considerably long distances. It is also used in density populated urban areas with each residential place supplied through its own single-phase transformer. Rural distribution in other countries like China, (10 kV), Australia (12.7 kV or 19.1 kV) also use high-voltage single wire system with earth return. The schematic diagram of single-phase high voltage distribution is shown in Fig. 6.7.

In electric traction in India and elsewhere, engineers use high voltage single phase distribution (25 kV) with one end of the phase grounded and the other connected to the catenary wire. This is similar the system in Fig. 6.7a expect that voltage is 25 kV and ground is the rail itself. The load is moving load, the electric loco.

6.3.1 AC Single-phase 2-wire System

The main difference between the corresponding dc and ac systems are that (i) lines have impedances, complex numbers with magnitude and phase and the loads are also complex with current magnitude and power factor (phase angle).



(a) 2-wire system (b) 3-wire system

Fig. 6.7 *Ac single phase systems*

The single-phase ungrounded 2-wire system is not used as there is no earth and hence earth currents can not be monitored for line to ground faults. The grounding of the neutral is very important and ground resistance (impedance) should be very low (< 5 ohms) although higher values up to 15Ω are encountered in rural hard soil grounds. Other systems like 2 phase with one ground or neutral wire, etc., are not used and hence not discussed.

Example 6.5 *An Ac 2-wire single-phase system shown in Fig. 6.8 has impedance per km (two conductors put together) = 0.20 + j0.10 Ω. Find the voltage drop and power loss (Fig. 6.8). Using the approximate formula for voltage drop, i.e., VD ≈ (IR cos θ + I X sin θ).*

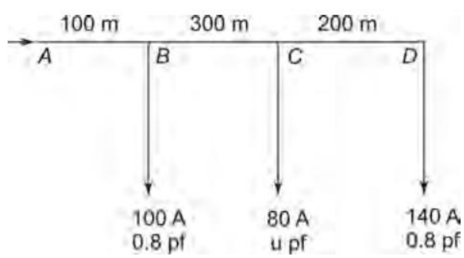


Fig. 6.8

Solution Let $I \cos \theta$ and $I \sin \theta$ are the load current real and j parts, R resistance and X reactance. Assuming that the phase angle difference between voltages at different points B, C, D

is negligible the procedure followed in Example 6.1 is followed.

Current in section CD = 140 A at 0.707 pf lag (i.e) – 45°

$\therefore \qquad I_{CB} = 140 \underline{|-45°} = 100 - j100\text{A}$

Current in section $BC = 140\text{ A} \underline{|.707\,pf}\ \ lag + 80\text{ A} \underline{|UPF}$

$= (100 - j100) + (80 - j0) = 180 - j100$

Current in section $AB = 140 \underline{|0.707\ pf\ lag} + 80\underline{|UPF} + 100\underline{|0.8\ pf\ lag}$

$= (100 - j100) + (80 - j0) + 80 - j60 = 260 - j180$

Voltage drop calculations:

Section	Length	Total current	Impedance	Voltage (VD) drop
AB	100 m	$(260 - j180) = 305.3$ A	$0.1(0.2 + j0.1) = 0.02 + j0.01$	$260 \times 0.02 + 180 \times 0.1 = 6.8$ V
BC	300 m	$(180 - j100) = 206$ A	$0.3(0.2 + j0.1) = 0.06 + j0.03$	$180 \times 0.06 + 100 \times 0.03 = 13.8$ V
CD	200 m	$(100 - j100) = 140$ A	$0.2(0.2 + j0.1) = 0.04 + j0.02$	$100 \times 0.04 + 100 \times 0.02 = 6$ V
			Total	= 26.6 V

Power loss calculation :

Section	Current	Resistance	Power loss (I^2R)
AB	305.3	0.02	1864
BC	206	0.06	2546
CD	100	0.04	400
			Total = 4810 watts

Example 6.6 *A* $\dfrac{11\text{ kV}}{\sqrt{3}}$ *single-phase, single-wire system has the following loads. Assuming that there is no phase difference in voltage at different points, determine the voltage drop and voltage available at the load point c (Fig. 6.9). Impedance of line (2.5 + j1.5) Ω/km.*

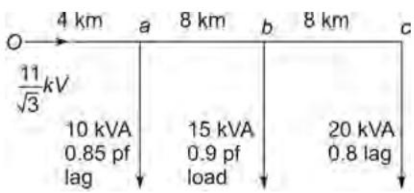


Fig. 6.9

Solution

Impedances of each section:

$oa = 4(2.5 + j1.5) = 10 + 6\,j\Omega$

$ab = 8(2.5 + j1.5) = 20 + 12\,j\Omega$

$bc = 8(2.5 + j1.5) = 20 + 12\,j\Omega$

Current at load c $= \dfrac{20\times10^3}{11/(11/\sqrt{3})\times10^3} = 3.15A\lfloor 0.8\ lag$

$= 3.15(0.8 - j0.6) = 2.52 - j1.89$

Current in section bc $= 2.52 - j1.89$ A

Current at load b $= 2.42$ A $\lfloor 0.9$ 0.9 lag

$= \dfrac{15\times10^3}{11/\sqrt{3}\times10^3} = 2.42(0.9 + j0.435) = 2.178 + j1.055$

Current in section ab $= (2.52 - j1.89) + (2.178 + 1.55j) = 4.698 - j0.735$ A

Current at load a $= \dfrac{10\times10^3}{11/\sqrt{3}\times10^3} 1.58A\lfloor 0.85\ lag = 1.58(0.85 - j05267)$

$= 1.343 - j0.8333$ A

Current in section oa $= (4.698 - j0.735) + (1.343 - j0.8323)$

$= 6.41 - j1.5673$ A

Section	Current	Impedance	Voltage drop
oa	$2.52 - j1.89$	$10 + j6$	2.52 × 10 + 6 × 1.89 = 25.2 + 11.34 = 36.5 V
ab	$4.698 - j0.735$	$20 + j12$	20 × 4.698 + 0.735 × 12 = 94 + 8.82 = 102.8 V
bc	$6.041 - j1.567$	$20 + j12$	6.041 × 20 + 12 × 1.567 = 120.8 + 18.8 = 139.6V
			Total = 278.9 V

Voltage at load point C $= \dfrac{11\text{ kV}}{\sqrt{3}} \times 10^3 - 278.9 = 6351 - 278.9 = 6072$ V

$$\%VD = \frac{278.9}{6351}\times100 = 4.39\%$$

It can be seen that regulation is far better with high-voltage, single-wire distribution system.

Example 6.7 *A single-phase, 230-V line has a uniform loading of 700 W / 100 m and one load of 5 kVA at 0.8 pf lag as shown in Fig. 6.10. Determine the voltage drop and voltage at end of the line. Impedance per 100m length is 0.14 + j0.105 and total line length = 1 km (Fig. 6.10).*

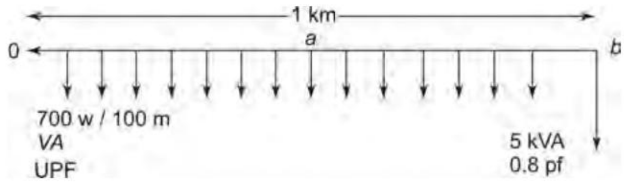


Fig. 6.10

Total uniform load = 700 × 10 = 7000 watts

$$\therefore \text{ current } = \frac{7000}{230} = 30.43A$$

This can be considered to the located at 0.5 km position as an equivalent concentrated load, i.e., at 'a'
Current of 5 kVA load is 5000/230 = 21.7, A, 0.8 pf

Hence current is $21.7(0.8 - j0.6) = 17.4 - j13.04$, which is current in the section *ab*

Impedance per km $= 10(0.14 + j.105) = 1.4 + j1.05$

Impedance of section *ab* $= 0.5(1.4 + j1.05) = 0.7 + j.5025$

Impedance of section *oa* $= 0.5(1.4 + j1.05) = 0.7 + j.5025$

Current in section *oa* $= 30.43 + 17.4 - j13.04 = 47.83 - j13.04$

Section	Current	Impedance	Voltage drop
oa	$47.83 - j13.04$	$0.7 + j.5025$	= 47.83 × 0.7 + 13.04 × .5025 = 33.50 + 6.55 = 39.05
ab	$17.40 - j13.04$	$0.7 + j.5025$	= 17.40 × 0.7 + 13.04 × .5025 = 12.18 + 6.55 = 18.73
			Total = 57.78 V

Voltage at the end off-line (at *b*) 230 – 57.78 = 172 V

(This is a typical example of rural single-phase lines with street light loading and the normal loads. More than 50-V voltage drop occurs from the supply end to the load end.)

Example 6.8 *A traction distribution system has a total feeder length of 25 km and impedance per km is 0.10 + j0.34 Ω. The feeder will be having two trains at a time with maximum load current of 200 A at 0.8 pf. Determine the voltage drop at line end for worst condition. The trains are maintained with a minimum spacing of 10 km.*

Worst load condition occurs when one train is at the end and the other one is 10 km before it as shown in Fig. 6.11.

Solution Impedance of section *ab* is $= 10(0.14 + j0.24) = 1.0 + j2.4$

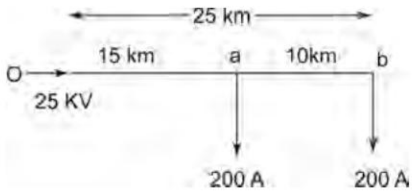


Fig. 6.11

Impedance of section oa is $= 15(0.10 + j0.24) = 1.5 + j3.6$

Current in section oa is $= 200(0.8 - j0.6) + 200(0.8 - j0.6) = 320 - j240$ A

Current in section ab is $= 200(0.8 - j0.6) = 160 - j120$ A

Voltage drop in section ab $= (I \cos \theta)R + (I \sin \theta) X = 160 \times 1.0 + 120 \times 2.4$

$= 160 + 28.8 = 448$

Voltage drop in section oa $= 320 \times 1.5 + 240 \times 3.6 = 480 + 864 = 1344$

Total drop $1344 + 448 = 1792 = 1.792$ kV

Voltage at the feeder end is $25 - 1.792 \approx 23.2$ kV

(This is slightly less than the allowable minimum voltage of 23.5 kV.)

6.3.2 3-Phase Ac Distribution: 3-Wire and 4-Wire

In case of 3-phase, high-voltage as well as low-voltage distribution, 3-phase loads are connected between the 3-line (phase wires) conductors and single phase loads are connected between phase and neutral. The single-phase loads are connected equally between all phases so that the system is nearly balanced. For balanced or nearly balanced loads, the 'VD' calculations and power loss calculations are done for one phase only. Power loss for total system is computed by multiplying with 3 for 3-wires and adding neutral conductor power loss (if any) for 4-wire system. In case of the system with more than one voltage level and in between transformers the single line equivalent is considered for computation.

Most of the practical 4-wire distribution networks are essentially unbalanced systems. The connected loads in each phase are usually nearly balanced. The single-phase loads are usually arranged equally in all phases. But, in operation, the loads are switched on randomly and will have different power factors, thus making the system unbalanced. Computation of voltage drop and power loss in such systems is difficult and analysis of such systems is quite complex. An illustrative example is presented at the end of this Chapter (Example 6.16).

Example 6.9 *A 400-V, 3-phase, 4-wire system has balanced loads and is fed from a 11 kV / 415 volts, 3-phase, 100-kVA transformer. Determine the VD, output kVA, kW and p.f of the transformer Fig. 6.12.*

Solution Impedance ab $= 0.1 + j0.05\ \Omega$

oa $= 0.05 + j0.04\ \Omega$

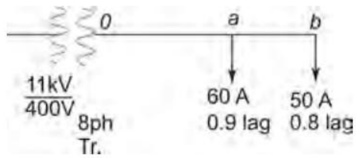


Fig. 6.12

Current in section $ab = 50$ A, 0.8 lag $= 50(0.8 - j0.6)\ 40 - j30$ A

Voltage drop in $ab = IR \cos\theta + IX \sin\theta = 40 \times 0.1 + 30 \times 0.05 = 4 + 1.5 = 5.5$ V

Current in $oa = I_A + I_B = 60(0.9 - j0.436) + (40 - I_A 30)$

$= 54 - 27.6j + 40 - 30j = 90 - 57.16j = 106.6 \underline{|-32.4}\,°$

Voltage drop in $oa = 90 \times 0.06 + 57.16 \times 0.04 = 5.4 + 2.3 = 7.7$ V

Total voltage drop $= 7.7 + 5.5 = 13.2$ V

Taking the nominal voltage per phase as $\dfrac{400}{\sqrt{3}} = 230V$

Active power of the two loads is $= 230 \times 50 \times 0.8 + 230 \times 60 \times 0.9 = 9200 + 12420$

$= 21620$ watts

Reactive power of the loads $= 230 \times 50 \times 0.6 + 230 \times 60 \times 0.436 = 6900 + 6016$

$= 12916$ VAR

$\therefore$ kVA of load/phase $= \sqrt{21620^2 + 12916^2} = 25184$ VA

$$pf = \frac{21620}{25184} = 0.858 \text{ lag}$$

Total power for 3-phase $= 21620 \times 3 = 64860$ watts

Total reactive for 3-phase $= 12916 \times 3 = 38748$ VARS

Total VA for 3-phase $= 25184 \times 3 = 75552$

Power loss in the line/ph is $= 50^2 \times 0.1 + 106.6^2 \times 0.06 = 250 \times 682 = 932$ watts/ph

Total power loss for 3-phase $= 2796$ watts

Reactive power in the line $\Sigma(I^2 X) = 50^2 \times 0.05 + 106.6^2 \times 0.04 = 125 + 622$

$= 747$ VAR/phase

Total reactive power $= 3 \times 747 = 2241$ VAR

Total power and reactive power supplied by a transformer is

$$P = 64860 + 2796 = 67656 \text{ watts} = 67.6 \text{ kW}$$

$$Q = 38748 + 2241 = 40989 \text{ VAR} = 40.0 \text{ kVAR}$$

Total kVA supplied is $= \sqrt{67.6^2 + 40.0^2} = 78.5kVA$

p.f at transformer is $= \dfrac{67.6}{78.5} = 0.860$

Note: In this problem the voltage at the load points is taken as 230 V nominal whereas it is different. Assuming transformer voltage 230 V, the actual voltage can be obtained. But in distribution calculations NOMINAL or RATED VOLTAGE is used.

The transformer output kVA and kW will be different from that of the load kVA and kW since the line will have some power loss and absorbs some kVAR. As such the transformer p.f is different from combined load p.f

Example 6.10 *Determine the distribution transformer rating (KVA) and its operating p.f. for a 3-phase 3-wire system. The per phase loading shown in Fig. 6.13.*

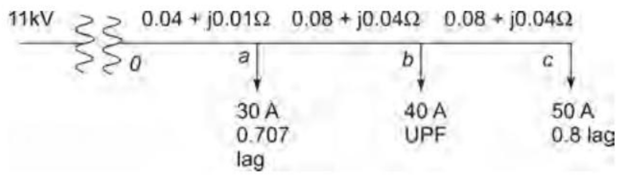


Fig. 6.13

The transformer is rated 11,000 V/415 V 3-phase. Also, find the phase voltage at the point c.

Solution Phase voltage $= \dfrac{415}{\sqrt{3}} = 240\ V$

SECTION	IMPEDANCE	LOAD CURRENT	VOLTAGE DROP
bc	$0.08 + j0.04$	$50\ \lvert\underline{0.8 \text{ lag}} = (40 - j30)$ A	$0.08 \times 40 + 0.04 \times 30\ 3.2 + 1.2 = 4.4$ V
ab	$0.08 + j0.04$	$40 - j30 + 40 + j0 = 80 - j30$	$80 \times 0.08 + 30 \times .04 = 6.4 + 1.2 = 7.6$ V
oa	$0.04 + j0.01$	(30 at .707 p.f) $= 21.21 - j21.21) + 40 + j0 + 40 - j30 = 101.21 - j51.21$	$101.21 \times 0.04 + 0.01 \times 51.21 = 4.04 + .051 = 4.091$ V

Total voltage drop $= 4.4 + 7.6 + 4.091 = 16.091 \approx 16.1$ V

$\therefore$ voltage at point '*c*' $= 240 - 16.1 = 223.9$ V

Regulation $= 16.1/240 = 0.067$ or 6.7%

Transformer rating taking nominal voltage of 240 V / Phase

LOAD/SECTION	CURRENT	IMPEDANCE	$P = VI \cos\theta$ POWER OR (I^2R)	$Q = VI \sin\theta$ REACTIVE POWER OR (I^2X)
c	50, 0.8 lag	–	9600	7200
bc	50, 0.8 lag	$0.08 + j0.04$	200	100
b	40, UPF	–	9600	–
ab	$80 - j30 = 85.44$	$0.08 + j0.04$	584	292
a	30, 0.707 lag	–	5090	5090
oa	$101.21 - j51.21 = 13.43$	$0.04 + j0.1$	515	129
		Total:	25589	12,811

Transformer kVA per phase = 25,589 + j12,811 = 28616 VA

Transformer total capacity 3-phase = 85868 or 85.8 kVA

$$\text{Transformer P.}f = \frac{25,589}{28,616} = 0.894\,VA$$

A transformer of 100 kVA capacity is to be installed as 85.8 kVA will not be available.

Example 6.11 *In Example 6.10, the transformer per unit impedeance is 0.03 + j 0.04 Ω. What will be the transformer output and load end voltage? The transformer rating is 100 kVA.*

Solution

$$\text{Current} = \frac{85.8}{100} = 0.858\,p.u;\ pf = 0.894$$

Voltage drop p.u = 0.858 × [0.03 × 0.894 + 0.04 × 0.447] = 0.0383

Voltage drop = 0.0383 × 240 = 9.2 V

∴ total voltage drop up to point c = 16.1 + 9.2 = 25.3 V

Voltage at point c = 240 – 25.3 = 214.3 V

Example 6.12 *For the distribution system shown in Fig. 6.14 fed from 415-V 3-phase, (240, single-phase) determine*

(i) the voltage drop in each section per phase (each phase)
(ii) the real and reactive power for each load
(iii) the KVA output and total load p.f. of the distribution transformer

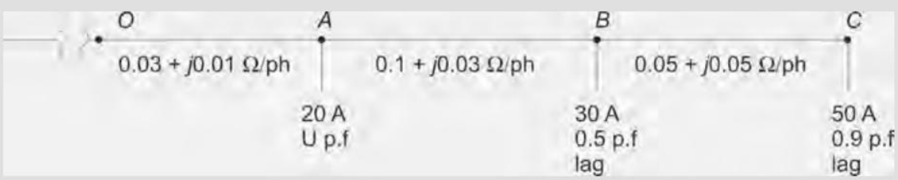


Fig. 6.14

Solution

(i) Current in section $BC = 50$ A, 0.9 lag

$= 50 - \angle{-25.84°} = 45 - j21.44$

Voltage drop in section $BC = IR \cos\theta + I \times \sin\theta$

$= 45 \times 0.05 + 21.44 \times 0.05 = 2.25 + 1.072 = 3.327$ V

Current at $B = 30$ A, 0.5 lag $= 30$ A $\angle{-60°} = 15 - j25.98$

Total current in section $AB = 50\angle{-25.84} + 30\angle{-60°}$

$= -(45 - j21.44) + (15 - j25.98)$

$= 60 - j47.42 = 76.5 \angle{-38.3°}$

Voltage drop in section $AB = (0.1) \times 60 + (0.03)\ 47.42$

$= 6 + 1.4722 = 7.422$ V

Current in section $OA = 20\angle{0°} + 30\angle{-60°} + 50\angle{-25.84°}$

$= (45 + j21.44) + (15 - j25.98) + 20$

$= 80 - j47.42 = 93\angle{30.65}$

Voltage drop in section $OA = 80 \times 0.03 + 47.42 \times 0.01 = 2.4 + 0.474 = 2.874$ V

(ii) Real and reactive power for each load.

Neglecting the small phase angle difference at each load point from that of sending end.

Voltage at load point $A = 240 -$ voltage drop in OA

$= 240 - 2.874 - 7.422 \approx 237.1$ V

Active power at $A = 237 \times 20\angle{0°} = 4742$ watts

Reactive power $= 0$ (UPF)

Voltage at load point $B = 240 - 2.874 - 7.422 \approx 229.7$ V

Current $= 30\angle{60°}$

Active power $= 229.7 \times 30 \times \cos(-60°) = 3445$ watts

Reactive power $= 229.7 \times 30 \times \sin 60° = 5949$ VARS

Voltage at load point $C = 240 -$ voltage drop OC

$= 240 - 2.874 - 7.422 - 3.322 \approx 226.4$ V

Current $= 50\angle{-25.84°}$

Active power $= 226.4 \times 50 \times \cos(-25.84°) = 10188$ watts

Reactive power $= 226.4 \times 50 \times \sin(-25.84) = 4855$ VARS

(iii) Transformer KVA output and power factor

Total load power/ph = 4742 + 3445 + 10188 = 18375 watts

Total reactive power of load/ph = 0 + 5949 + 4855 = 10804 VARS

SECTION	TOTAL CURRENT (A)	'Z'/PH	POWER LOSS $I^2 R$	REACTIVE POWER $I^2 X$
OA	$93\angle 30.65$	$0.03 + j0.01$	259.5	86.5
AB	$76.5\angle -38.3°$	$0.10 + j0.03$	585.2	175.6
BC	$50\angle -25.84$	$0.05 + j0.05$	125.0	125.0
		Total /phase	969.7	387.1

Total output of transformer per phase (load power + losses)

= 18375 + 969.7 = 19,344.7 watts

3-phase power output = 58,304 watts

Reactive power output of transformer per phase (load + losses)

= 10804 + 387.1 = 11191.1 VARS

3-phase reactive power output = 33,573 VARS

∴ output $= \sqrt{58304^2 + 33,573^2} = 67279\ VA$

Transformer output KVA ≈ 67.28 kVA (phase angle = –27.9°)

Transformer p.f ≈ 0.866 lag

6.4 VOLTAGE DROP (% VD) COMPUTATION BASED ON LOAD DENSITY

In Chapter 4, voltage drop computation is done in terms of line parameters (R and X) and load current $(I\angle\theta)$. The voltage drop constant 'k' has been obtained as a function of the above quantities and the system voltage. This is relevant for computation with existing system or to design a new feeder or substation. But it will be more convenient to obtain the VD% as a function of load density, whenever loads increase and the feeders are to be modified. Consider the 3-phase 4-wire system with one main feeder and a few sub-feeders or distributors as shown in Fig. 6.15.

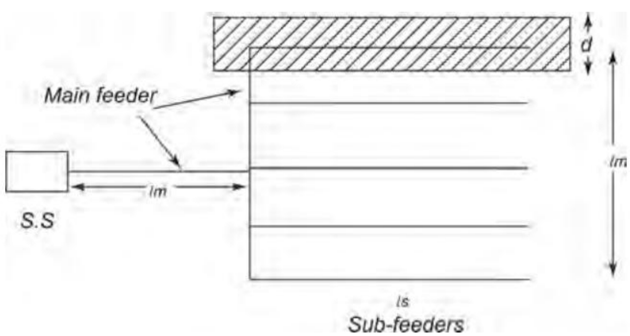


Fig. 6.15 *Main and sub-feeder arrangement*

Let the service area covered by a square area ($l_s \times l_s$) with uniformly distributed load of density = D kVA/km

Let V_s be the system operating voltage (line to line)

and $V_s/\sqrt{3}$ system line to neutral voltage in kV

Let the impedance of main feeder = $r_m + jx_m$ /unit length

Let the impedance of sub-feeder = $r_s + jx_s$ /unit length

Total kVA fed to the load = Dl_s^2

The voltage drop up to the farthest point F consists of voltage drop in main feeder length

voltage drop in half the length l_s

+ voltage drop in sub-feeders of lenth l_s

Voltage drop in terms of line kVA, line parameters and system voltage is given by (Equation 4.16)

$$(VD)pu = \frac{Sl(r\cos\theta + x\sin\theta)}{3V_rV_h} \times 1000$$

Taking $V_r = V_b = V_s/\sqrt{3}$ and expressing $V_s/\sqrt{3}$ in kV

Load kVA = $S = Dl_s^2$

$$VD\ Pu = \frac{Dl^2}{1000V^2}(r\cos\theta + x\sin\theta).l$$

(i) For main feeder for length lm

$$VD\ pu = \frac{Dl^3}{1000V_s^2}(r_m\cos\theta + x_m\sin\theta) \qquad \text{....(6.1)}$$

(ii) For main feeder of length ls / 2 with uniform load distribution

Effective length is $\left(\frac{l_s}{2}\right) \times \frac{1}{2} = \frac{l_s}{4}$

Area covered is $\left(\frac{l_s}{2}\right) \times l_s = \frac{l_s^2}{2}$

$$\therefore\ VD\ Pu = \frac{D.l_s^2/2}{1000V_s^2}(r_m\cos\theta + x\sin\theta)\frac{l_s}{4} \qquad \text{....(6.2)}$$

$$= \frac{D.l_s^3}{1000V_s^2}(r_m\cos\theta + x_m\sin\theta)$$

(iii) For sub-feeders, let each feeder cover an area $l_s \times d$. so that kVA supplied is $Dl_s.d$

Hence $VD\ Pu$ $$= \frac{D\cdot(l_s\cdot d)}{1000V_s^2}(r_l\cos\theta + x_l\sin\theta)\cdot l_s$$

$$= \frac{D.l_s^2 d}{1000V_s^2}(r_m\cos\theta + x_m\sin\theta) \qquad \text{.... (6.3)}$$

Expressing D' in MVA/km^2 = D / 1000

$\therefore$ VD P.U. will be (i) + (ii) + (iii), i.e., Eq. 6.1 + Eq. 6.2 + Eq. 6.3

$$= \frac{D'l_s}{V_s^2}(r_m \cos\theta + x_m \sin\theta) + \frac{D'l_s^3}{8V_s^2}(r_m \cos\theta + x_m \sin\theta) + \frac{D'l^3 \cdot d}{V_s^2}(r_l \cos\theta + x_l \sin\theta)$$

$$\text{i.e., VD P.U} = \frac{D'l_s^3}{V_s^2}\left(\frac{9}{8} r_m \cos\theta + \frac{9}{8} x_m \sin\theta\right) + \frac{D'l_s^2 d}{V_s^2}(r_l \cos\theta + x_l \sin\theta) \quad \text{... (6.4)}$$

This expression gives regulation as a function of load density, power factor, line parameters and its length.′

6.5 VOLTAGE DROP (VD) WITH UNDERGROUND CABLE DISTRIBUTION

It is often necessary in busy localities and large industrial and commercial areas to avoid overhead distribution and use cables only. In such cases the cable size and ratings are decided on the following basis.

(a) Voltage drop is calculated using approximate formulae for regulation (Equation 4.4 or 4.7)
(b) When motor loads (Induction motors) are connected, starting current should considered. When motors are being started voltage dip should not be more than 5% (additional).
(c) For normal operation, voltage drop in the system i.e., (transformer end voltage drop + feeder line drop + cable drop) should not be more than 5% of the nominal voltage
(d) Voltage drop computations is done taking nominal system voltage, i.e., 415-V, 3-phase or 240-V, single-phase
(e) In all voltage drop calculations, balanced conditions are assumed for 3-phase system

To illustrate the cable system, as example of a single-phase feeder is shown in Fig. 6.16.

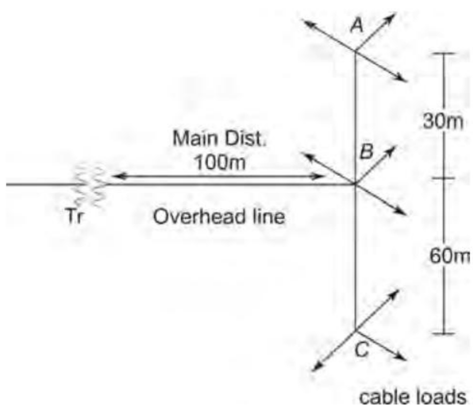


Fig. 6.16 *Cable distributor*

Example 6.13 *Determine the voltage drop and voltage at the farthest consumer point for the distribution system shown in Fig. 6.16.*

Assume diversity to be unity.

Transformer 50 kVA	z	$= (0.01 + j0.014)$ PU
Main dist.	z	$= (0.01 + j0.09)/100$ m
Cables	z	$= 0.017 + j0.014/30$ m
Loads at	A	$= 3,8$ and 3 kVA
	B	$= 6,4$ and 3 kVA p.f $= 0.8$ lag (all loads)
	C	$= 3,2$ and 9 kVA

Solution

Taking 50 kVA base and 240 V as l pu,

total load on transformer $=$ load at A + load at B + load at $C = 16 + 18 + 20 = 54$ kVA

$\therefore$ p.u current of transformer $= \dfrac{54}{50} = 1.08$; $\quad \cos\theta = 0.8$, $\sin\theta = 0.6$

VD in transformer in p.u $= I(R\cos\theta + X\sin\theta)$

$= 1.08\,(0.01 \times 0.8 + 0.014 \times 0.6) = 0.177$ p.u

Voltage drop in main feeder

Current in main feeder $= \dfrac{54 \times 10^3}{240} = 225$ A

Voltage drop in main feeder is $225\,(0.01 \times 0.8 + 0.009 \times 0.8) = 3.015$

$$VD \text{ p.u.} = \frac{3.015}{240} = 0.0125$$

Voltage drop in sub-feeder BC

Since the farthest point is 'C', load at C is 20 kVA $= \dfrac{20 \times 10^3}{240} = 83.3$ A

$$\text{Voltage drop} = 83.3\,(0.01 \times 0.8 + 0.014 \times 0.63) \times (60/100) = 2.14$$

(since feeder is only 60 m)

$$VD \text{ p.u.} = \frac{2.14}{240} = 0.0092 \text{ p.u}$$

Voltage drop in cable connection

Highest load at $C = 9$ kVA

Current $= \dfrac{9 \times 1000}{240} = 37.5$ A

Voltage drop in cable $= 37.5\,(0.017 \times 0.8 + 0.014 \times 0.6) = 0.814$ V

VD p.u. $= \dfrac{0.814}{240} = 0.0034$ p.u.

Total voltage drop

= (VD) in transformer + (VD) in main feeder + (VD) in sub-feeder + (VD) cable

$= 0.0177 + 0.0125 + 0.0092 + 0.0034 = 0.0428$ p.u.

i.e., $0.0428 \times 240 = 10.27$ V

$\therefore$ voltage at the consumer point is

$240 - 10.27 = 229.73 \simeq 230$ V

It can be seen that with the selection of proper transformer, feeder lines and cables correct voltage can be maintained at consumer point. For a 3-phase distribution (400-V or 415) the per phase quantities can be taken and the solution is worked out in the same manner.

Example 6.14 *A 33-kV/11-kV substation feeds a uniformly distributed load with load density of 1 MVA/km² and a lumped load of 2 MVA at the feeder end as shown in Fig. 6.17. What will be the voltage drop and net voltage available at the lumped load point if*

(i) SS maintain 1.0 p.u voltage for feeders

(ii) SS is set to give 1.05 p.u voltage

Take 'k' for the line as 0.3×10^{-3}/kVA – km for load p.f = 0.8

(iii) Also, calculate the voltage drop for off-load period with load density of 0.3 MVA /km² and 1 MVA load at far end.

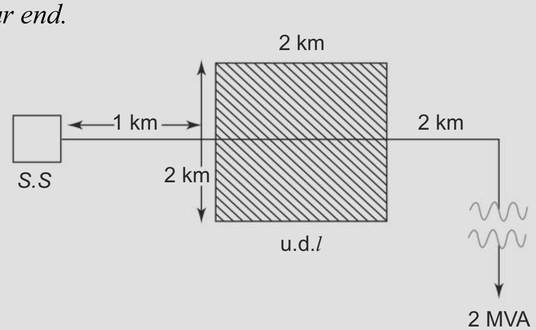


Fig. 6.17

Solution

Total load is 2 × 2 × 1 MVA/km^2 + 2 MVA = 6 MVA

% VD in section 1 km is $0.03 \times 10^{-3} \times 1 \times 6000 \times 10^2 = 1.8\%$

VD in section '2 km', since it is uniformly distributed

$l = 2/2 = 1$ km

Hence % VD = $3 \times 10^{-3} \times (4000) \times 10^2 = 1.2\%$

Distance for lumped load = 2 km in uniformly distributed area + 2 km = 4 km

∴ VD for lumped load $= 3 \times 10^{-3} \times 2 \times 4 \times 10^2 = 2.4\%$

Total voltage drop $= 1.8 + 1.2 + 2.4 = 5.4\%$ or .054 p.u

For voltage available at far end 1 – 0.054 = 0.946 p.u

If the tap is raised by 5% (i.e.) voltage is 1.05 p.u at substation

Voltage at load end = 0.946 × 1.05 = 0.993 p.u

At light load condition

Total load is (0.3 × 4 km^2) + 1 MVA = 1.2 + 1 = 2.2 MVA = 2200 kVA

Voltage drop in uniformly distributed load area due to it is

$$= 3 \times 10^{-3} \times \frac{2}{2} \times 2200 \times 10^2 = 0.66\%$$

Distance for lumped load = 2 + 2 = 4 km

VD for lumped load $= 3 \times 10^{-3} \times 1 \times 4 \times 10^2 = 1.2\%$

Total *VD* = 0.66 + 0.66 + 1.2 = 2.52% or 0.0252 p.u

∴ voltage at load end = 1.0 – 0.0252 = 0.9748

There in no need to raise the tap at substation to 1.05 since voltage drop is 2.52% (<5%).

6.6 POWER-LOSS ESTIMATION IN DISTRIBUTION SYSTEM

In distribution system, power loss mainly occurs in (i) Transformer (ii) feeder lines. In transformer power loss in due to (i) core losses, and (ii) the winding (copper) losses and in lines it is I^2R_l where R_l is line resistance and I the current in the line. The percentage power loss is expressed as $\frac{I^2 R_l}{P} \times 100$ where P is the total power supplied. It can be shown that the power loss in related to %VD approximately as

$$\frac{\%I^2 R_l}{\%VD} = \frac{\cos\phi}{\cos\theta \times \cos(\phi - \theta)} \qquad ...(6.5)$$

where $\cos\phi = \frac{R_l}{Z_l}$, ϕ the impedance angle of the line and $\cos\theta$ = power factor of the load.

Example 6.15 *What is the % power loss in the feeder line in Example 6.14, if the line impedance in p.u is 0.0033 + j0.003.*

Solution load p.f = 0.8 hence $\theta = 36.9°$

Impedance angle of the line $\phi = \tan^{-1}\dfrac{0.003}{0.0033} = 42.27°$

$$\therefore \text{ \% power loss } \approx \frac{\cos\phi}{\cos\theta\cos(\phi-\theta)} = \frac{0.74}{0.8 \times 0.9956} \approx 0.93$$

$[\cos\phi = 0.74;\ \cos(\phi - \theta) = \cos 5.39° = 0.9956]$

The power-loss estimation by Eq. 6.5 is a gross approximation, but is quite sufficient for quick calculation.

Example 6.16 *A 3-phase 4-wire distributor has the loads shown in Fig. 6.18. The impedance of phase 0.05 + j0.05 Ω and that of neutral conductor is 0.12 + j0.1 Ω. The 3-phase balanced load at line end is 40 A, 0.8 pf lag. Estimate the voltage drop in each phase and power loss.*

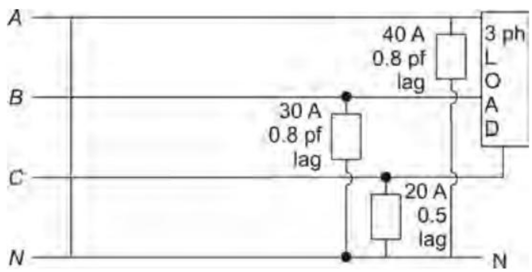


Fig. 6.18

Solution Neutral current $I_A + I_B + I_C$ is (No current due to 3-phase load)

$40\ (0.8 \text{ lag}) + 30\text{ A}\ (0.8 \text{ lag} \underline{|-120°}) + 20\text{ A}\ (0.5 \text{ lag} \underline{|-120°})$

$= 40(0.8 - 0.6) + 30\ (0.8 - j0.6)\ (-0.5 - j0.866) + 20\ (0.5 - j0.866) + (-0.5 + j0.866)$

$= 32 - j24 - 27.9 - j11.77 + 10 + j17.32$

$= 14.1 - j18.45 = 23.22\ \underline{|-52.6°}$

Voltage drop in neutral wire

$\approx I_n\,(R\cos\theta + X\sin\theta)$

$= 23.22\ \{0.12 \times 0.607 + 0.794 \times 0.1\}$

$= 23.22\ \{0.0728 + 0.0794\}$

$= 23.22\ \{.1722\} \approx 4$ V

Current in Phase 'A' $= \{40\text{ A}\}\ \angle 0.8\text{ lag} + 40\text{ A}\ \angle 0.8\text{ lag}$

Motor current + single-phase $= 80\text{ A}\ \angle 0.8\text{ lag} = 80\ \{0.8 - j0.6\}$

(load current) $= 80\ \angle -36.9°$

Voltage drop in 'A' conductor

$\approx\ 80\ \{0.05 \times 0.8 + 0.05 \times 0.6\}$

$\approx\ 80\ \{0.07\} = 5.6$ V

$\therefore$ Total voltage drop in 'A' phase conductor

$5.6 + 4 = 9.6$ V

(This is a very approximate calculation.)

Current in phase 'B'

(motor current + single-phase load current) $40\text{ A}\ \angle 0.8\text{ lag} + 30\text{ A}\ \angle 0.8\text{ lag}$

$= 70\text{ A}\ \angle 0.8\text{ lag} \qquad = 70\ \{0.8 - j0.6\}$

$\therefore$ voltage drop $= 70\ \{0.05 \times 0.8 + 0.05 \times 0.6\} = 70\ \{0.07\} = 4.9$ V

Total voltage drop $= 4 + 4.9 = 8.9$ V

Current in phase 'C'

$=$ motor current + single-phase load current $= 40\text{ A}\ \angle 0.8\text{ lag} + 20\text{ A}\ \angle 0.5\text{ lag}$

$= 40\ \{0.8 - \mathrm{j}\ 0.6\} + 20\ \{0.5 - \mathrm{j}\ 0.866\}$

$= 32 - j24 + 10 - j17.32 = 42 - j41.32 = 58.9\ \angle 44.5°$

$\therefore$ voltage drop in 'C' phase conductor

$= 58.9\ \{\ 0.05 \times 0.72 + 0.05 \times 0.7\} = 4.19$ V

Total voltage drop in 'C' phase $= 4.19 + 4 = 8.19$ V

Note: In computing voltage drop in 'B' and 'C' phase shift of 120° from 'A' need not be taken as the calculation is with respect to that phase only. But for calculating neutral current phase shift of 120° for other phases 'B' and 'C' must be taken.

The voltage drop in each phase is almost equal even with unbalanced single-phase loads when a 3-phase balanced load is present. This will not be the case if no balanced load of sufficient magnitude is present.

Summary

Voltage drop and power loss calculations in the commonly adopted systems like 2-wire and 3-wire Dc and single end 3-phase Ac systems is discussed in this section. Both radial and ring type feeders are analyzed and comparison is given between different types systems. Feeders fed at one end and both ends as well as ring distributors are cited along with a variety of examples. Computation of voltage drop and power loss in feeders considering load density and feeder parameters is illustrated.

Keywords

Distribution systems
DC 2-wire system
DC 3-wire system
AC single-phase
AC 3-phase
Radial feeders
Ring or loop system
Power loss estimation
Voltage drop computation

Review Questions

1. What are the different distribution systems for ac and dc? Give comparison
2. Explain the advantages and difficulties with ring type feeders compared to
   (a) radial feeder, and (b) feeder fed at both ends.
3. Give comparison between a 3-wire Dc system and a single-phase Ac system with mid-point earthed.
4. What are the advantages for adopting 3-phase, 4-wire distribution for LT supplies and 3-phase, 3-wire for high-voltage distribution ?
5. Why is voltage drop consideration important in distribution systems ? How is it computed when line parameters and load density of an area are given.
6. What are the power losses in Ac distribution? How is it estimated approximately?
7. Show that the power loss due to the load currents in conductors of single-phase ungrounded neutral case is 3 times more than one in the equivalent 3-phase system.
8. Show that power loss due to load currents in conductors in a single phase two wire ungrounded system with full capacity neutral (3-wire system) is six times more than that in the equivalent 3-phase 4-wire system.
9. Explain how voltage drop (VD) with a main feeder and cable distributor is estimated.
10. How is power loss in a distributor system estimated approximately ?

Problems

11. A distribution is supplied from 250-V Dc and has loads as shown in Fig. P. 6.11. The resistance/100 m is 20 mΩ. What is the voltage at point *P* and voltage drop in each section?

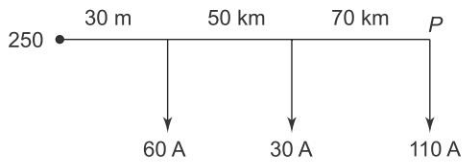


Fig. P 6.11

12. In Q. 11 if there is a uniforms distributed load of 1 A/m, determine the voltage at load point *P*.
13. In Q. 11 if the point *P* is also maintained at 250-V, determine the minimum voltage location and voltage at that point. Estimate the total power loss in the line.
14. (a) For the ring feeder shown Fig. P 6.14 determine the minimum voltage point. Resistance per km = 0.50Ω.

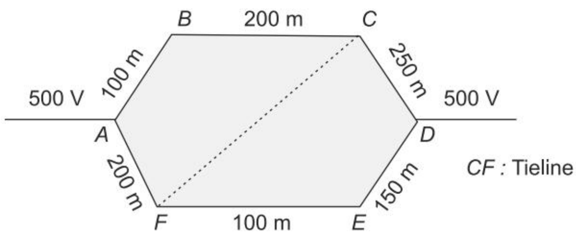


Fig. P 6.14

(b) If a line of 350 m in connected between *CF* what will be the voltage at points *C* and *F*.

15. A single-phase 3.3-kV, 3-wire distributor has loads as shown in Fig. P. 6.15. Each line has an impedance $0.2 + j0.3\Omega$ and neutral wire $0.3 + j0.4\Omega$. What is the current supplied by the transformer its kVA and pf. Assume 3.3-kV is maintained at transformer end and all the loads are connected to the same point.

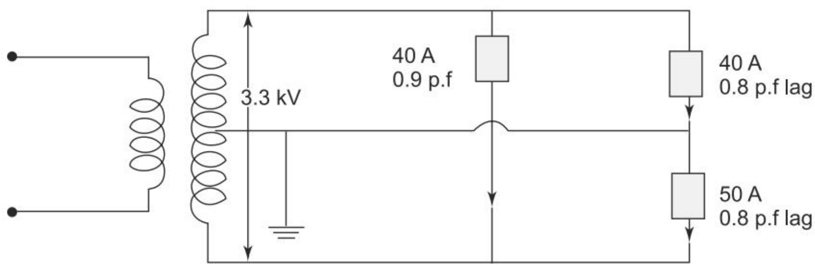


Fig. P 6.15

16. For the distributor shown in Fig. P 6.16 the supply voltage at feeding end is 2450 V determine the % VD. Line impedance = $(0.1 + j0.02)\ \Omega/100$ km.

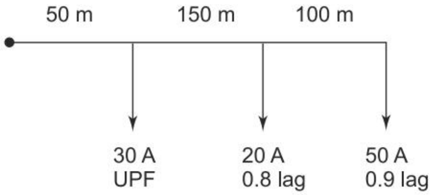


Fig. P 6.16

17. Determine the power loss, the kVA, kW and power factor at the supply end in Q.16.
18. $11/\sqrt{3}$ kV single line feeder has the loads shown in Fig. P. 6.18, estimate the voltage drop, power loss and kVA supplied from the source end.

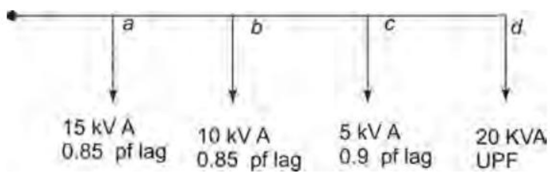


Fig. P 6.18

Impedances section $oa = 4 + j2\ \Omega$

section $ab = 5 + j3\ \Omega$

section $bc = 5 + j3\ \Omega$

section $cd = 10 + j5\ \Omega$

19. In Example 6.8, if the feeder is 30 km long and there are 3 trains located at an interval of 10 km from the feeding end taking 100 A, 150 A and 150 A respectively, what will be the voltage at the feeder end ?
20. In Example 6.9, another section bc is added with a load of 40 A UPF at c. Impedance of bc is $0.1 + j0.05\ \Omega$. Determine the % VD at the load c, output kVA, kW and p.f of the transformer.
21. Repeat Problem 6.15, if the transformer has per unit impedance of $0.03 + j0.05\ \Omega$. What should be the tap setting if the voltage at lumped load point is to be more than 0.95 P.U?
22. A 3-phase feeder line is fed from as 11-kV supply and has line impedance of $20 + j30\ \Omega$ / km / per conductor. A delta-connected, 3-phase induction motor is connected at the end of the feeder and takes 400 kW at 0.8 p.f. lag. If the feeder length is 3 km. Determine the line voltage drop and voltage at the load end.
23. In Problem 22, if the voltage at the load end is to be 11-kV, what should be voltage at the source point?
24. Estimate the power loss in Problem 22, using approximate formula given in Eq. 6.5.

25. A 415-V, 3-phase, 4-wire system shown (Fig. P 6.25) has line conductors with impedance $0.4 + j0.2$ Ω and neutral conductor of impadence $0.6 + j0.4$ Ω. The loads at line ends are A phase 25 A UPF, B phase 30 A, 0.8 p.f lag and C phase 20 A, 0.9 p.f lag. Estimate the voltage drop in each phase.

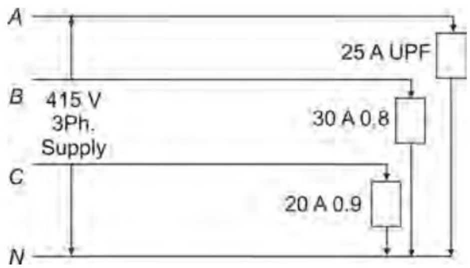


Fig. P 6.25

Multiple Choice Questions

1. In a 3-wire dc distribution system, the ground point is
   (a) positive pole (b) negative pole
   (c) mid point (d) any one
2. Single-phase ac distribution with midpoint ground is used for
   (a) rural low voltage systems (b) agricultural loads
   (c) urban street lights (d) all the three above
3. Standard 3-phase 4-wire LT distribution in India is
   (a) 230-V 3-ph (b) 400-V 3-ph
   (c) 11-kV 3-ph (d) 3.3-kV 3-ph
4. The line impedance angle and load p.f angle are both 30º. If % VD is 5, what will be the power loss % ?
   (a) zero (b) 2.5
   (c)1.0 (d) 5.0
5. VD % for underground cables is estimated as
   (a) same as overhead lines
   (b) cable capacitance and line charging current is to be taken
   (c) only reactance of cable is considered
   (d) cable is taken as capacitor
6. In case unbalanced 3-ph 4-wire system % VD is
   (a) same as in case of 3-ph balanced system
   (b) it should estimated for each phase
   (c) not possible to estimate
   (d) to be solved as a network problem

7. In order to reduce the voltage drop % and power loss for long rural feeders, the distribution system adopted is
   (a) single-phase 440 V Ac with midpoint earthed
   (b) DC, 3-wire system
   (c) High-voltage (11-kV) single conductor with earth return
   (d) Any one of the above
8. If % VD is known, power loss is estimated as power loss =, (given line impedance angle ϕ, load p.f $\cos\,\theta$)
   (a) $\%\,\text{VD} \times \dfrac{\cos\phi}{\cos\theta\cos(\phi+\theta)}$
   (b) $\%\,\text{VD} \times \dfrac{\cos\phi}{\cos\theta\times\cos(\theta-\phi)}$
   (c) $\%\,\text{VD} \times \dfrac{\cos\theta}{\cos\theta\cos(\phi+\theta)}$
   (d) $\%\,\text{VD} \times \dfrac{\cos\theta}{\cos\phi\cos(\phi-\theta)}$

Fill in the Blanks

9. Give the % VD interms of line parameters, load p.f and load density
10. Ring feeders will have % VD __________
11. For a 3-wire Dc system the midpoint or ground potential can be _________
12. The current in the 3rd or ground wire in 3-wire Dc system will be _________
13. The relation between % VD and power loss in 3-ph balanced Ac distribution is ________________
14. When motor loads are connected through cables and distributors, while estimating % VD ________ ________ should and considered
15. Neutral conductor cross section will be ______________ compared to the line conductors in 4-wire distribution

Answers

1.	c	2.	a
3.	b	4.	d
5.	a	6.	b
7.	c	8.	b
9.	See Equation 6.3 or 6.4	10.	Less than
11.	Either positive or negative w.r.t. ground with unbalanced loads		
12.	Small compared to line wires	13.	See Eq. 6.5
14.	Starting current of motors	15.	Less (half)

Seven

In distribution systems mostly the loads require inductive reactive power and have low p.f. To compensate for it and improve voltage regulation, capacitors are needed and used. Here, we shall be learning about causes for reactive power, how it is compensated, location of capacitors voltage improvement obtained and optimum p.f. for a given system.

Reactive Power Compensation and Applications of Capacitors

Introduction

Most of the electrical utilities like induction motors, electroplating and welding equipment manufacturing units, lighting loads using fluorescent lamps etc. operate at low power factors. This means that larger amount of current is drawn from the source. Most of these equipments operate between 0.6 to 0.8 p.f lagging. If the power factor in near unity (> 0.9) then current drawn in less for a given power. Also the voltage drop in the line is reduced and hence the power loss. Adding leading power factor loads, like connecting capacitors is generally the most economical way to improve the power factor of the equipment and utilities.

For existing plants with low p.f, best solution is to connect capacitors and hence the emphasis is on capacitor choice even through, in some cases, application of synchronous motors may be convenient and economical. In addition to the relatively low cost, the advantages are (i) easiness in installation and maintenance (ii) very low losses compared to synchronous motor application and (iii) availability in small ratings to high ratings (kVAR). The individual units, if required can be combined to obtain the required large power ratings.

7.1 ADVANTAGES AND BENEFITS OF POWER FACTOR IMPROVEMENT

(i) The cost and bill for the energy is reduced since there is penalty for poor power factor (<0.85)

(ii) Voltage improvement and better regulation

(iii) Overall system losses becomes reduced and hence is important from conservation of energy

Typical operating power factor of different loads without compensation are listed in Table 7.1.

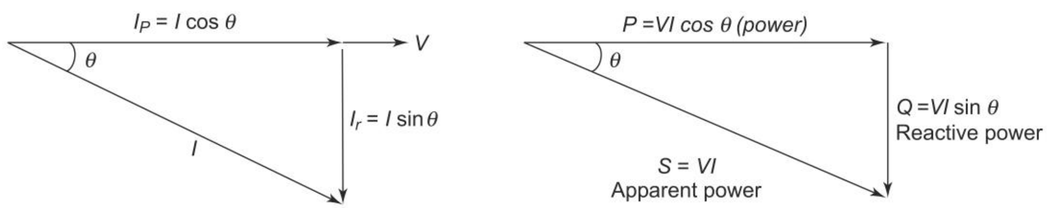
Table 7.1: *Typical power factor values of industrial loads and plants*

P.F RANGE (LAG)	LOADS/INDUSTRIES/PLANTS
0.50 to 0.70	Chemical industries, oil pumps, paints plastics spraying machine, manufacturing electronics.
0.60 to 0.75	Textile industry, weaving, electroplating
0.70 to 0.80	Metal forging, foundry, auto industries, compressors, brewery, coal mines and mining industry
0.75 to 0.85	Hospitals, domestic and commercial loads, office buildings, lighting loads using florescent lamps, etc.
Generally less than 0.6	Welding, metal working units, stamping, florescent lamps without capacitors, etc.

In addition to the above, the static control motor drives using thyristors etc., also operate at poor power factor. The power factor in approximately proportional to the controlled firing angle of the unit and is less when output Dc voltage is less. This ratio of Dc output voltage to the rated maximum voltage is an indication of the p.f at which the unit is operating. Electric furnaces, fluorescent lamps and other gas discharge lamps, arc lamps, etc., also operate at very less p.f (0.5 to 0.75). Transformers operating at less than 40% load also operate at low p.f due to their magnetizing current. Normally in distribution systems, (33-kV and below) the reactance of the line will be less compared to resistance. Usually X/R ratio of lines will be 0.5 to 0.75. Hence the operating p.f of lines alone may be between 0.8 to 0.85.

7.2 POWER-FACTOR ANALYSIS AND BASICS

In Ac systems, the inductance or capacitance of the power utility contributes for reactance (X). Hence the electrical element or utility is an impedance Z with a phase angle θ i.e., $Z\angle\theta$ which in the complex form is written as $R + jX$. The element takes two components of current, the power or working component that converts electrical energy into other forms like mechanical energy, light or heat energy etc. and the magnetizing or reactive (watt less) component of current that is required to produce flux in electromagnetic machines. The phasor relation is shown in Fig. 7.1.



(a) V, I phasors

(b) power, reactive power and V A taken

Fig. 7.1 *Phasor diagram*

If I_l = active component of current I_r = reactive component of current and I total current

$$I = \sqrt{I_p^2 + I_r^2} \quad \text{or} \quad I_p = I\cos\theta,\ \ I_r = I\sin\theta \qquad \text{....(7.1)}$$

Multiplying by V, supply voltage

$$VI = S = \text{apparent power VA}$$

$$P = VI\cos\theta,\ Q = VI\sin\theta \qquad .....(7.2)$$

Phase angle $$\theta = \tan^{-1}\frac{I_r}{I_p} = \cos^{-1}\frac{I_p}{I} \qquad ...(7.3)$$

$$\text{Power factor} = \frac{\text{active power } P}{\text{apperent power } S} = \frac{\text{kW}}{\text{kVA}}$$

$$= \text{cosine of the phase angle } \theta\ (\cos\theta) \qquad .....(7.4)$$

θ = angle between active component of current I_p and total current I

Power factor of a device of impedance Z is $\cos\theta = \dfrac{R}{Z}$

Electromagnetic devices which have inductance will have phase of the total current I, behind I_p and are lagging in p.f.

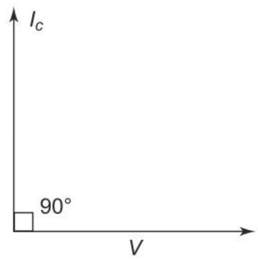


Fig. 7.2 *Phasor diagram for a capacitor*

Capacitive devices take leading current i.e., the current taken by them leads the applied voltage or power component of the current. The phasor diagram for a pure capacitor is shown in Figure 7.2. Hence when a capacitor and a electromagnetic device like an induction motor are connected in parallel to the supply, the capacitor current which is leading compensates for the inductive or lagging current. Hence the power factor of the total unit can be made to be unity (1.0) or as close to 1.0 as possible. The total current I is reduced and becomes nearly equal to I_p the active component of the current.

7.3 POWER-FACTOR IMPROVEMENT USING CAPACITOR'S MATHEMATICAL CALCULATION

$$\cos\theta = \text{p.f} = \frac{\text{kW}}{\text{kVA}} \quad \text{and} \quad \tan\theta = \frac{\text{kVAR}}{\text{kW}} \qquad ...(7.5)$$

Hence $$\text{kVAR} = \text{reactive power} = \text{kW}\tan\theta \qquad ....(7.6)$$

Let a device or motor operate with a p.f $\cos\theta$ so that its reactive power is $P\tan\theta_1$ where P is the power taken by it.

If it is desired to improve the power factor $\cos\theta_1$ to a new value $\cos\theta_2$ with the capacitors, assuming that the power does not change, the new reactive power is $P \tan\theta_2$

$$\therefore \text{ the reactive power compensated is} = (P\tan\theta_1 - P\tan\theta_2) \quad \ldots (7.7)$$

Example 7.1 *An induction motor takes 50 kW at 0.76 p.f lagging from a 400-V, 3-phase supply. It is needed to improve the p.f to 0.90. Determine the RKVA of capacitor bank needed.*

Solution Phase angle of induction motor is $\cos^{-1} 0.76 = 40.5°$

$$\therefore \quad \tan\theta_1 = 0.8551$$

Phase angle with p.f $= 0.9$ is $\cos^{-1} 0.9 = 25.8°$

$$\tan\theta_2 = 0.4843$$

$$\therefore \quad \text{RKVA needed is} = 50(\tan\theta_1 - \tan\theta_2)$$

$$= 50(0.8551 - 0.4843) = 18.54 \text{ kVAR}$$

Example 7.2 *If the capacitor bank in Example 7.1 has 5% losses on its capacity, what is the total power taken and the actual p.f after capacitor connection ?*

Solution 5% losses on the capacitor is $18.54 \times \dfrac{5}{100} = 0.929$ kW

$$\therefore \quad \text{total power taken from the mains} = 50 + 0.929 = 50.929 \text{ kW}$$

Net reactive power is $50 \tan\theta_2 = 24.21$ KVAR

$$\therefore \quad \text{KVA taken} = \sqrt{50.929^2 + 24.21^2} = 55.8 \text{ kVA}$$

$$\text{Phase angle} = 25.7°$$

$$\text{Actual p.f} = 0.901$$

With capacitor connection the total power intake in creased by 1.86%. The phasor diagrams with and without capacitor are shown in Fig. 7.3.

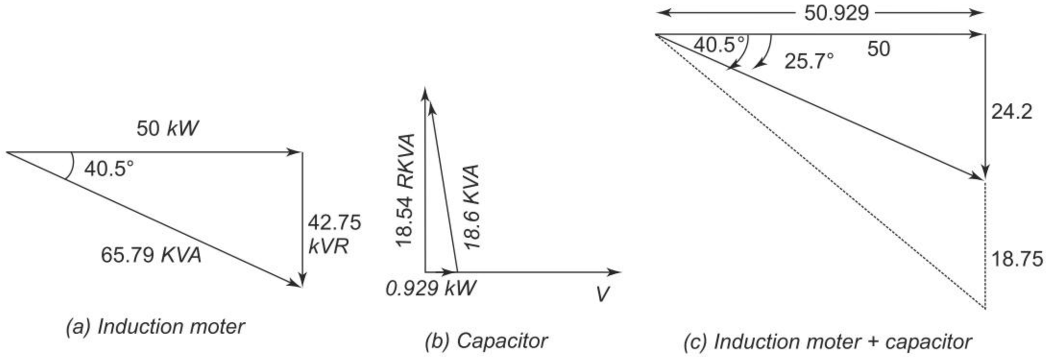


Fig. 7.3 *Power-factor improvement with capacitor*

7.4 LOCATION OF CAPACITORS

The best possible location for the capacitor is to install it beside or as near to the motor or device as possible. But sometimes it may be convenient to locate them for a group of motors together or at the supply in coming point within the industry or utility, supplied from a high voltage distribution network. Four possible locations are shown in Fig. 7.4.

(a) On the HV side of the supply (C_4),
(b) On the LV side of the supply transformer (C_3)
(c) At the distribution board (C_2)
(d) At the motor location itself (C_1)

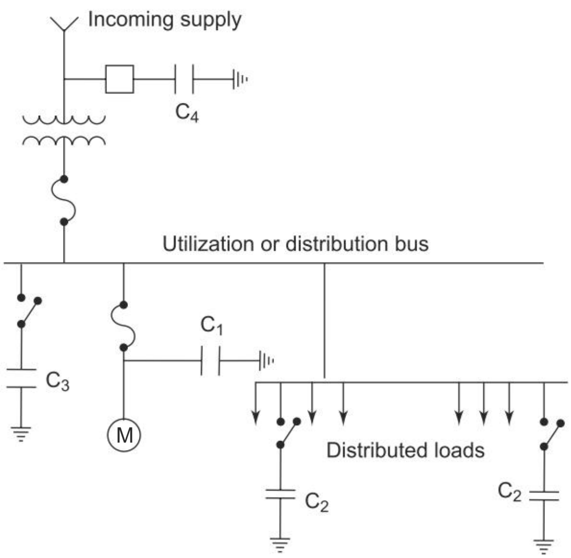


Fig. 7.4(a) *Shunt capacitor locations*

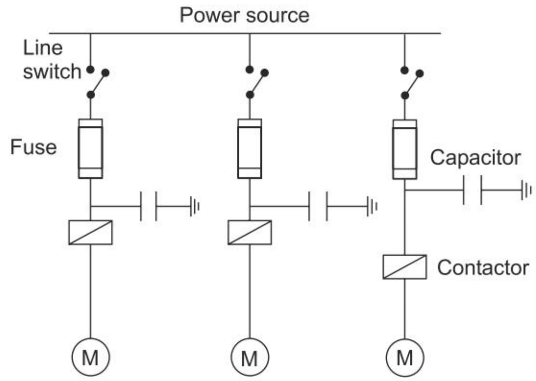


Fig. 7.4(b) *Location of capacitor when used with inductor motors*

The order being given in the least preferred to best preferred place. Usually location C_4 is avoided and either C_1 or C_2 is preferred. The C_1 location provides for p.f improvement of loads and permits switching off along with the load. C_2 or C_3 locations reduce the number of units that can be used with the load units and permit for automatic switching and inter locking of its switching with other devices and equipment. Also location C_3 may prove economical if the overall plant is to be considered.

7.5 VOLTAGE IMPROVEMENT ACHIEVED USING CAPACITOR BANKS

The voltage dip or drop (VD) for feeders or lines is given by (VD) $\approx I(R\cos\theta + X\sin\theta)$. With lagging p.f ($VD$) for any p.f is $I(R\cos\theta \pm X\sin\theta)$, '$-$' sign being used with leading p.f. With the power factor of the system improved, for a given power, I total current reduces and hence VD reduces. In other words if power remains the same, I cos θ will be the same but I sin θ reduces. Hence, $VD = IR\cos\theta + IX\sin\theta$ will be low as $I\sin\theta$ is reduced with improved p.f.

For a transformer regulation ΔV

$$\Delta V = \frac{IR\cos\theta \pm IX\sin\theta}{V} \approx \frac{IX\sin\theta}{V} \quad \text{as } IR\cos\theta \text{ will be small}$$

With p.f improvement, $IX\sin\theta$ changes, hence change in ΔV is due $IX\sin\theta$. When a capacitor bank of Q kVAR is connected on the secondary side.

$$\Delta V = \frac{IX\sin\theta}{V} = (\text{pu reactance of the transformer}) \times \sin\theta$$

With a capacitor bank of 'Q', $\sin\theta = \dfrac{Q}{\text{Transformer kVA}}$

$$\text{and hence } (\Delta V)\text{ p.u} = \frac{((\text{p.u}) \text{ reactance of transformer}) \times Q}{\text{Transformer kVA}} \qquad \text{....(7.8)}$$

Example 7.3 *A 1 MVA transformer has 8% reactance and a capacitor bank of 400 R kVA is connected to its secondary side. What is the approximate, voltage improvement obtained ?*

Solution $$\Delta Vp.u = \frac{(\text{p.u reactance}) \times Q}{\text{Tr. kVA}} = \frac{0.08 \times 400}{1000} = 0.032 \text{ or } 3.2\%$$

7.5.1 Reduction of Line Current and Power Losses in Distribution Lines

For establishments and industries with long feeders, agricultural and remote rural loads, pumping stations, etc., additional benefit of reduction in power losses and line current is obtained and it is often justified for the financial return. Also energy or power saved is power generated. System conductor losses are proportional to I^2 and hence to square of p.f as such

$$\text{Power loss} \propto \left(\frac{\text{original p.f}}{\text{improve p.f}}\right)^2 = \left(\frac{\cos\theta_1}{\cos\theta_2}\right)^2$$

$$\text{or reduction in power losses} \propto \left[1 - \left(\frac{\text{original p.f}}{\text{improve p.f}}\right)^2\right] \text{i.e.,} \propto \left[1 - \left(\frac{\cos\theta_1}{\cos\theta_2}\right)^2\right]$$

$$\text{Also the reduction in line current } \Delta I = \left[1 - \frac{\text{original p.f}}{\text{improve p.f}}\right] = \left(1 - \frac{\cos\theta_1}{\cos\theta_2}\right)$$

Example 7.4 *In Example 7.1, what will be the % reduction to in line current and power losses?*

Solution ΔI reduction in line current is $\left(1 - \dfrac{\cos\theta_1}{\cos\theta_2}\right)$ $\cos\theta_1 = 0.76$, $\cos\theta_2 = 0.9$

$$\therefore \quad \Delta I = \left[\left(1 - \frac{0.76}{0.90}\right)\right] = 0.1555 \text{ or } 15.55\%$$

$$\text{Reduction in power losses} = \left[1 - \left(\frac{0.76}{0.90}\right)^2\right] = 0.2286 \text{ or } 28.6\%$$

7.5.2 Shunt Capacitor Application to Feeders

As pointed out in Section 7.5 connecting capacitors at the end of feeder or at receiving substation will reduce the voltage drop and improve the voltage at the receiving end. Capacitor banks of the order of 1 MVAR at 11-kV and 5 to 10 MVAR at 33-kV substation are installed to improve the voltage regulation of the feeders. The voltage profile of a typical 11-kV feeder, with uniformly distributed load and capacitor connected at 0.75l of the feeder is shown in Fig. 7.6.

In tables 7.2 to 7.5 RKVA required to prove the p.f from the given value to desired value, capacitor bank ratings for induction motors and transformers are tabulated for ready reference and use.

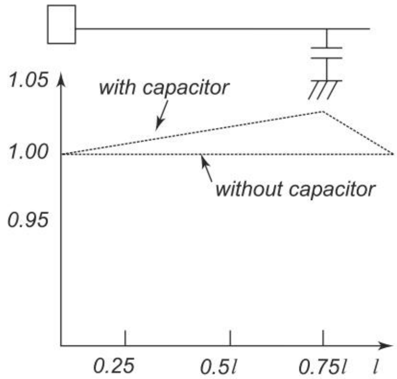


Fig. 7.5 *No load voltage profile without and with capacitor*

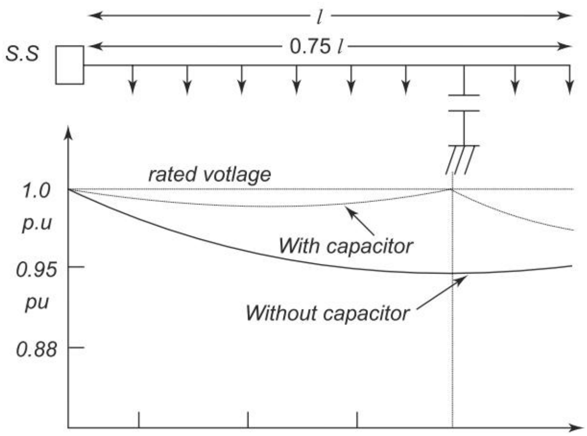


Fig. 7.6 *Voltage profile with load, with and without capacitor (full load)*

Table 7.2 Multiplying factor to determine RKVA for p.f improvement

Original	Corrected p.f						
pf	0.80	0.85	0.87	0.90	0.92	0.95	1.0
0.5	0.902	1.112	1.165	1.248	1.306	1.403	1.732
0.55	0.769	0.899	0.952	1.035	1.093	1.190	1.519
0.60	0.583	0.713	0.766	0.849	0.907	1.004	1.333
0.65	0.419	0.549	0.602	0.685	0.743	0.806	1.169
0.70	0.270	0.400	0.453	0.536	0.594	0.657	0.020
0.75	0.132	0.262	0.315	0.398	0.456	0.519	0.882
0.80	-	0.130	0.183	0.266	0.324	0.421	0.75
0.85	-	-	0.053	0.136	0.194	0.291	0.620
0.90	-	-	-	-	0.089	0.155	0.484

Note: If 50 kW motor is running with 0.60 p.f and it is required to improve p.f to 0.9, the capacitor needed is 50 × 0.849 (from above Table 7.2) = 42.45 RKVA.

Table 7.2 is useful when the operating p.f. of the load and desired improvement is known. The RKVA of the capacitor bank is readily obtained by referring to Table 7.2.

Table 7.3 Capacitor ratings for typical induction motors (in RKVA)

	Squirrel cage motors			Slip ring motors
Motor h.p	1500 rpm	1000 rpm	750 rpm	1000/1500 rpm
5	2	2.5	3.5	3.0
7.5	3	3.0	4.5	4.0
10	3.5	4.0	5.5	5.5
15	5	6	7.5	6
20	5	6	9.0	7
25	6	7	10.5	7
50	12	15	18.0	17.5
75	20	22.5	25	25
100	30	35	37.5	35

Table 7.4 Capacitor ratings for distribution transformer 11-kV/415 V

kVA	Capacitor Rating
25	9.0
63	27
100 – 150	36 - 50

Table 7.5 Capacitor ratings for welding transformers/plants

KVA	KVAR capacitor bank
5.0	2
10.0	4
12.5	6
18.0	8
24.0	12
30.0	15
50.0	25
100.0	45

7.6 APPLICATION OF CAPACITORS FOR POWER-FACTOR IMPROVEMENT

Static capacitors can be connected at almost any voltage level. Individual capacitor units can be added in parallel to get the desired kVAR and they can be connected in series to achieve the required voltage. When connected in series, care should be taken for equal voltage division along the individual units. It has been found that 50 to 60% of the capacitors connected are at the feeder end and load points, about 30% at the substation bus terminals and the rest in the transmission system. A typical series parallel connected capacitor unit is shown in Fig. 7.7.

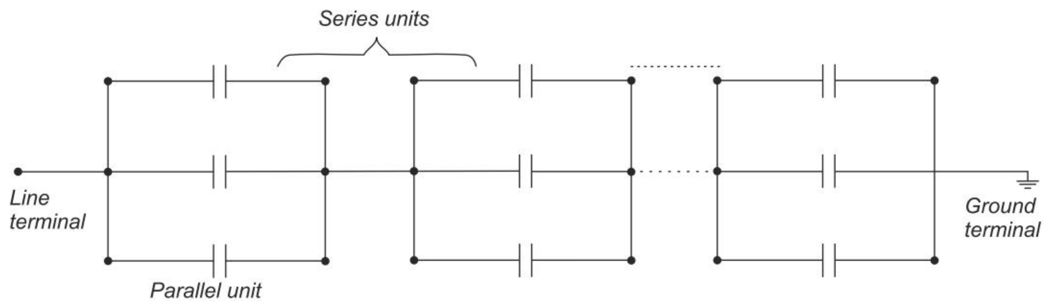


Fig. 7.7 *Capacitor bank unit of one phase*

Example 7.5 *$\frac{11}{\sqrt{3}}$ kV capacitor bank of 1000 A is needed from 1000 V, 200 A capacitor units (20 KVAR). Find the total rating of the capacitor bank and its arrangement.*

Solution For 1000-A current, 5 units are connected in parallel and for $\frac{11}{\sqrt{3}} \approx 6350$ V, seven such above units may be connected in series. The total kVAR capacity of the bank is as follows.

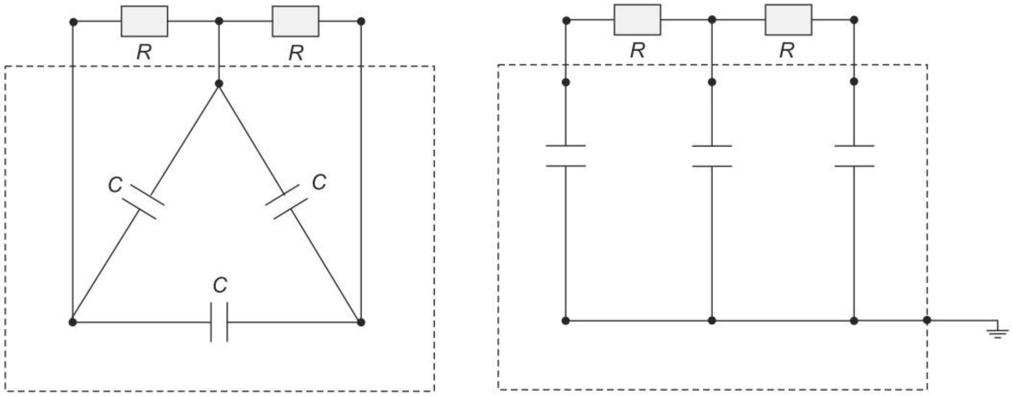
Parallel unit bank $5 \times 20 = 100$ kVAR

Total series units are 7 hence 700 kVA at 7 kV, since it is operated at 6.35 kV only, its rating will be

$$\left(\frac{6.35}{7.00}\right)^2 \times 700 \text{ kVA} = 576 \text{ kVAR}.$$

Individual capacitor banks can be connected either in 'Δ' or 'Y' as shown in Fig. 7.8.

Discharge resistance '*R*' are fitted at the external terminals so that they get automatically discharged when disconnected. Usually a small charge will be left out when switched off and this has to discharged for safety reasons.



(a) Delta-connected capacitor bank with discharge resistor 'R'

(b) Star-connected capacitor bank with tank connected to neutral point and grounded

Fig. 7.8 *Capacitor banks for 3-phase system*

Example 7.6 *A 50-hp, 50-Hz, 415 V delta connected induction motor has a full load efficiency of 0.85 and power factor 0.75. The power factor is to be improved to 0.9 using static capacitors.*

Determine (i) rating of capacitor bank kVAR, (ii) capacitance of each unit, if they connected as (a) delta, and (b) star, in μF.

Solution

(i) Power input to motor at 415-V

$$P = \frac{50 \times 0.746}{0.85} = 43.88 \text{ kW}$$

$$p.f = \cos \theta_1 = 0.75, \qquad (\therefore \tan \theta_1 = 0.882)$$

$$Q_1 = P \tan \theta_1 = 38.7 \text{ KVAR}$$

With $$p.f = 0.9 = \cos \theta_2 \text{ ; } \tan \theta_2 = 0.484$$

$$Q_2 = P \tan \theta_2 = 43.88 \times 0.484 = 21.25$$

KVAR of capacitor bank $P(\tan \theta_1 - \tan \theta_2) = 38.7 - 21.25 = 17.45$ KVA

i.e., 17.45 kVA, 415-V, 50-Hz, 3-phase bank

(ii) Line current $I_L = 24.27\text{A}$ = phase current for Y connection

$$\text{Phase current} = \frac{I_L}{\sqrt{3}} = 14 \text{ A}, \qquad \text{for '}\Delta\text{' connection}$$

For Δ connection $$X_c = \frac{415}{14} = 29.64\ \Omega = \frac{1}{2\pi\ fc}$$

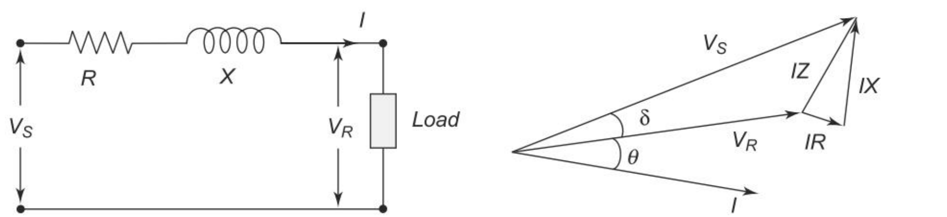
at 50 Hz $$C = \frac{1}{2\pi\ f X_c} = 107.4\ \mu F$$

For Y connection $$X_c = \frac{415}{\sqrt{3}} \times \frac{1}{24.27} = 9.92\ \Omega \ (\because \text{ phase voltage is } \frac{415}{\sqrt{3}} \text{ V})$$

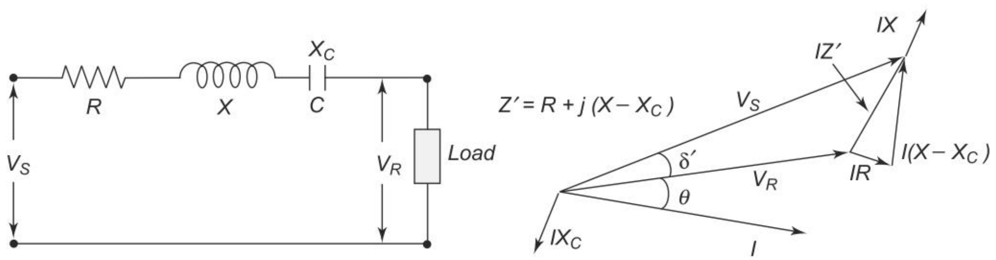
$$C = \frac{1}{2\pi\ f X_c} = 322\ \mu F$$

7.6.1 Application of Series Capacitors to Feeders for Voltage Regulation

This distribution lines are normally represented as short lines with the line to ground capacitance neglected. When a load with lagging p.f is connected at the end, a voltage drop $\Delta V = I(R\cos\theta + X\sin\theta)$ occurs. If a capacitance 'C' with reactance X_C is connected in series with the line, X will be reduced to $(X - X_c)$ and hence the voltage drop ΔV is reduced. Further the reactive power, 'VARS' taken by the line are also reduced. In Fig. 7.9, the equivalent circuit of a feeder and its series compensation are presented.



(a) Equivalent circuit of short line and its phasor diagram



(b) Line compensated with series capacitance

Fig. 7.9 *Equivalent circuit of feeder and its series capacitor compensation*

It can be seen from the phasor diagram of Fig. 7.9c that the voltage frop

$$\Delta V = IR\cos\theta + I(X - X_c)\sin\theta$$

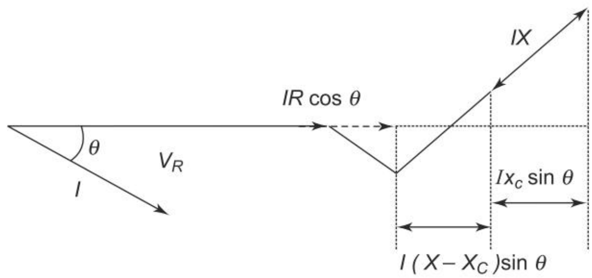


Fig. 7.9c *Voltage drop with capacitor compensation*

The use of series capacitors in distribution lines is to (i) reduce the voltage drop in the lines with low power factor and improve the voltage at the receiving end particularly with low p.f loads, and

(ii) reduce the reactive power consumed in the lines and hence reduce the phase angle difference between sending end and receiving end voltage.

[Phase angle 'δ' between V_s and V_R is reduced to δ' with series capacitances (Fig. 7.9 a and b].

Hence power transmitted can be increased. Long overhead lines of 11-kV and 33-kV (25 to 50 km or more) are usually compensated especially when X/R ratio is high (more than 2.5).

Example 7.7 *A 33-kV feeder has (0.1 + j0.25) Ω impedance per phase per km and is supplying a load of 6 MVA over a distance of 80 km at 0.75 p.f. What will be the receiving end voltage and voltage drop of the line if compensated to 50% by series capacitance compensation? Find the receiving end voltage and improvement in voltage.*

Solution Voltage per phase is $= \dfrac{33}{\sqrt{3}} = 19.05$ kV and line current is $= \dfrac{6 \times 10^3}{\sqrt{3} \times 33.00} = 105$ A

Total impedance of the line per phase = 80 (0.1 + j0.25) = 8 + j20

$$\text{P.f} = \cos\theta = 0.75,\ \sin\theta = 0.661$$

$$\therefore \quad \text{voltage drop} \approx I(R\cos\theta + X\sin\theta)$$

$$= 105[8 \times 0.75 + 20 \times 0.661]$$

$$= 105(6 + 13.22) = 2018 \text{ V}$$

Receiving end voltage $= 19050 - 2018 = 17032$ V

or line voltage is ≈ 29500 or 29.5 kV

$$\text{regulation} = \frac{2018}{19050} \times 100 = 10.60\%$$

with 50% compensation $X_c = -0.5 \times 20j = -10j$

$\therefore$ $X' = X - X_c = 10j$

Impedance of the line $= 8 + j10\ \Omega$

Voltage drop $= I\,(R \cos\theta + X' \sin\theta)$

$= 105(8 \times 0.75 + 10 \times 0.661)$

$= 105(6 + 6.61) = 1324$ V

Receiving end voltage $\approx 19050 - 1324 = 17726$ V or line voltage is 30702 V

$$\text{Regulation} = \frac{1324}{19{,}050} = 6.95\%$$

Regulation is improved by 3.65%

Reactive power per phase without compensation is $105 \times 20 = 2100$ VA $= 2.1$ kVAR

Total reactive power $3 \times 2.1 = 6.2$ kVAR

with compensation $X' = 10\ \Omega$ and hence total reactive power is 3.1 kVAR

Note: In European distribution system sending end voltage is maintained at 34.5 kV, receiving end between 33 and 31.5 kV with series capacitor compensation

The disadvantage of series capacitors are the following :

(i) The line reactance and hence impedance reduces under fault conditions (line to ground or line to line fault) current increases and as such the rating of the protective equipment like CBS, etc., increases very much.

(ii) Sub-harmonic resonance in lines and transformers like ferro-resonance (see Section 7.7) occurs.

(iii) Difficulty in protection of capacitors during faults, since the voltage across the series capacitors IX_C rises to very high value under faults.

Series capacitors are located at the receiving end of the line or split into two or three units and kept at the intermediate switching points in the feeder. They are protected with a surge arrester or a over voltage expulsion fuse (HRC) (Fig. 7.10).

7.7 SUB-HARMONIC OSCILLATIONS AND FERRO-RESONANCE DUE TO CAPACITOR BANKS

Transformers connected to the distribution lines have large magnetizing inductance and is nonlinear due to the non-linear characteristic of B-H relations of the core of the transformers. The line capacitance and the extra series capacitance connected in the line forms a series resonant circuit with the transformer inductance L_m (Fig. 7.11). Neglecting the line and transformer resistance the voltage across the transformer (L_m) is

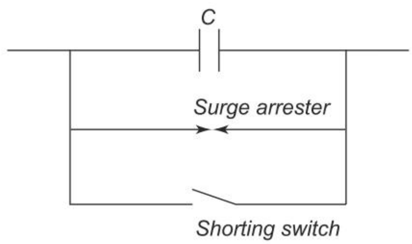


Fig. 7.10 *Protection of series capacitors*

$$E_L = \frac{E}{jX_L - jX_c} \cdot jX_L = \frac{E}{\left(1 - \dfrac{X_c}{X_L}\right)}$$

Voltage across the series capacitor is

$$E_c = \left(\frac{E}{1 - \dfrac{X_L}{X_C}}\right)$$

$$\text{if } \frac{X_c}{X_L} = 0.8 \quad \text{or} \quad \frac{X_L}{X_c} = 1.25$$

$$E_L = \frac{E}{1 - 0.8} = 5E$$

$$\text{and } E_c = \frac{E}{1 - 1.25} = -4E$$

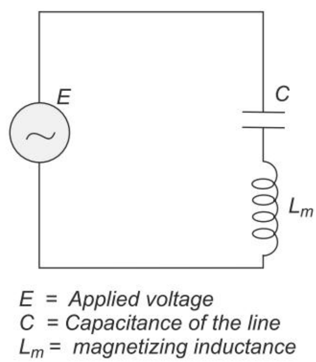


Fig. 7.11

The voltage across transformer and capacitor, are quite high and cause damage. The phenomenon is not so simple as explained. Usually under light load conditions, as the no load current varies, the core saturation will be different resulting in variable L_m. This will result in either sub-harmonic or higher harmonic resonance with the capacitance included, which will give voltage peaks at the resonant frequency causing high voltages. This is prevented by either including non-linear resistances or designing transformers to operate at higher saturation levels.

7.8 SYNCHRONOUS MOTORS FOR REACTIVE POWER COMPENSATION AND POWER FACTOR IMPROVEMENT

Synchronous machines which are over excited, take leading current and hence can compensate for reactive power. The advantage of synchronous machines is that they can be operated at both lagging (under excitation) or leading (over excitation) power factors. The reactive power output that can be supplied to the line is a function of excitation and motor load. Fig. 7.12 show the reactive power output, the motor is capable of giving under different load conditions and excitation.

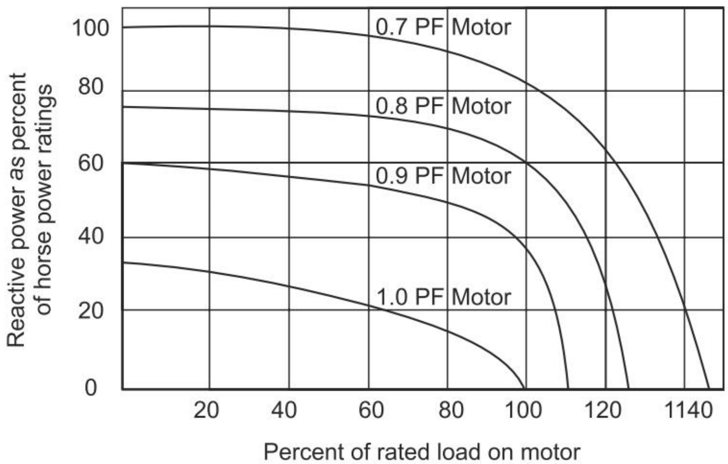


Fig. 7.12 *Leading reactive power in percent of motor horsepower ratings for synchronous motors at part load*

In few industrial applications, where constant speed drive is needed and reactive power is to be controlled, synchronous motors are employed. Compared to the static capacitors, the cost involved is more (2.5 to 3.0 times) but continuous variation of reactive power can be obtained and switching problems and transients do not occur.

Example 7.8 *An industrial plant has 300 hp induction motor load that runs at 0.8 p.f lagging and efficiency 0.85. A synchronous motor of 150 hp and an average efficiency 86% is available. If the motor is run on no load with same losses, determine the p.f of the motor, to make the over all power factor of the plant to 0.9. Can the p.f of the plant be raised to u.p.f ? If so what will the kVA intake of synchronous motors ?*

Solution $\cos\theta_1 = 0.8$, $\sin\theta_1 = 0.6$

$$\text{Power input to induction motor} = \frac{300 \times 0.746}{0.8} = 263.3 \text{ kW}$$

KVA input to induction motor $= \dfrac{263.3}{0.85} = 329.1$

RKVA taken by induction motor $= 329.1 \sin\theta_1 = 329.1 \times 0.6 = 197.5$

synchronous motor efficiency is 0.86

$\therefore$ KVA / kW rating of synchronous motor $= \dfrac{150 \times 0.46}{0.86} = 130$

power losses in synchronous motor $130(1 - 0.86) = 18.2$ kW

with both *IM* and synchronous motors, total power taken = 263.3 + 18.2 = 281.5 kW

$$\cos\theta_2 = \text{new p.f} = 0.9 \text{ hence } \tan\theta_2 = 0.484$$

$\therefore$ RKVA taken $= 281.5 \tan\theta_2 = 136.3$

$\therefore$ RKVA supplied by syn. motor $197.5 - 136.3 = 61.2$

$\therefore$ KVA taken by syn. motor $\sqrt{18.2^2 + 61.2^2} = 63.8$

p.f of syn. motor $\dfrac{18.2}{63.8} = 0.285$ leading

To improve p.f to unity RKVA required is 197.5. The synchronous motor rating is only 130 kVA. Hence the plant p.f cannot be U.P.F.

Note: Normally power factor is improved to 0.87 to 0.9 and never to 1.0 as large amount kVA is needed and the benefit obtained i.e., reduction in line current or improvement voltage regulation is not much. This can be seen from Example 7.8.

7.9 OPTIMUM POWER FACTOR FOR DISTRIBUTION SYSTEMS

Usually shunt capacitors are applied to each substation bus or at distribution boxes in an industry with reactive power compensation given to improve the p.f to or around 0.9. But a logical and better way to arrive at the optimum size for capacitor banks and improvement to p.f is to determine an economic power factor so that the benefit obtained is made equal to the cost of the capacitors and the annual interest and the expenses there. For a given power P_k the peak power supplied, Q_c required capacitor bank RKVA, is obtained by

$$Q_c = P_k (\tan \theta - \tan \theta')$$

Where $\tan \theta$ is the original p.f and $\tan \theta'$ the optimum p.f. $\tan \theta'$ is obtained with the following procedure.

(i) The best desired p.f (a value chosen between 0.90 to 0.98) is set.

(ii) Additional savings in 'kW' losses at the set p.f value, when all capacitors are connected to the substation or distribution bus is determined.

(iii) Reduction in losses due to capacitors applied to substation buses and additional losses due to capacitors are computed.

(iv) Reduction in KVA demand and hence the additional capacitors needed at buses and feeders is computed.

(v) Total annual savings in demand reduction due to additional capacitors applied, is computed (Rs/year).

(vi) Total annual saving due to additional released capacity per year and hence the annual savings due to energy losses (Rs/year).

(vii) Total annual losses due to cost of capacitors, energy losses in capacitors and other operating expenses are computed.

(viii) Net savings (annual) is arrived at (Rs/year)

(ix) Is the power factor set economical? For this, the procedure is repeated by setting a new value.

(x) Best p.f is one which gives maximum value for step viii.

The above procedure is a bit tedious and computer studies are needed to get the optimal solution.

7.9.1 Best Capacitor Location and Optimum Capacitor Size

The capacitor size and location is usually determined by minimising (i) power loss (ii) voltage regulation, and (iii) additional cost and other expenses for illustration. The procedure usually followed is

(i) to determine the desired p.f for the given load or circuit from the data, viz., kW or KVA and p.f

(ii) the feeder or line voltage and improvement needed

(iii) to determine correction factor needed to correct either load or feeder circuit p.f from the existing one

(iv) to check the existing capacitors or other p.f correcting devices, their capacity, location, etc., and improvement given

To find the distance of the capacitor bank and its location, the inductive current line loss is divided by the capacitive current line loss per km and the quotient is determined. If the quotient is greater than the line or section length, the remaining line loss is adjusted to the next section capacitive line loss and the new location is determined. The procedure is continued to the next line length or section. The voltage profile obtained with the capacitor is prepared and checked for the improvement (see Section 7.5.2 for voltage profile in Figure 7.5 and 7.6)

Optimal Location of Capacitor

To obtain the best location for the capacitor banks, the feeder line is decided into a number of sections with a combination of both uniformly distributed loads and concentrated loads. The reactive component of current (or RKVA) is determined. This component is counterbalanced by a capacitor bank in each section or segment such that power loss due to inductive current is reduced by the capacitor allocated in that section. The ratio of the reactive (capacitive) 'RKVA' of the capacitor to the total reactive load is determined along with the ratio reactive current at the end of the line segment to the beginning of the line segment (a). The distance of capacitor bank from the feeding point of the line segment is obtained by considering (a) the ratio, (b) original losses due to reactive current, (c) capacitance, and (d) compensation ratio. The optimum number of capacitor banks is obtained by making the cost function of th above variables a minimum. The procedure is very tedious and in practice the locations indicated in Section 7.4 are preferred.

7.9.2 Benefits with Capacitor Installation in Distribution Systems

In the previous sections, it has been shown that by installing capacitors, line current taken for a given power is reduced and voltage dip in feeders, transformers etc. is also reduced. Further the reactive power (lagging) needed by the loads in supplied by the capacitors and hence the source or power plants are relieved to that extent. Hence the substations as well as generating stations can supply an additional power without increase in the current. In general, the benefits from installation of capacitors are

(i) The generation plant capacity, together with transmission and distribution substations and network capacity is released and hence increased to that extent
(ii) Reduced energy losses (power losses)
(iii) Reduced voltage drop and improved voltage regulation
(iv) Increase in revenue due to voltage improvement, reduced losses and hence supply of more energy

Quantitative estimate of the above benefit and hence the revenue increase is a more involved procedure and complex calculations are needed.

The total benefits due to capacitors installation can be put as total financial (benefit) obtained due to (i) Demand reduction + (ii) Energy savings (reduction) + Revenue increase due to release of additional capacity.

Summary

In this chapter, the causes for low power factor and their source (lagging p.f) together with the different loads and their p.f is given. The need for power factor improvement, the compensation given by capacitors is illustrated. Connection and location of capacitors, compensation using synchronous condensers, optimum power factor for a given system and benefits desired by the capacitor illustration is discussed.

Keywords

Power factor improvement
Power factor analysis
Capacitor compensation
Series and shunt capacitors
Location of capacitor banks
Voltage regulation
Synchronous motors
Optimal p.f

Review Questions

1. Explain the need for p.f improvement in distribution systems.
2. How in the capacitor bank ratings obtained when the load p.f is to be improved from cos θ_1 to cos θ_2?
3. Explain how reduction in line current and hence power losses are obtained with p.f improvement.
4. What are the different locations for p.f improvement capacitors? Discuss their relative advantages and disadvantages.
5. How does p.f improvement help in reduction in % VD and hence voltage regulation of distribution transformers? With transformer of 6% reactance and 2% magnetizing current, what will be the probable ratings of capacitor bank to compensate for magnetizing current and improve regulation by 2%?
6. What is series capacitor compensation in feeder lines ? How does it improve the regulation of the lines? Discuss with suitable examples.
7. What is ferro-resonance ? Explain the phenomenon and how it occurs with capacitance compensated lines.
8. Discuss how voltage profile of a long feeder can be improved by connecting shunt capacitor banks at the end of the feeders.
9. How is economical power factor arrived at for a given distribution system with different loads ?
10. What is the justification for p.f improve and what are the benefits ?
11. Compare and explain role of shunt and series capacitors in p.f correction.

Problems

12. An industry has a total induction motor load of 100 hp, efficiency 0.88 and power factor 0.8 *a*. It is necessary to correct the p.f to 0.9 lag. Determine the capacitor bank needed. If the capacitor bank has 4% losses find the % increase in power in take and the p.f with capacitors.

13. In Problem 12, the motor load is divided as 75 hp induction motors with same efficiency and 30 hp synchronous motor. What is the p.f at which the synchronous motor has to operate on full KVA load to correct the p.f to 0.9 lag. Synchronous motor efficiency is 92%.

14. A 11-kV/415-V transformer is Δ / Y connected and supplies 150 A load at 0.75 p.f connected at the end of the feeder. Transformer impedance is 0.03 + j0.06 p.u and line impedance 0.05 + j0.125 Ω
    (a) What is the rating of shunt capacitor bank to be connected at load end to improve the p.f to 0.9?
    (b) What is the reduction in line current and power losses in the line ?
    (c) What is the change in percentage VD if the voltage is maintained at 11-kV on primary side?
15. An induction motor takes 5 times the normal current at starting and has a p.f = 0.3 lag. The normal full load current is 15 A at 0.85 p.f lag. The motor is connected to the 11-kV transformer. What is the series capacitor bank needed to improve voltage regulation and limit the voltage dip to 5% ?
16. 7500-KVA, 3-phase 33/11-kV transformer has a connected load of 9000 kVA at 0.8 p.f lag. The transformer can withstand 20% over load. Find
    (i) kVAR rating of shunt capacitor bank to improve the p.f of transformer to 0.95.
    (ii) The maximum kW load that can be supplied with the corrected p.f. so that its maximum capacity is not exceeded.
    (iii) If the kVA rating is to be limited to its normal capacity, and using the same capacitor bank, what is the additional kW that can be supplied ?
17. A 22-kV, 3-phase distribution feeder is 50 km long and has an impedance of 0.2 + j 0.5 Ω/km and supplies a load of 3 MVA at 0.72 p.f lag.
    (a) What is the regulation and voltage drop?
    (b) If the line is compensated by 60%, what will be the regulation for the same load?
    (c) If the voltage drop is to be limited to 4% what should be the capacitance value needed?
    (d) What will be the voltage rise in no load condition, if a shunt capacitor bank taking 30 A per phase exists at receiving end?
18. (a) In Problem 12, assuming that the capacitor bank is loss free and the supply system is 3-phase 400-V 50-Hz, determine the value of the capacitance in μF per phase when capacitor bank is star connected to improve the p.f to 0.92.
    (b) If the capacitor bank is to be delta connected what is the capacitance per phase and what is the total kVAR ?
19. A 3-phase, 50-Hz, 2200-V induction motor develops 40 h.p at a p.f 0.8 lag with efficiency 90%. The p.f is to be raised to unity by connecting a bank of condensors in delta across the supply mains. If each of the capacitors unit is to be built up with 4 similar 550-V capacitors, calculate the required capacitance of each condensor and its kVA rating.
20. A 400-V, 50-Hz, 3-phase, line delivers 207 kW at 0.8 p.f lag. It is desired to bring the line p.f to unity by installing shunt capacitors. Calculate the capacitance if they are (i) Y connected (ii) Delta connected
21. A 3-phase transformer is rated 7 MVA and has over load capacity of 125% of the rating. If the connected load is 1.15 MVA with 0.8 p.f (lag) determine (i) the MVAR rating of the shunt capacitor required to decrease the load of the transformer to its capacity (rating) (ii) p.f at the corrected level (iii) MVAR capacity of shunt capacitor bank required to correct the p.f to unity.
22. An industrial consumer has the following loads :
    (i) Induction motor loads, total of 300 h.p runs at average efficiency of 89%, p.f = 0.85 lag.

(ii) Synchronous 100-h.p motor with average efficiency = 86%

(iii) Heater loads 100 kW

The consumer uses synchronous motor to correct its over all p.f. Determine the required p.f of the synchronous motor to correct overall p.f at peak load to (a) u.p.f, and (b) 0.96 lag.

Multiple Choice Questions

1. Chemical industries and plants generally have a load p.f of
   (a) 0.2 (b) 0.3 to 0.5 (c) 0.5 to 0.7 (d) 0.75 to 0.90
2. Lighting loads such as fluorescent lamps have a p.f of
   (a) 0.2 (b) 0.5 to 0.6 (c) 0.8 to 0.9 (d) 1.0
3. A lossy capacitors have loss factor (power factor) of
   (a) 0.01 to 0.05 (b) 0.1 to 0.2 (c) 0.5 (d) <0.005
4. ‘Reactive power compensated, when p.f is improved from cos θ_1 to cos θ_2 is given by (P = power and S = kVA)
   (a) $P(\tan\theta_1 - \tan\theta_2)$ (b) $S(\tan\theta_1 - \tan\theta_2)$
   (c) $P(\sin\theta_1 - \sin\theta_2)$ (d) $S(\cos\theta_1 - \cos\theta_2)$
5. Multiplying factor to determine kVAR of capacitor banks is
   (a) $(\sin\theta_1 - \sin\theta_2)$ (b) $(\cos\theta_1 - \cos\theta_2)$
   (c) $\theta_1 - \theta_2$ (d) $(\tan\theta_1 - \tan\theta_2)$
6. A 37.5 kW induction motor has a p.f of 0.707 and is to be improved to 0.90. The kVAR of capacitor bank needed is
   (a) 33.75 (b) 26.5 (c) 7.50 (d) 19.3
7. Series capacitor compensation is used to
   (a) improve p.f (b) reduce line reactance
   (c) reduce fault levels (d) compensate for reactive power of load
8. Series capacitors are located at
   (a) sending end of the line (b) middle of the line
   (c) receiving end of the line (d) all the three above
9. A 700-kVA load is operating at 0.65 lagging. What is the multiplying factor to improve it to 0.92 lag?
   (a) 0.65 (b) 0.85 (c) 0.907 (d) 0.743
10. In *Q* 9 above, what will be the MVAR rating of the capacitor bank?
   (a) 0.41 (b) 0.338 (c) 0.954 (d) 0.50

Fill in the Blanks

11. The most suitable and best location for capacitors is ______________.
12. Hospitals, commertial locations, etc., will have p.f of ______________.

13. The disadvantage of a series capacitors is ______________.
14. Ferro-resonance occurs in a power system due to ______________.
15. Series capacitors in distribution lines and protected against over voltage by ______________ and ______________.
16. A 100-kVA transformer has 8% reactance. If a 30 RKVA capacitor bank is connected, the improvement in voltage is ______________.

Answers

1. c	2. b	3. a	4. a
5. d	6. d	7. b	8. c
9. d	10. b		

11. Either at the load (motor) end or at the distribution bus
12. 0.75 to 0.85 lagging
13. Fault current or fault MVA is increased due to decrease of line reactance
14. The capacitance of the line, series or shunt capacitors going in resonance with the magnetizing inductance of transformers
15. Surge a rester or HRC fuse in series
16. 0.024 p.u or 2.4%

Eight

This chapter is devoted to substations, basic equipment and components, layouts, busbars and their arrangement, grounding and earthing. Introduction to recent type of substation, i.e., gas insulated substations is given.

Substations Equipment, Location and Grounding

Introduction

Substation is an important and vital entity in the distribution networks. Power is transmitted from the source to various load centres through high voltage and extra high voltage network. At a substation the voltage level is stepped down and fed to the primary distribution network. Further smaller substations are located at the customer location or at convenient locations where the voltage level is further stepped down to the user's level. Where ever a voltage transformation is needed, a substation with a transformer, metering and control equipment will be installed.

8.1 SUBSTATION TYPES

Substations are mainly classified as (i) outdoor, and (ii) indoor. Outer door substations are located in open space and conductors and equipment is mounted on insulators. The main insulation is atmospheric air only and hence require larger clearances or space between several items of the equipment. These are called air insulated substations (AIS).

The insulation and clearances are also designed for wet conditions such as rain and pollution. Indoor substations are located where space available is very less for the given voltage levels. Conductor connections from outside is taken through insulated cables, wall bushings etc. The equipment is not exposed to wet conditions and hence are quite close. Nowadays due to further limitations of space gas filled stations (GIS) are being put into service. In these substations the entire equipment is put inside a closed room or cubicle which in under pressurized gas (SF_6). SF_6 under a pressure of 6 to 8 atmospheres has dielectric strength more than 5 times that of air and hence the clearances required for insulation are much less.

All the equipment such as disconnecting switching (isolators), circuit breakers, metering and relaying equipment (CT and PTs etc.), transformer connections and bushings to take the leads out, are all put as a single module. At present GIS are operated up to 220 kV.

8.2 SUBSTATION COMPONENTS, EQUIPMENT AND LAYOUTS

A substation essentially consists of

1. The incoming feeders or sources
2. Disconnecting switches or isolators
3. Surge protection or over voltage protection devices (Surge diverters or lightning arresters)
4. Fuses or circuit breakers
5. Bus bars (where power is received and distributed)
6. Transformers
7. Metering equipment
8. Out going feeders
9. Axially power supply (battery source) for operation of isolators. CBS etc.
10. Control room from where all required operations are done

Typical substation layouts (single line diagram) of a 11-kV/415-V, 3-phase LT substation as well as 33/11-kV primary distribution substation are given in Fig. 8.1 to 8.2.

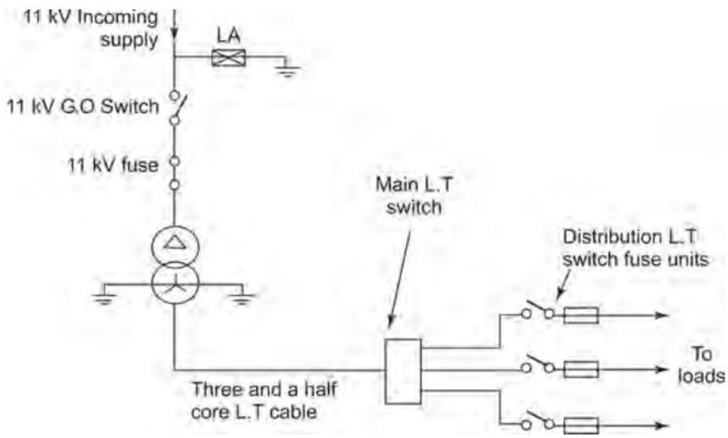


Fig. 8.1 (a) *Single-line diagram of a pole-mounted substation*

Most of the LT substation i.e., 400 – 440 V, 3-phase substations up to 250 kVA are pole-mounted or platform mounted. In the arrangement shown in Fig. 1 the transformer is mounted on a H shaped poles and equipment is suitably arranged on the pole as shown. The gang operated (GO) isolator switch is meant for no-load operation and fuse is put for protection on HV side. The low voltage side of the transformer is connected to the distribution network through a LT main switch and fuses. Larger capacity (> 500 kVA) LT substations will have on the LT (400 V) side, a busbar, distribution box with circuit breakers, disconnecting switches and fuses. Industrial substations may have generators (stand by) connected to the substation LT side through suitable switch gear and protection equipment. The primary distribution substation usually will have a capacity more than 1 MVA and can be up to 20 MVA are more.

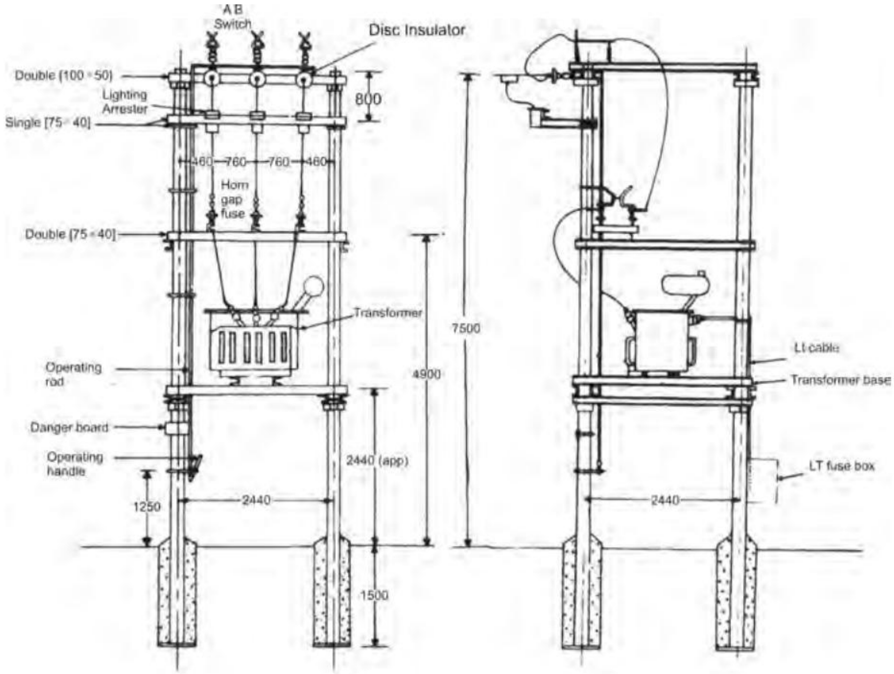


Fig. 8.1 (b) *Pole-mounted distribution transformer*

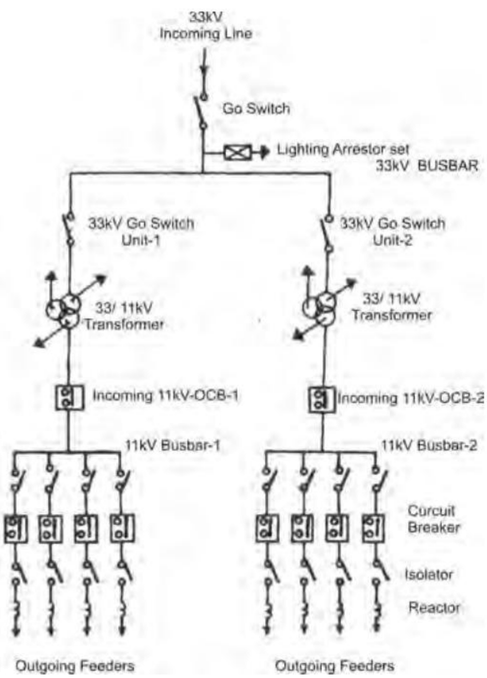


Fig. 8.2 *Single diagram of 33-kV / 11-kV substation*

In a 33/11-kV or any other voltage substation the incoming feeders connected to the busbar or common point for the high voltage supply through isolator switches (GO or gang operated) on no load only. The transformers are given supply from the busbars through an isolator switch individually. The secondary side of the transformer is connected through circuit breaker to the secondary bus. Outgoing feeders are taken from the secondary bus through an isolator switch and circuit breaker (CB). Sometimes to the secondary bus bars two or more transformer are corrected through CBS, so that if one transformers is out of service, the other can feed the secondary loads. Duplicate or standby busbar arrangements are shown in Figure 8.3. The purpose of a few important components are as follows.

i. *Gang operated(G.O)* Or other *isolator switches* are meant for closing or opening the circuit under no-load. A few switches are designed to be closed on load also.

ii. *Fuses* These are for protecting the transformer on over loads and faults. Once a fuses blows off, the supply is disconnected. The circuit can not be closed automatically after the fault.

iii. *Circuit breakers* These are switches which will operate automatically under heavy over loads or faults. They can be closed or opened on load as well as under fault conditions.

iv. *Bus bars* These are heavy duty conductors which can carry both the entire load current corresponding to the capacity of the substation and also fault current for few seconds. They are designed to withstand heavy mechanical forces that develop under fault conditions since the force between two parallel conductors is proportional to square of the current. They are arranged as parallel bars mounted on insulators. Supply to transformers is given from busbars through isolator switches or CBS.

v. *Transformers* These are used to step down the supply voltage. Distribution transformers operate from no-load or light load conditions to full load condition with varying power factors. Their impedance usually range from 4 to 6% (0.04 to 0.06 pu) and no load losses are a minimum. Power transformers in primary distribution substation are usually loaded from 50% to full load and operated at p.f of 0.8 to 0.9 lag with suitable power factor correction capacitor banks. Their impedance may be 0.06 to 0.1 so that current under faults is limited by their impedance.

vi. *Metering equipment* It is necessary at the substation to know the electrical quantities pertaining to the supply, i.e., voltage, current, power, p.f. KVA of the incoming supply and outgoing supply. The difference gives the power loss and the energy loss. Hence the substations will have potential transformers (PTs) and current transformers (CTs) connected to the incoming and outgoing feeders. The output of the CTs and PTs is fed to voltmeters, ammeters, wattmeters which measure the above quantities. In addition a separate set of PTs and CTs are installed to feed to the relays for switch gear operation. The standard ratings adopted on the secondary side of the PTs is 110/120 V and for CTs (0 – 5A) or (0 – 1A).

vii. *Auxiliary power supply/battery room* Usually for independent operation of CBS, remote controlled isolator (Gang operated) switches and other equipment, a battery supply of 110 V or 220 V with adequate ampere hour capacity is maintained. The batteries are charged from the substation supply it self.

viii. *Control room* A central room is located in primary substations where all the metering equipment, relays and auxiallary controls are installed. All the electrical quantities are fed to recording equipment for continuous record when the substation is remote controlled using ‘SCADA’ or such other means. The data is fed to the controlling centre from this point.

ix. *Surge diverters or lightning arresters* These are installed at the incoming point of the feeders as well as the outgoing feeder points to protect the substation from over voltages due to lightning as well as switching surges. In addition, spark gaps such as rod gaps are installed across the bushing of transformers, switch gear etc. for the same purpose. Rod gaps are much cheaper compared to surge diverters but the risk factor for protection is high.

8.2.1 Bus Arrangement and Switching Systems in Substations

In order to affect the reliability, the bus and switching arrangements provided in substations play an important role. The maintenance requirement, protection schemes, cost of substation and future expansion also depends on the initial configuration chosen. In section 5.1 two typical arrangements, viz., the single bus system and ring (loop) arrangement are shown in (Fig. 5.1 and 5.2). Here all the commonly used systems are given. These are

(a) Single bus
(b) Double bus (single and double breaker)
(c) Main and transfer bus
(d) Ring bus
(e) Breaker and half

(a) Single-bus system (Fig. 8.3.1) This is the simple and widely used arrangement where in all the feeders, transformers or the other equipment is connected to single bus directly. There is no other parallel arrangement for a bypass and hence reliability is least. The entire system suffers outage if there is a fault at bus or circuit section in between bus, CB, or other equipment in that line. This is used only in light loaded and unimportant substations.

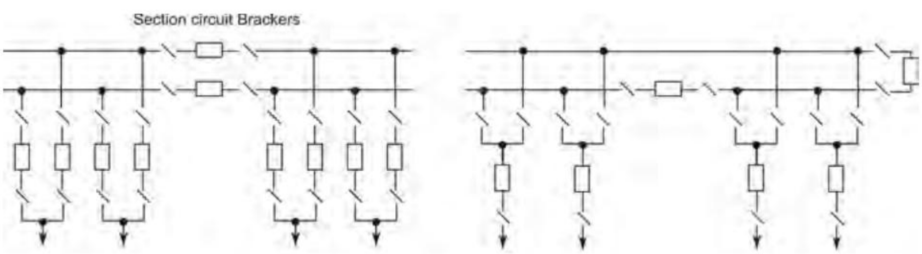


Fig. 8.3 *Duplicate bus arrangement*

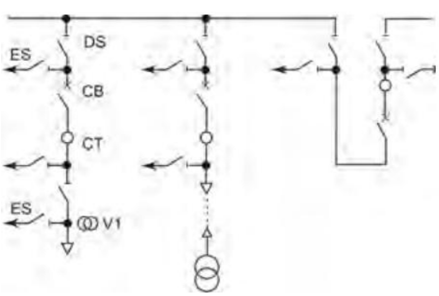


Fig. 8.3.1 *Single busbar system*

(b) Double-bus single breaker system (Figure 8.3.2) This system has two bus bars and any feeder or equipment can be connected to either of the bus bars through the proper isolator switch closed. Only one CB is used. The loads can be transferred from one bus to the other utilizing the transfer CB or bus coupler. Usually the bus tie breaker (transfer CB) will be in closed position and the failure of this will cause complete outage of the substation. If the transfer CB is in open position, the system is equal to two single bus systems.

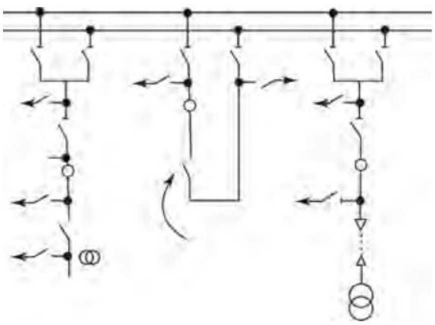


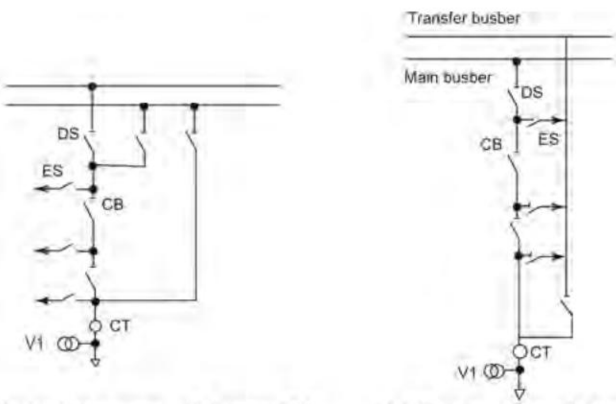
Fig. 8.3.2 *Double busbar system*

(c) Double-bus double-breaker system (Fig. 8.3.3a)

This is a bit complex arrangement but has a high reliability. Two separate breakers are utilized for each circuit or apparatus. This arrangement allows for flexible operation as well as adding more circuits. Loading can be shifted from one circuit to other, but this arrangement will cost more.

(d) Main and transfer bus (Fig. 8.3.3b)

This arrangement is similar to the double bus double breaker system except the bus 2 is used temporary. Both buses are coupled with a bus tie CB. For maintenance or for temporary shutdown loads are transferred to bus 2 (transfer or auxiliary bus). Usually complete protection will not be available with transfer bus operation (Fig. 8.3.3b).



(a) Double busbar system with bypass DS (b) Main and transfer busbar system

Fig. 8.3.3 *Double-bus double-breaker system*

(e) Ring bus (Fig. 8.3.4) In this arrangement the CBS are arranged in a loop or ring manner with circuit connection tapped between two CBS. Fault or disconnection of any one circuit does not affect the system since the two adjacent CBS trip making the ring open. This scheme is best and more reliable. But the disadvantages are (i) protection scheme is complex and costly (ii) when main bus is taken out of service adequate protection will not be available.

(f) Breaker and half scheme (1½ CB system) This is a modification of ring bus arrangement. There will be two buses and each circuit is connected between two CBS. The failure of circuit due to fault or other wise will trip only that circuit. The advantage is the maintenance of a CB can be done without interruption or loss of any circuit. Protection scheme for this arrangement is complex and the substation requires more space and is costly because of additional equipment.

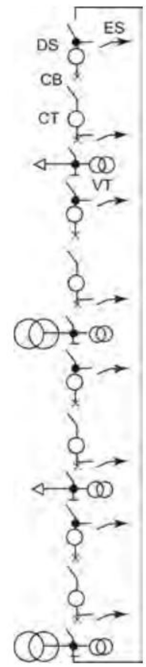


Fig. 8.3.4 *Ring bus system*

8.3 SUBSTATION LOCATION AND SIZE

The criteria for location of a substation are the following :

i. Minimum losses and better voltage regulation which means that it should be as close to the loads in the service area as possible, i.e., the sum of (load KVA) × (distance) is minimum.
ii. The substation should have proper access for the incoming and outgoing lines and also allows for growth in future.
iii. In cities and busy or densely populated areas, the substation should occupy the minimum possible place.

The substation size (MVA) depends on, the load density growth, utilization of transformer capacity, fault levels and flexibility in operation. The size of the substation will be larger and compact in urban areas as it will not be possible to have more substations. A HV distribution network may be adopted. The choice of the voltage levels depend mainly on the load density and the distance over which the feeders have to run. In India the distribution voltage levels are standardized and hence little choice is left between adopting either a HV distribution (11-kV) or LT distribution (400-V).

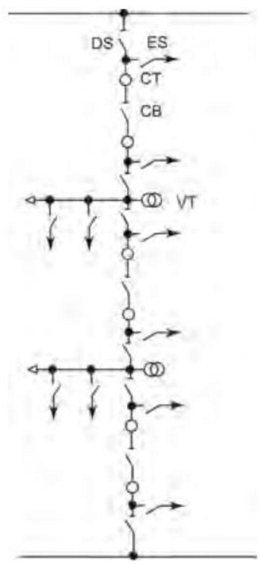


Fig. 8.3.5 *Breaker and half scheme*

8.4 GROUNDING

8.4.0 Introduction

Grounding and earthing practices are most important and vital aspect of power system. All equipment casings, the neutral of the 3-phase system and that of the source have to be kept and zero potential or ground. Hence all the facets of the grounding techniques that relate to the distribution system and equipment are presented here. The grounding aspects may be subdivided as

i. System grounding
ii. Equipment grounding
iii. Protection (static and lightning) grounding and
iv. Methodology and connections to earth

A good grounding system should provide a low impedance path to ground and dissipate repeated fault currents and surge currents. It should also provide effective earth for personnel and equipment.

8.4.1 System Grounding

Distribution system grounding is connecting or inter connection between electric conductors and ground or earth. It also deals with nature and location of intended connection of same electric conductors to earth. The grounding in generally classified as

(i) ungrounded,
(ii) resistance grounded,
(iii) reactance grounded, or
(iv) solidly grounded.

The nature of grounding has an effect on the magnitude of line or ground voltages both under steady state operation and transient conditions (faults etc.) Also grounding has an effect on the insulation life and voltage stress on the equipment insulation. Depending on the type of distribution system and voltage levels, the type of grounding is decided.

(a) All 3-phase 4-wire 3-phase 3-wire and single-phase, 3-wire (midpoint earthed) for voltage of 400 V and below are solidly grounded, i.e., neutral point is directly connected to the earth.
(b) All distribution system of medium voltages like 3.3 kV, 6.6 kV, 11 kV, 3-wire systems are usually grounded through resistance to limit the fault current for L-G faults. Resistance grounding employs connection of resistance between neutral and earth. If the capacitive reactance of the system is X_{CO}, then the resistance connected between neutral and earth acts as a pure resistance and if $R \leq X_{CO}/3$ and will be enough to reduce or curb the over voltage that is produced during the fault. Also this acts for accessing the L-G fault current for securing selective earth fault relaying. In such cases the system is said to be 'effectively grounded'.

Low resistance grounding requires a resistor of a value that can take about 400 A for high power devices. In low voltage applications the grounded fault current may be very small (20 – 50 A). Resistance grounding is generally adopted for generators and large power transformers. Solid grounding has the advantage of reducing the over voltage during fault to a very minimum but ground fault current will be quite high. In order to avoid electric shock under abnormal conditions, solid grounding is recommended. Reactance grounding is adopted only for generators.

8.4.2 Equipment Grounding

This relates to the system of electric conductors by which all metallic parts, through which energized conductors run, will be inter connected. The main purpose of equipment grounding is

(i) To maintain low potential difference between nearby metallic members in the area and to ensure freedom from electric shock hazard to personnel working in that area
(ii) To provide effective conductor system over which short circuit currents involving ground can flow without sparking or terminal distress and avoid fire hazards.

Whenever there is an insulation failure between the energized conductor and some part of metal or conducting part of the enclosure, there exists a tendency to impart the same potential to the metal part as that of the energized conductor unless all that parts are connected to earth or zero potential. There is a possibility of electric shock hazard and this should be avoided and permit sufficient flow of current to the earth. Hence the metallic and conducting parts of the equipment etc. should be connected to the earth as per specifications with good electric conductors of 1/0 gauge or larger cross section wires. Grounding of the following types of equipment is a must as per specifications :

(i) Structures of substations (ii) Outdoor station equipment (iii) Large generators and motors (iv) Portable equipment such as hand drills, etc. (v) Conductor enclosures of miscellaneous equipment (metal conduits).

8.4.3 Substation Grounding

Proper grounding of the substation is needed because (i) it provides a path for dessipating the electric current into earth without exceeding the operating limits (ii) it also provides a safe and protected vicinity for the persons from the danger of shock under abnormal conditions like faults etc.

Grounding system is all interconnected earth (or ground) in the substation area i.e., the ground grid, overhead earth wires, neutral conductors, ground rods, deepwell foundations, etc. It is also meant to provide a safe condition and atmosphere with in and around the substation area. Grounding and earthing design is based on the safe permissible body current. Basically, there are about 'five' voltages (potential differences) where a person may be exposed that can cause shocks.

(i) Ground Voltage The maximum potential that a substation ground grid can attain under faults etc., with respect to a far-off ground point and is at earth or zero potential. This is the magnitude of the voltage rise due to the grid current portion of the fault current conducted and the resistance of the ground circuit.

(ii) Mesh Voltage Maximum touch voltage within the loop or mesh of the ground grid

(iii) Step Voltage The difference in surface potential felt by a person who bridges a length of 1 m with his feet without touching any other part or element of other grounded equipment or objects

(iv) Touch Voltage The difference between ground voltage rise and the surface potential at any point when a person stands on the ground and touches or comes into contact with other grounded objects or structures.

(v) Transferred Voltage This is the voltage felt when a surge is transferred into or out of the substation from a remote source external to the substation

Permissible Body Currents The magnitude of current, its duration, frequency and nature has an impact on the human body. The most dangerous situation is the heart condition known as 'ventricular fibrillation', stoppage of heart beating resulting in immediate loss of blood circulation. The other common effect with increase in body current is perception, muscular contraction, fibrillation resperatory nerve blockage and burning, becoming unconcious leading to death. The safe current that can be tolerated is 100 µA or less. The threshold of perception and ability to control the muscular movement and release of the source of current can be up to 1 ma. 9 to 25 ma may cause loss of muscular control and may lead to fatal shock. Larger currents have severe effects, leading to death. Hence the substation grounding system should be such that body currents are withen the safe limits. The body current flow (I_b) according to Chales Dalzial is given by the emperical relation

$$I_b = \frac{0.116}{\sqrt{t_s}}$$

where t_s is the contact time which is about 0.03 to 3 seconds for a person with an average wt. = 50 kg.

Touch and Step Potentials within Ground Grid Area

In any substation, after the ground grid is designed and established, the soil resistivity and grid currents are to be determined for safety reasons. The soil resistivity and hence the soil resistance is very important and it depends on (i) moisture content, (ii) temperature (iii) chemical composition, and (iv) type of soil like sand, loam, clay, etc. Soil resistance or resistivity can be different and vary both in horizontal and vertical directions. As such, soil resistance must be measured and acertained in the substation area and ground.

The substation grid resistance i.e., the resistance of ground grid with respect to a remote earth without any metallic conductors should be measured or known. From this, the maximum grid current should be determined since this is the current that gives the ground potential rise and the local largest surface potential gradient. It is the flow of grid current to a remote earth that determines ground potential rise. Any ground fault that occurs like a L-G or L-L-G fault (refer Chapter 9) usually produce maximum grid current. The flow of grid current will be in different ways if the ground grid is complex. Substation grounding and ground grid design should be such that the 'Touch Potential' and 'Step Potential' are withen the limits and will not give rise to unnecessary shocks.

8.4.4 Static and Lightning Protection Grounding

Static Protection Outdoor equipment, substations, tall structures, etc., are exposed to lightning. Lightning discharge is transfer or induction of electric charge on the structure etc. when lightning discharge occurs. Further in some industries like textile, chemical, oil purification etc., electric charge accumulates on insulating parts and can give rise to large potential above the earth or zero potential. The protection of human life against shock or other wise is also a prime objective of controlling electrostatic charges. Sometimes the accumulated charges also lead to imperfect or un desirable finishing such as in case smoothing non conductors, finishing of fibre in textile mills etc. As such it is necessary to find causes, methods of testing and control of static charges so that effective earthing can be provided.

Grounding for Lightning Protection This is important for the conducting of current discharge originating in atmosphere during cloud formation and thunder storms. The grounding system should safely carry all the discharge currents to earth without causing damage to electrical insulation of power system and its equipment. Also it should not over heat the conductors and also cause any disrupting breakdown of air between ground conductor and other structures. The lightning currents can be as high 10 to 100 kA and have rate of change of current (accelaration of charge di/dt or d^2q/dt^2) 1 to 10 kA/μ second. In case the earth conductor or path possesses an inductance of as little as 1 μH, with di/dt = 10 kA/μ sec will give rise to a potential drop of 10 kV which quite dangerous to the personnel as well as the insulation of the equipment and structure. Hence effective grounding of tall buildings, out door or indoor substations structures etc., is very very important. Even running a grounding cable over 100 m and connecting it to a metallic buried plates in a pond may have very little resistance for Dc or 50 Hz Ac, but can present a high impedance for surge currents.

8.5 EARTH CONNECTIONS AND EARTHING SYSTEM

Connections to earth must have low values of resistance and also low dynamic impedance for fault and lightning currents. It should effectively drain off the static accumulated charge and dissipate high values of currents of several hundreds of ampers. Further the earth resistance that is resistance of soil should be as low as possible. Ground or earth resistance of below 1 Ω is recommended for large substations and generating stations. The following are the recommended values.

(i) Large substations, generating stations, etc. < 1 Ω

(ii) Transmission substations, primary distribution stations, large industries etc. 1 to 5 Ω

(iii) Substations, equipment rated for 10,000 V and below, 400 – 440 V substations, etc., 5 to 10 Ω but any case not more than 25 Ω

Resistivity of Soil and Soil Treatment

The resistivity of the soil plays an important role in earthing. This depends on nature of the soil, moisture content, temperature and chemical composition and content. Sandy soils, clay and black cotton soils have low resistivity while red soils, rock soils etc., have a very high resistivity. Recently moisture retaining low resistance compound "BENTONITE" is being used in the ratio 1:4 by volume for improving earth conductance.

8.5.1 Earth Electrodes and Earthing Procedure

Usually earth electrodes will be either copper, wrought iron or galvanized iron pipes or plates driven into the soil or pit. For plate earthing a number of plates are taken and placed inside the soil at a depth of about 1 to 1.5 m and are interconnected. Usually two or more earth pits are formed. The pit is filled with alternate layers of soil, common salt and charcoal powder to reduce the resistivity further. Other chemicals like “bentonite” etc., may be added. In case of pipe earthing GI pipes of 2 to 5 m length are driven in to the soil. The pipe diameter may be 12 mm to 30 mm or more. It is important that the contact of plate or rod with the soil must be good. Sometimes a buried strip is used to interconnect all the rods or plates put inside the soil, thus forming an earth grid. The earth electrode is connected to the metal parts of the equipment through a straight strip of iron or wire of 0/1 gauge. The resistance of the connecting strip or wire should be very small compared to the driven rod or plate resistance. Provision will be made to wet the soil and earth electrodes with water to improve the contact and reduce the resistance. It may be noted that in case of driven rods, the earth resistance is substantially reduced with increase in diameter and the depth to which it is driven. It was found that for 25 mm rod, increasing the depth from 3 m to 10 m reduces the earth resistance by about 6 times and increasing the diameter from 12 mm to 30 mm reduces the earth resistance to half.

To conclude grounding and earthing is a very important aspect in distribution system. Improper grounding may lead to unsafe condition and is dangerous for personnel as well as equipment.

8.6 GAS INSULATED SUBSTATION (GIS)

In cities and busy localities the space available and cost of land is a major constraint for location on substation. If the substation is to be located in open and free space, the clearances required and the size of the equipment is much larger compared to using the insulation or dielectric with a gas like SF_6. As such, nowadays SF_6 gas insulated equipment and substations are coming up in cities and urban areas. In a gas insulated substation, the high voltage conductors, switch gear (CBS, isolator switches, instrument transformers, the bus bars and all other equipment are housed in metal enclosers filled with SF_6 gas under moderately high pressure (4 to 6 times atmospheric pressure). Power transformers are located separately with suitable connection to switch gear.

The clearances and spacing required which will be in meters, reduces to few centimeters. As such the GIS will be much smaller than conventional or air insulated substation by a factor of 10 (i.e., by 1/10th). In GIS active parts are protected from deterioration from exposure to atmospheric air, moisture, pollution etc., and as such has longer life, more reliable and requires less maintenance.

8.6.1 SF_6—The Insulating Gas

Sulpher hexa floride is as electrical insulating gas colorless, odorless, inert, non toxic and inflammable. Its density is about five times that of air. Its dielectric strength is about 2.5 to 3.0 times that of air and is an electronegative gas. It has better arc interrupting capability and is extensively used in gas insulated circuit breakers (for 132 kV and above) and is now extensively used for arc interruption in high voltage and high capacity CBS replacing 'oil' or 'Air'. SF_6 is usually made available in cylinders (50 kg) in liquid state at high pressure.

SF_6 has one disadvantage. When decomposed, fluorine ("F_2") is released which is highly toxic and hence should not be let out. Further small conducting particles of micron or millimeter size considerably reduce the dielectric strength and hence should always be maintained free from dust and other particles. Also, SF_6 is a greenhouse gas (i.e.,) it can contribute for global warming and hence its emission is prohibited. Nowadays all the negative aspects with respect SF_6 are taken care to a high degree by adopting better handling and recycling practices.

8.6.2 GIS Modules and their Components

Usually a gas insulated substation comes in airtight SF_6 gas-filled metal boxes (enclosures). A single module may be three single-phase units or one unit of three phase. The module or unit may comprise of (a) disconnector or isolator switch, (b) bus bars, (c) circuit breakers, (d) current transformers, (e) earthing switches or ground switches, (f) potential transformers, (g) surge arresters, and (h) termination units. Power transformers usually will be separate and oil filled units and have their own cooling arrangements. The schematic diagrams of some of the above equipment is shown in Fig. 8.4.1 to 8.4.6*.

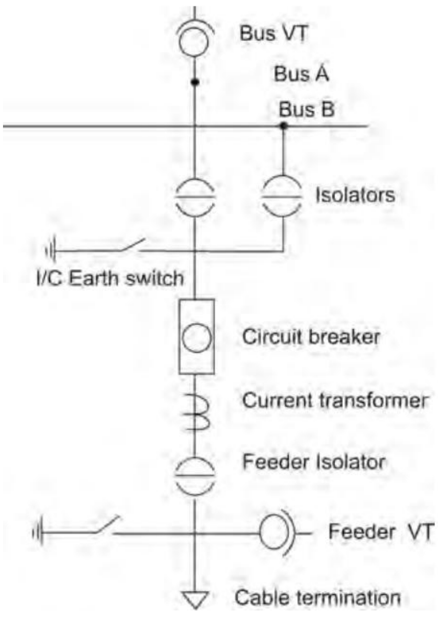


Fig. 8.4.1 *GIS unit single-line diagram*

* (*These figures are taken from the book Gas Insulated Substations by Late Dr. M.S.Naidu, Ref. 27*)

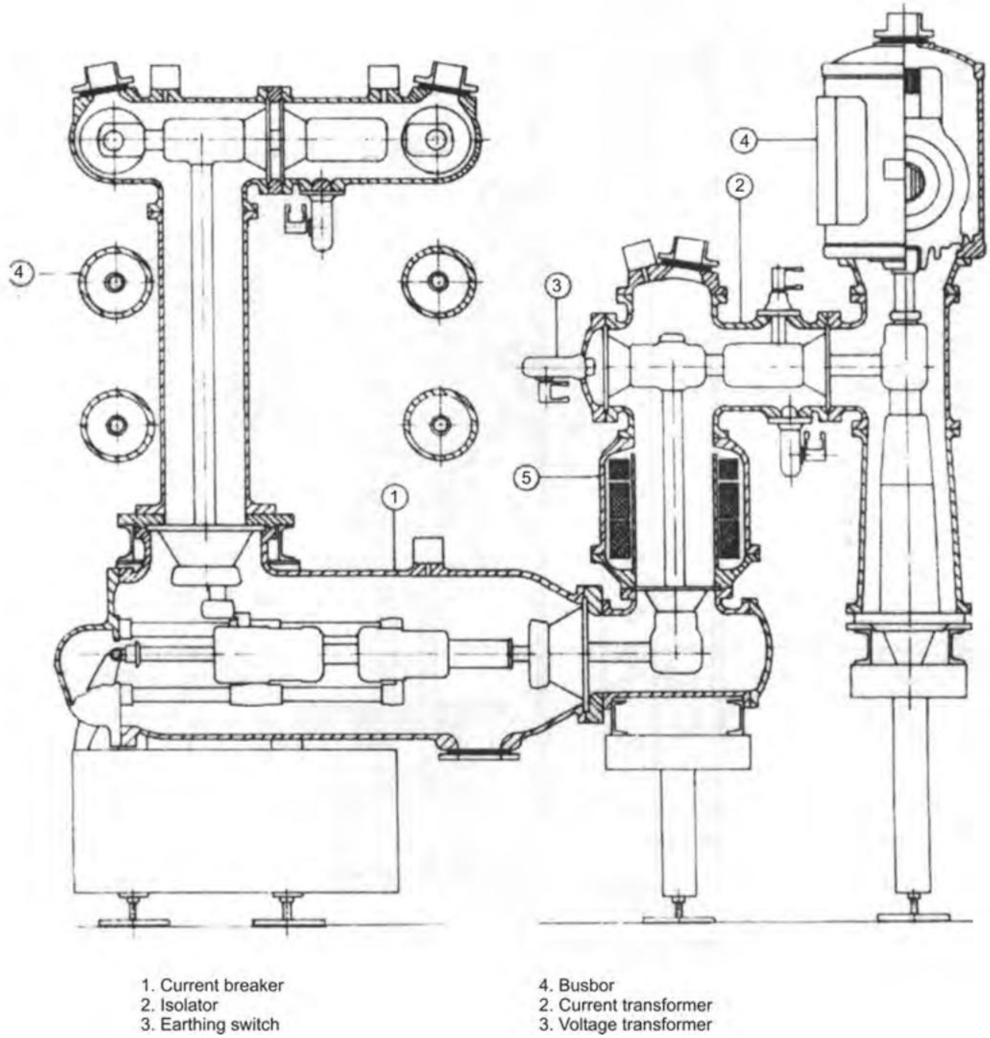


Fig. 8.4.2 *Schematic diagram of SF_6 gas insulated metal enclosed switch gear*

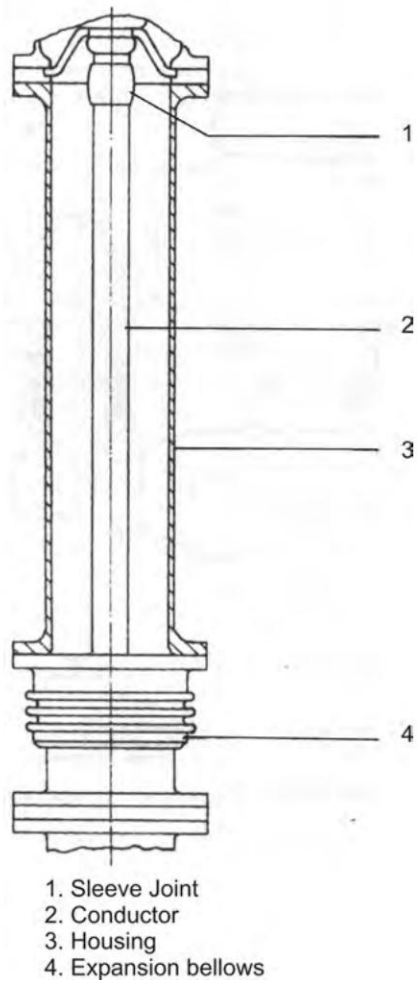
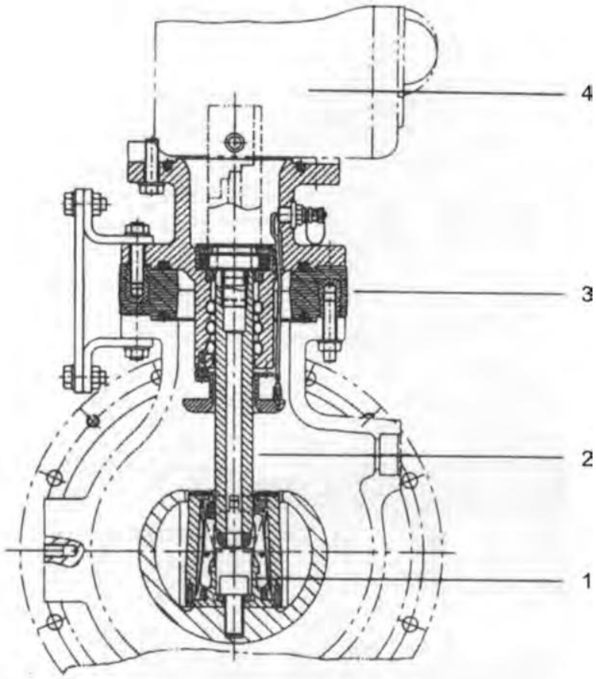
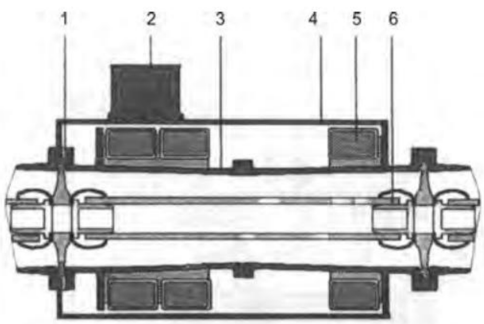


Fig. 8.4.3 *Single-phase busbar*



Legend
1 Fixed contact with fingers
2 Moving contact rod
3 Optional insulation
4 Operating mechanism (Motor drive)

Fig. 8.4.4 *Earthing switch*



Legend
1 insulation
2 Terminal box
3 Ring-Core support
4 Sheet metal casting
5 Ring-Cores
6 Primary tubular conductor

Fig. 8.4.5 *Current transformer*

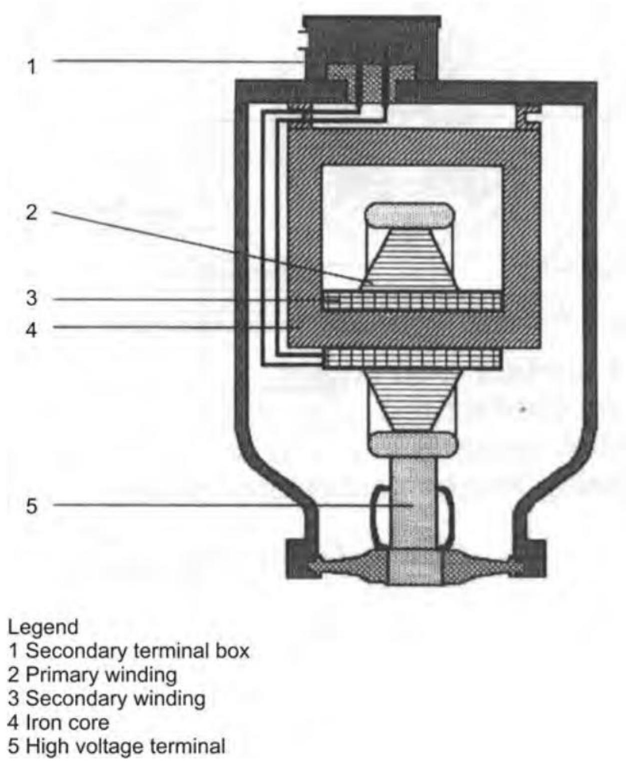


Fig. 8.4.6 *Voltage transformer*

Disconnection Switches Since the electric circuit in the gas system has to open or close under load (not under fault conditions) it has to make or break few hundred amperes of current. Hence it usually has a spring loaded moving contact that sits or plugs into a stationary contact. The moving contact, is activated by an insulating rod which is moved by a shaft in the enclosure wall. The stationary contacts are provided by proper shields that make the electric field uniform and as linear as possible in the surrounding volume. The moving contact moves slowly (compared to CB contact movement) with a speed of 0.1 to 0.2 m/second. They usually can interrupt small reactive (inductive or capacitive currents). The contact surfaces are usually made of silver plated forged copper or of copper beryllium alloy. A firm contact is established between the two contacts with either spring loaded fingers or with multicam contacts. The isolator gap is designed for voltage class of isolator and safe dielectric strength of the gas at that pressure.

The Ground or Earth Switch (Fig. 8.4.4) This is needed to earth or ground the unit safely so that inspection, maintains repairs etc., can be carried out. This is a slow moving device operated under gas pressure or otherwise. There are fast earth switches used with PTs to protect them from core saturation currents etc., and drain accumulated electric charge. Ground switches are mounted on insulator mounting. The moving contact system is an assembly consisting of (a) moving contact, (b) current transfer contacts, and (c) a cam arrangement to get linear motion from roating mechanism and a metal enclosure. This is the smallest sub-unit in a GIS.

Bus bars (Fig. 8.4.3)

A bus is used to connect different modules that are not directly connected to each other. Bus bars can be of different length depending on the requirements of the circuit and substation. The conductor will be usually a tubular one made of copper or aluminium and is centrally located in cylindrical metal enclosers. Conductors are supported by either post insulators or by spacer discs.

Circuit Breakers (Fig. 8.4.1)

The most important and critical part in the GIS is CB (circuit breaker). SF_6 gas is used both for electrical insulation as well as for arc interruption during faults. The gas pressure is around 6.5 to 7.0 atmospheres (0.65 to 0.7 Mpa). The CB is connected either to the isolator or CT module directly. Since CBS operated at higher pressure compared to the other units a barrier is used to maintain pressure difference. A puffer SF_6 CB is used for fault current interruption. The hot gases formed during arc interruption are diverted and not allowed to mix with the rest of the SF_6 gas. The conductors move and operate at speeds up to 0.6 to 0.8 m/second. The CB enclosures are usually the main supports for the GIS.

Current and Potential Transformers (Fig. 8.4.5 and 8.4.6)

CTs and PTs are required in substations for metering as well as for relaying (protection) purpose. In air or open substations the CTs can be of live tank or mounted on insulators. In GIS current transformers are in-line with co-axial geometry in construction. The CT has one turn or solid conductor as its primary and the secondary and core has to be properly shielded from the electric field of the primary conductor potential. Hence the construction consists of a tubular primary conductor, an electrostatic shield, ribbon core (toroidal or ring shaped) and secondary winding. The primary conductor is firmly supported on both sides of a disk insulator. One end is firmly fixed while other will have a little sliding joint to compensate for thermal expansion. The connection to the secondary winding is through a leak proof terminal box seal.

Potential or Voltage Transformers (Fig. 8.4.6)

Since most of the present GIS are in EHV range ≤ 400 kV these are electromagnetic type only (inductive and not CVTS). The primary winding is supported on an insulating plastic films in SF_6 gas and the secondary winding is supported on an insulator support. Electrostatic shielding is provided between the two windings and the terminals are brought through a leak proof terminal box. PTS are connected to the bus through a disconnector switch and a ground switch.

The other important units in GIS are the following :

(i) AIR-SF_6 Connection

This is made by attaching a hallow insulator cylinder to a flag on the GIS enclosure. The cylinder will have pressurized SF_6 on the inside and an air exposure to outside atmosphere on the outer side. The conductor continues from SF_6 into air exposure and is terminated by metal end cap. The design is such that a capacitance grading is obtained and the electric field is semi uniform.

(ii) Transformer Connections

The GIS module is directly connected to power transformer through an SF_6 / oil or any other type bushing. On oil side bushing conductor is directly connected to the transformer winding terminal, where as on SF_6 end there will be a removable link or sliding constant. SF_6 leakage if any is allowed only into the atmosphere and not to oil side.

Surge Arrester or Surge Diverter

Metal oxide or zinc oxide surge arrresters are the one that are suitable to be kept in SF_6 and the zinc oxide elements are arranged and supported by an insulating cylinder in gas. The arrester is housed in a grounded metal enclosure. The surge or impulse waves enter the system (GIS) through the conductor i.e., connection to the GIS cables and direct connection of transformers is not exposed to lightning. Hence only SF_6 to air bushing is directly subjected to lightning. Usually an air insulated surge arrester in parallel with air to SF_6 bushing will be adequate for over voltage protection. But usually surge arresters are provided at the terminals of transformer end and at cable connection to give greater safety.

Control Panel

Usually, a local as well as a remote controlled control panel is used. The control circuitry and power wiring for each of the CB position, isolator, PTs, etc., is done using shielded multiconductor cables. The mimic (single-line) diagram for each part of GIS is displaced along with indicators and push button switches. The control system also monitors the temperature, gas pressure, gas leakage if any, and suitable alarms will be provided for warning.

The local control panel is capable of communicating with the remote control panel through RS-232 bus system or similar unit. Usually auto control is used through a suitable micro controller – microprocessor unit. Another important aspect in GIS is gas seals and gaskets which must have

(i) resistance to decomposition in SF_6, oil, etc.
(ii) mechanical resistance for tension, compression and elongation
(iii) good service life in SF_6 and moisture permeability

Material used for gaskets and seals is usually ethylene propylene rubber (EPR), silicon rubber or nitrile rubber. PTFE pre loaded seals are used for rotary motion feed at earth switches, disconnectors, etc.

8.6.3 Advantages and Economics of GIS

The chief advantages of GIS are

(i) compactness, (ii) cost-effectivity, (iii) reliability, (iv) maintenance (v) effective alternative to conventional air-insulated (AIS) substations, (vi) can be upgraded in vertical direction very easily, and (vii) long life and freedom from frequent maintenance.

The cost of the GIS equipment is high compared to the conventional substation. The high cost is due to its metal enclosure and assembly at the factory. But GIS is less expensive for installation.

Also, the site required and site development cost is very less. In urban areas where site availability and its cost is very high, the over all cost of a 220 kV / 132 kV or 400 kV / 220 / 132 kV substation for an expected life of 25 years is almost comparable. Although it may look at first instance that GIS is costly, it is cost effective for long term solution for large power substations. Although GIS has been a well-established technology for a long time over the last 30 to 35 years with proven reliability and almost no need for maintenance, it is at present perceived as costing too high and is applicable in special cases where space is the important factor. Currently, GIS costs are being reduced by integrating functions like bus, CB, ground switch combined upto 3-position switch etc. and replacing PTs and CTs with optical VTs and Rogowski coil CTs, etc., the units can be made cheeper. GIS can nowadays be considered for a new installation or expansion of a existing one without enlarging the area of the substation.

Summary

In this chapter, substation components, layouts and single line diagrams are given. Different bus bar schemes are discussed. Grounding and earthing of substations is dealt with in detail. A comparison of AIR Insulated (AIS) and Gas insulated substations along with the components and details of gas insulated substations is discussed. Typical substation photos are given.

Keywords

Substation components
Substation types layouts
Bus bar arrangements
Grounding and earthing
GIS modules
GIS components
Economics of GIS

Review Questions

1. What is a substation ? Why is it needed ?
2. Give the arrangement of a single transformer 11,000 / 415 V substation and describe its layout.
3. What are the features of large size substation? Briefly mention the different equipment and the layout.
4. Why is grounding needed ? How is system grounding done?
5. Discuss the importance of grounding with respect to static electricity protection and lightning protection?
6. How is the earthing effectively done ? What are the methods of reducing earth resistance?
7. What is a gas insulated system and gas-insulated substation?
8. Give the different components of GIS with brief description?
9. What are the advantages of GIS over conventional air substations. Give the limitations for GIS?
10. With single-line diagram give the typical layout of a GIS of one phase?
11. Briefly discuss the different bus bar schemes adopted in substations. What are advantages of each scheme?
12. What is a breaker and half arrangement? Compare this with that of ring bus system.
13. Explain the need for substations grounding.

Multiple Choice Questions

1. Isolator switch in a substation is used for
   (a) disconnecting supply under fault condition
   (b) connecting the equipment and disconnecting it under no-load conditions
   (c) operating the switch only on load conditions
   (d) none of the above

2. Earth resistance for LT installation (400 V) should be
   (a) less than 0.5 Ω (b) 50 to 100 Ω (c) 1 to 5 Ω (d) 5 to 15 Ω
3. For lightning protection, ground connection should have inductance
   (a) < 1 µH (b) 10 to 100 µH (c) 100 µH to 1 mH (d) 1 mH and above
4. Earth electrodes are usually
   (a) copper rods (b) GI wire (c) GI pipes (d) spherical electrodes
5. The gas used in GIS is
   (a) nitrogen (b) oxygen (c) air (d) SF_6
6. GIS operates at
   (a) high pressure above 10 atmospheres (b) 5 to 6 atmospheres
   (c) 2 to 3 atmospheres (d) less than one atmosphere
7. Which one of the following is not a component of GIS
   (a) earth switch (b) transformer (c) CB (d) CTS
8. Controlling of the GIS is done by
   (a) control panel at remote place (b) control panel placed locally
   (c) both 'b' and 'a' (d) none of the two 'a' and 'b'
9. Touch voltage is
   (a) step voltage
   (b) mesh voltage
   (c) potential difference between ground potential rise and surface potential when the hand of a person is in contact with ground structure
   (d) the difference in potential between the surface of an earthed structure and ground when a person bridges one meter on the ground
10. The safe body current that can be allowed through a person when a contact is made for 0.3 to 3 seconds is
   (a) 100 µA (b) less than 1 ma (c) 1 to 6 ma (d) 25 ma

Fill in the Blanks

11. A circuit breaker is mainly meant for ______________.
12. In distribution system (400 – 440 V) the transformer neutral is usually ______________.
13. To improve the soil conductivity nowadays ______________ is being used
14. Effective grounded system is ______________.
15. For distribution transformers % Z will be usually ______________.
16. Gaskets and SF_6 seals are made out of ______________.
17. Bus bars are used in GIS to connect ______________.
18. Breaker and a half scheme uses ______________ breakers per bay and two buses together
19. A tie breaker is used to connect ______________
20. Step voltage is ______________.

Answers

1. b	2. d	3. a	4. c
5. d	6. b	7. b	8. c
9. c	10. b		

11. Disconnecting the supply under fault conditions
12. Solidly earthed
13. Bentonite
14. The ground or neutral resistance $\leq 1/3$ of the positive sequence impedance of the system
15. 4 to 6 %
16. EPR or silicone rubber
17. to connect components that are not directly connected to each other
18. one
19. main bus to transfer or duplicate bus
20. the difference in surface potential fealt by a person bridging 1 m. distance with feet without touching ground object

Nine

Short circuits and faults are a common feature. This Chapter deals with faults and transient overvoltages in distribution systems. Fault analysis is presented via symmetrical component analysis.

Faults and Overvoltages in Distribution Systems

Introduction

Even in a best designed systems, faults or short circuits are common. The faults will occur due to (i) failure of insulation between two lines or line to ground, (ii) snapping or cut in an overhead conductor which can touch ground or other phase conductor, (iii) a conducting body such a metal piece, a tree branch accidentally falling on the conductors and bridging then, (iv) a burn-out or a short in an equipment. When an accident occurs, a large current flows and it is limited by the impedance of the line or the sources. The current flowing into the fault comes from (i) rotating machines such as generators, synchronous motors and induction machines, and (ii) capacitors and inductive devices in the system. The purpose of the fault analysis is to know how much extra or over current flows so that proper protective device can be placed to isolate the fault and also to limit the fault current by inserting extra impedance.

9.1 TYPES OF FAULTS

In a 3-phase (3-wire or 4-wire) system, the possible types of faults or short circuits are

i. Line to ground (L-G)

ii. Line to line (L-L)

iii. Two lines to ground (L-L-G) and

iv. 3-phase (to ground or ungrounded)

There are two more types (a) one conductor open and (b) two conductor open faults. These do not give rise to large currents, but over voltages only.

The relative occurrence of different faults is about 70% -L-G, 15% L-L, 10% L-L-G and less then 5% 3-phase faults. Further, the fault current in the grounded faults depends on the earth or ground impedance. Normally, fault calculations are done assuming that fault occurs at the farthest end and load current is zero and a fault impedance ranging from 10 to 50 Ω is assumed depending on the system voltage. Zero impedance condition is referred as BOLTED fault in American systems.

9.2 SYMMETRICAL COMPONENT ANALYSIS

Since fault condition becomes an unbalanced condition in 3-phase system, symmetrical component analysis in made use of. An unbalanced 3-phase system consisting of 3-phase quantities I_A, I_B and I_C can be resolved into 3-balanced systems consisting of the positive sequence, the negative sequence and zero sequence quantities as shown in Fig. 9.1 and Equation 9.1 (a to d).

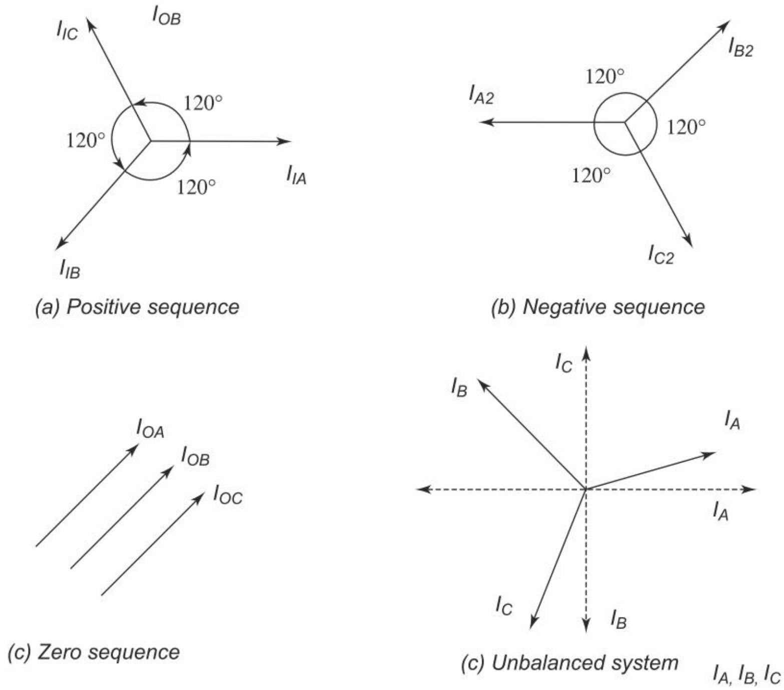


Fig. 9.1 *3-phase unbalanced system and sequence components*

The sequence operator $a = 1\ \angle 120° = -0.5 + j0.866$ which is the cube root of unity and $a^2 = \angle -120°$ $= -0.5 - j0.866$, and $a^3 = 1.0$. Also $1 + a + a^2 = 0$

The symmetrical components of any set of phasor quantities I_A, I_B and I_C, i.e., I_P, I_N and I_O are

$$I_{A0} = \frac{1}{3}[I_A + I_B + I_C] \qquad \text{...(9.1a)}$$

$$I_{AP} = \frac{1}{3}[I_A + aI_B + a^2 I_C] \qquad \text{...(9.1b)}$$

$$I_{AN} = \frac{1}{3}[I_A + a^2 I_B + aI_C] \qquad \text{...(9.1c)}$$

The phasor current I_A, I_B and I_C interns of the symmetrical components I_{AP}, I_{AN} and I_{AO} are

$$I_A =, I_{AO} + I_{AP} + I_{AN} \qquad \text{...(9.2a)}$$

$$I_B = I_{AO} + a^2 I_{AP} + aI_{AN} \quad ...(9.2b)$$

$$I_C = I_{AO} + aI_{AP} + a^2 I_{AN} \quad ...(9.2c)$$

and $$I_{AO} = I_{BO} = I_{CO} \quad ...(9.2d)$$

Note that $I_{AO} = I_{BO} = I_{CO}$ are all in phase. In fault analysis, it is assumed that the source always is a balanced three supply giving only positive sequence components.

9.2.1 Measurement of Sequence Currents in a 3-phase 3-wire system

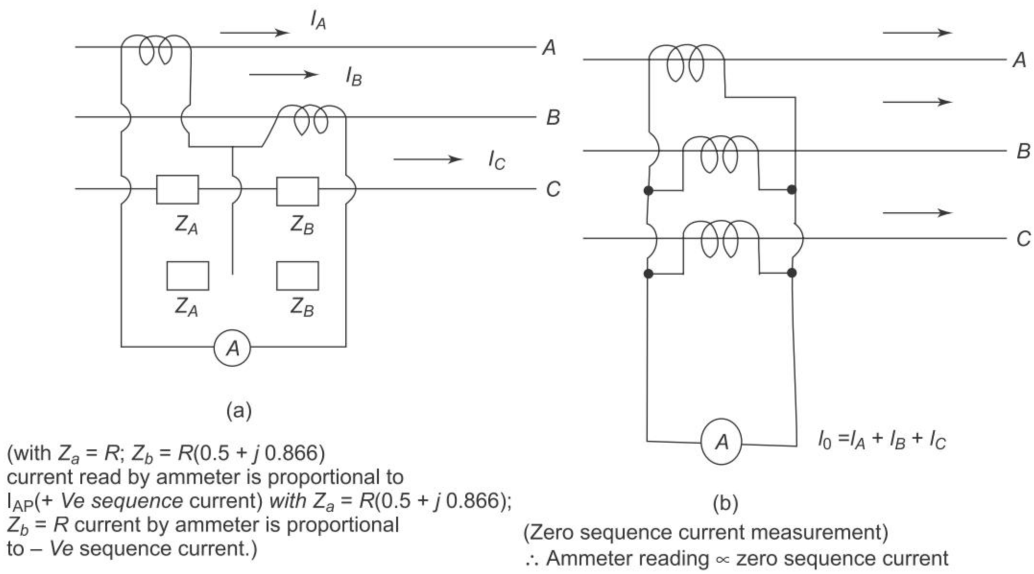


Fig. 9.2 *Sequence current measurement*

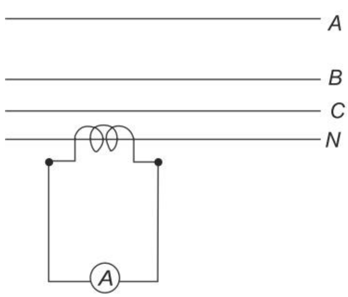


Fig. 9.2c *Measurement of zero sequence current in 4-wire system*

The symmetrical component currents in any 3-phase 3-wire system can be measured using current transformers and ammeter connected as shown in Fig. 9.2.

The sum of the 3-phase currents read by the ammeter in circuit of Fig. 9.2.b give the zero sequence current and circuit in Fig. 9.2 a is used to measure the positive and negative sequence component currents. With $Z_a = R$ and $Z_b = R(0.5 + j0.866)$, positive sequence currents are obtained and by interchanging Z_a and Z_b negative sequence currents are obtained. For a 4-wire system the neutral current (Fig. 9.2 c) gives the zero sequence current and the other circuits remain the same.

9.3 FAULT ANALYSIS FOR DISTRIBUTION SYSTEM

It is of importance to know what the maximum and minimum fault currents will be, so that the system protection can be coordinated.

Maximum fault current occurs when

(a) all generators or sources are connected and feeding power into the network

(b) the load is at its peak (maximum) and the fault impedance is zero

The minimum fault current occurs when

(a) only few generators or sources are feeding power into the network

(b) The load is minimum or zero and the fault impedance is considered (20 to 50 Ω) depending on voltage level

Fault calculations are made for each section of the distribution network as well as for the entire feeder circuits. Usually, at high voltage side for maximum fault current condition the system is taken as infinite bus, i.e., source impedance zero and only transformer impedance and line impedance are taken.

9.3.1 Line to Ground (L-G) Fault

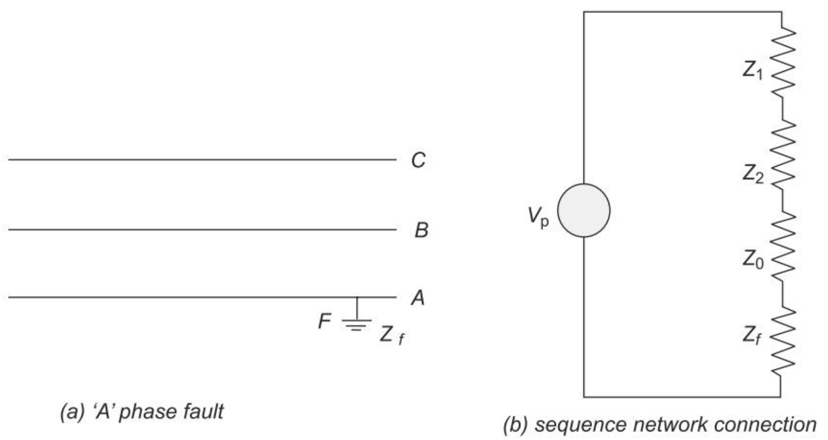


Fig. 9.3 *L-G fault and its sequence network connection*

Let the, positive, negative and zero sequence impedance of the system be Z_1 and Z_2 and Z_0 and fault impedance Z_f. Let V_p be (A phase) line to neutral voltage. The equivalent circuit for the fault conditions $V_{PA} = 0$; $I_B = I_C = 0$.

$$I_f = \text{fault current} = \frac{V_p}{Z_g} \qquad ...(9.3)$$

$$Z_g = \frac{Z_1 + Z_2 + Z_0 + Z_f}{3} \qquad ...(9.4)$$

For transformer and lines $Z_1 = Z_2$ so that

$$I_f = \frac{V_P}{\frac{1}{3}(2Z_1 + Z_0) + Z_f}$$

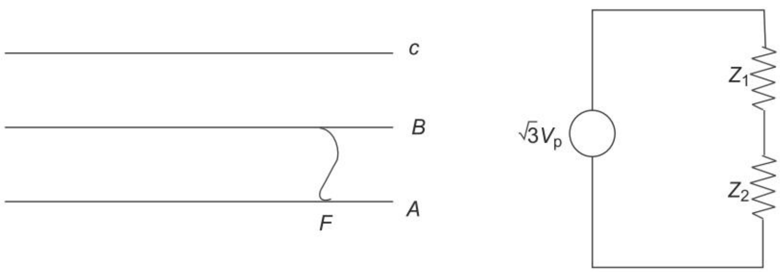
or $$I_f = \frac{3V_p}{(2Z_1 + Z_0) + 3Z_f} \qquad ...(9.5)$$

If the primary distribution network is delta and the lines are connected by delta/star transformers with solid grounding of the neutral point, the current on primary side of transformer is

$$I_f = \frac{V_{LL}}{\sqrt{3}\, V_T} \times I_f \qquad ...(9.6)$$

V_{LL} secondary side line voltage, V_T = primary distribution line voltage (line to line). In case of source, transformer and feeder line network are included. Fault impedance is modified as $2Z_{SP} + 3Z_{Tr} + 6Z_C + 3Z_f$, where Z_{sp} = source impedance, Z_{tr} transformer impedance and Z_c circuit or network impedance and Z_f fault impedance.

9.3.2 Line to Line Fault



(a) Line A to B fault

(B) Sequence network

Fig. 9.4 *L-L fault and its sequence network*

Fault condition $\quad I_C = 0;\ V_{AB} = 0$

$$I_{f\,LL} = I_{fA} = -I_{fB}$$

where I_{fLL} line to line fault current, I_{fA} and I_{fB} current is lines A and B

The applied voltage to fault is V line = $\sqrt{3}\,V_P$ and since $Z_1 = Z_2$ for lines,

$$I_{f\,LL} = \frac{\sqrt{3}\,V_P}{Z_1 + Z_2} = \frac{\sqrt{3}\,V_P}{2\,Z_1} \qquad ...(9.7)$$

If a fault impedance Z_f is included,

$$I_{f\,LL} = \frac{\sqrt{3\,V_P}}{2Z_1 + 2Z_f} \qquad ...(9.8)$$

It will be shown that this fault current will be 0.866 of the 3-phase symmetrical fault current.

9.3.3 Three-Phase Grounded / Ungrounded Symmetrical Fault

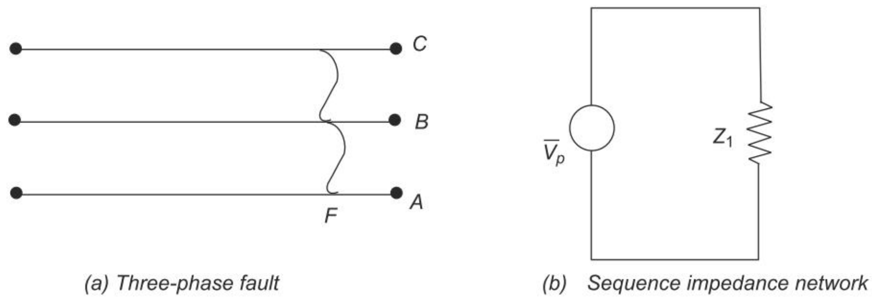


Fig. 9.5 *Three-phase fault and its network*

Fault condition $V_{PA} = V_{PB} = V_{PC} = 0$

$$I_f 3\phi = I_{fa} = I_{fb} = I_{fc} = \frac{V_P}{Z_1} \quad \text{...(9.9)}$$

If the fault impedance is included,

$$I_f 3\phi = \frac{V_P}{Z_1 + Z_f} \quad \text{...(9.10)}$$

If the fault position is such that the transformer and line impedance are also included then

$$Z_1 = Z_{1S} + Z_{1Tr} + Z_{1C} \quad \text{...(9.11)}$$

where Z_{1S} = positive sequence impedance of source

Z_{1Tr} = positive sequence impedance of transformer

Z_{1C} = positive sequence impedance of line or network

In case the fault current is needed on the primary side of transformer

$$I_{f3\phi} = \frac{V_{LL}}{V_T} \times I_{f3\phi} \quad \text{...(9.12)}$$

where V_{LL} = distribution or secondary side of transformer voltage

V_T = feeder of tranformer primary side voltage (line to line)

9.3.4 Double line to Ground Fault

Fault Condition

$I_C = 0$ phase voltage $V_{CN} = V_{P,}$ $V_{an} = V_{bn} = 0$

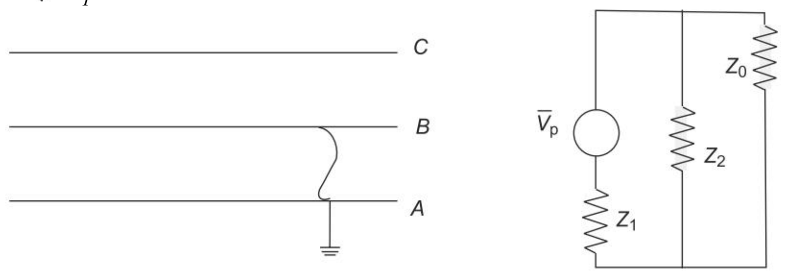
$$I_{fLLG} = I_a + I_b$$

$$I_a = \frac{Z_2(1-a) + Z_0(1-a^2)}{Z_1Z_2 + Z_2Z_0 + Z_1Z_0} V_p \quad \text{...(9.13)}$$

$$I_b = \frac{Z_2(1-a^2) - Z_0(1-a)}{Z_1Z_2 + Z_2Z_0 + Z_1Z_0} V_P \qquad \text{...(9.14)}$$

In case the fault current is needed on the primary side of the transformer,

$$I_{F\ LLG} = \frac{V_{LL}}{\sqrt{3}\,V_T} I_{f\ LLG}$$



(a) L-L-G fault

(B) Equivalent Sequence Impedance network

Fig. 9.5.1 *Double line to ground and its equivalent network*

In Table 9.1, the nature of fault and the fault currents are tabulated.

Table 9.1 Fault current formula

Type of fault	Connection	Fault current
L-G	Grounded Y	$I_f = \frac{3V_p}{2Z_{ST} + 3Z_{Tr} + 6Z_c + 3Z_f}$
L-G	Δ	0
L-L	Δ or Grounded Y	$I_{fa} = -I_{fb} = \frac{-j\sqrt{3}V_p}{2Z_1 + Z_f}$
3-ph	Δ or Grounded Y	$I_f = \frac{V_f}{Z_1 + Z_f}$

Z_{sy} = system equivalent impedance, Z_{Tr} = transformer. Z_C = circuit impedance

Z_f = Fault impedance $Z_1 = Z_{sy} = Z_{Tr} + Z_C$

9.3.5 Faults with Single-Phase 3-wire System

The two types of common faults are (i) line to ground (ii) line to line (Fig. 9.6).

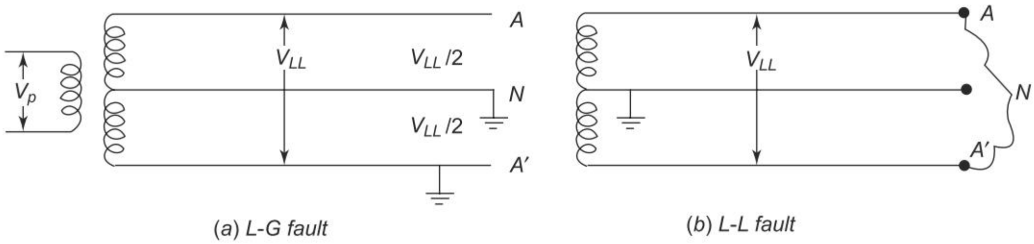


Fig. 9.6 *Faults in single-phase 3-wire system*

(i) For a line-to-ground fault,

$$I_{f\ L-G} = \frac{V_{LL}}{2Z_e} \quad \text{...(9.15)}$$

(and referred to primary side of the transformer) $I_{FL-L} = V_P/Z_e$

where $Z_e = Z_f + Z_g + Z_L + Z_T$ = total impedance in the fault circuit

Z_f = fault impedance referred to primary side

Z_g = ground impedance referred to primary side

Z_L = line impedance upto fault referred to primary side

Z_T = transformer impedance referred to primary side

(ii) For a line to line fault,

$$I_{F\ LL} = \frac{V_L}{Z} \text{(and } I_{F\ LL} \text{ referred to primary side is } I_{F\ LL} = \frac{V_P}{Z_e}) \quad \text{...(9.16)}$$

where $Z_e = Z_T + Z_L + Z_f$

Z_f = fault impedance referred to primary side and Z_T and Z_L (Transformer and line impedance referred to primary side).

It may be noted that in single phase distribution network it is better to compute the fault impedance of the network given, rather than applying formulae.

Example 9.1 *A single-phase, 3-wire distribution line 120 V – 0 – 120 V, feeds a load of 10 kVA line to line and 3 kVA on each line to ground. The transformer is 7620 V / 240 V 25 kVA with 5% impedance. The line impedance is j0.05 Ω per wire. Calculate the fault current and fault MVA for the following case:*

(i) L-L fault 1 km from transformer

(ii) L-G fault 1 km from transformer

Solution

(i) *L-L fault* Full load of transformer

$$= \frac{25 \times 10^3}{240} = 104.4\text{A}$$

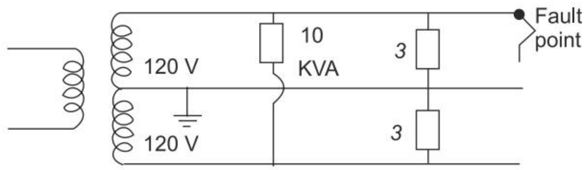


Fig. 9.7

Total load 10 + 2 × 3 = 16 kVA (taken as UPF load)

$$\text{Load current } = \frac{16 \times 10^3}{240} = 66.7\text{A}$$

$$\text{Load impedance } = \frac{240}{66.7} = 3.6\ \Omega$$

Line impedance up to fault = j × 0.05 × 2 = j0.1 Ω

Transformer impedance (taken as reactance only) 0.05%

$$= \frac{5}{100} \times \frac{240}{104 \cdot 1} = j0 \cdot 1152\ \Omega$$

$$\text{Fault current} \quad = \frac{240}{j(0 \cdot 1 + 0 \cdot 1152)} = -\, j0 \cdot 1115 \cdot 2\text{A}$$

Total current = 66.7 – j1115.2 A = 1117 A

Fault KVA = 240 × 1117 × 10^{-3} = 267 kVA

(ii) *Line to ground fault*

Total load = line load + one phase load = 13 kW

Line impedance up to fault = 2 × 0.05j = 0.1j

$$\text{Transformer impedance} \quad = \left(\frac{1}{2}\text{winding only}\right) = \frac{j0.1152}{2} = 0.0596\ \Omega$$

$$\text{fault current} \quad = \frac{240/2}{j0 \cdot 0516 + j0 \cdot 1} = \frac{120}{j \cdot 1576 \cdot} = j761 \cdot 2\text{A}$$

$$\text{Load current} \quad = \frac{73 \times 10^3}{240} = 54 \cdot 1\text{A}$$

fault current (total) = 54 – j 761.2 = 763.1 A

Fault KVA = 120 × 763.1 = 91.6 kVA

Fault currents referred to primary side of transformer

L-L fault $1117 \times \dfrac{240}{7620} = 35 \cdot 2\text{A}$

L-G fault $763 \cdot 1 \times \dfrac{240}{7620} = 24 \cdot 03\text{A}$

Fault kVA will not change.

Example 9.2 *A 11√3 KV/240-0-240 V transformer of 20 KVA capacity and 10% reactance supplies the following single-phase loads. A line to ground fault occurs on line AN. Determine the fault current referred to primary side and fault MVA. Impedance of each line is j0.1 Ω and fault occurs after the load.*

Load AN = 8 kVA UPF

Load BN = 8 kVA UPF

Fault impedance is j2 Ω

Line impedance (2-wires) = 2 × j0.1 = j0.2 Ω

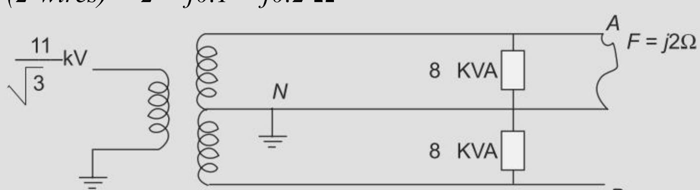


Fig. 9.8

Solution Transformer current, full load $= \dfrac{20 \times 10^3}{480} = 41 \cdot 7\text{A}$

Transformer impedance total $= \dfrac{10}{10} \times \dfrac{480}{41 \cdot 7} = j1.151\,\Omega$

each section $= j\dfrac{1 \cdot 151}{2} = j0 \cdot 5755\,\Omega$

Transformer current *AN* $= \dfrac{8 \times 10^3}{240} = 33 \cdot 3\text{A}$

Total fault impedance $= j0.5755 + j2 + j0.02 = j2.5955\,\Omega$

$\therefore$ fault current $= \dfrac{230}{j2 \cdot 5955} = -\,j86 \cdot 61\text{A}$

$\therefore$ total current $= 33.3 - j86.61 = 92.8$ A

Fault kVA $= 240 \times 92.8 \approx 22270$ or 22.27 kVA

Fault referred to primary side $= 92 \cdot 8 \times \dfrac{240 \times 10^{-3}}{11/\sqrt{3}} = 3 \cdot 507\text{A}$

(It may be seen that for the usual faults at the line ends in single-phase rural distribution networks, the fault currents are not very much and proper fuse protection will be sufficient.)

Example 9.3 *A distribution substation 5 MVA with 66/11 kV Δ Y connected transformer feeding loads as shown in Fig. 9.9. The transformer has reactance of 0.065 p.u and the source is of 600 MVA (max) and 360 MVA (min). The fault has zero impedance. The substation takes 1 MVA from 66 kV source at Bus I. Calculate fault currents at Bus I and Bus II and fault MVA for a 3-phase, L-L and L-G faults with (a) maximum generation, and (b) minimum generation*

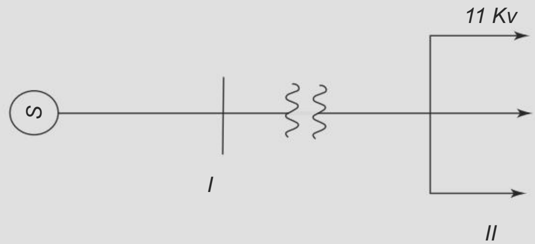


Fig. 9.9

Solution

$$Z_{\text{base}} = \frac{(V_{base})^2}{S} = \frac{(66 \times 10^3)^2}{1 \times 10^6} = 4356\ \Omega$$

For maximum generation $$Z_{sy} = \frac{(600 \times 10^3)}{600 \times 10^6} = 7 \cdot 26\Omega = \frac{(V_{base})^2}{\text{source MVA}}$$

and p.u is $= (7.26)/4356 = .00167$

$$\text{Base current} = \frac{1 \times 10^6}{\sqrt{3 \times 66 \times 10^3}} = 8 \cdot 75A = 0 \cdot 00875\text{kA}$$

For faults at Bus I

3-phase fault $$I_f = \frac{Base\ MVA}{Z_{fault}} = \frac{1 \cdot 0}{0 \cdot 00167} \approx 600 \text{ p.u}$$

(i.e.) $600 \times 8.75 = 5250$ A or $600 \times 0.00875 = 5.25$ kA

fault MVA $= \sqrt{3}\ \text{Vbase}\ I_f = \sqrt{3} \times 66 \times 5.25 = 600$ MVA

(*Note:* This is limited to the source of generation)

L-L fault

$$I_f = \frac{\sqrt{3}}{2} I_f \cdot 3_{ph} = \frac{\sqrt{3}}{2} \times 5 \cdot 525 = 4 \cdot 546\text{kA}$$

fault MVA = $V_L I_f$ = 66 × 4.546 = 300 MVA (one half of 3-phase fault)

L-G fault

$$I_f = \frac{3 \times 1 \cdot 0}{2(0 \cdot 00167) + 0} = 882 \cdot 3\text{pu}$$

$$\text{fault MVA} = \frac{66}{\sqrt{3}} \times 7 \cdot 875 = 300\text{MVA}$$

(Same as L-L fault)

Fault at Bus II

$$\text{Base MVA} = 1.0 \text{ Base kV} = 11.00$$

Transformer impedance on 5 MVA base is Z_T = j0.065 pu.

$$\text{on 1 MVA base} = \left(\frac{1\text{MVA}}{5\text{MVA}}\right) \times j0 \cdot 065 = j0 \cdot 013\text{pu}$$

$$Z_{\text{base}} = \frac{(11 \times 10^3)^2}{1 \times 10^6} = \frac{(V_{base})^2}{S_{base}} = 121\,\Omega$$

$$I_{\text{base}} = \frac{S_{base}}{\sqrt{3}\, V_{vase} \times 10^3} = \frac{1 \times 10^6}{\sqrt{3} \times 11 \times 10^3} = 47 \cdot 71\text{A}$$

3-phase fault

$$I_f = \frac{1 \cdot 0}{j0 \cdot 00167 + j0 \cdot 0013} = \frac{(base\ MVA)}{Z_{sy} + Z_{Tr} + 0} = 68 \cdot 12\text{p} \cdot \text{u}$$

$$= 68.18 \times 47.71 = 3253 \text{ A} \quad \text{or} \quad 3.253 \text{ kA}$$

$$\text{fault MVA} = 68.18 \times 1 \text{ MVA} = 68.18 \text{ MVA}$$

L-L fault

$$\text{Fault current} = \frac{\sqrt{3}}{2} \times I_f 3_{ph} = 59\, p.u = 2 \cdot 816 \text{ kA}$$

$$\text{Fault MVA} = (11.00) \times 2.816 = 31 \text{ MVA}$$

L-G fault

$$I_f = \frac{3 \times V_{base}}{2Z_{sy} + 3 \times Z_{Tr} + 0}$$

$$= \frac{3 \times 1.0}{2 \times j0 \cdot 00167 + 3 \times j0 \cdot 013} = 70 \cdot 86\text{p} \cdot \text{u}$$

(i.e) 70.86 × 47.71 × 10^{-3} kA = 3.381 kA

$$\text{fault MVA} = \frac{11}{\sqrt{3}} \times 3\cdot381 = 21\cdot5\text{MVA}$$

when the source is minimum i.e., 360 MVA, $Z_{Sts} = j0.0028$ pu

The fault current will be as follows proceeding with calculations as above:

Table 9.2 The fault current with minimum generation 360 MVA

S.No.	Type of fault	Bus I		Bus II	
		Fault ct (kA)	MVA	Fault ct (kA)	MVA
1	3-phase	3.150	360	3.019	63.3
2	L-L	2.727	180	2,615	28.77
3	L-G	4.723	180	3.018	19.16

(*Note:* The fault currents will be of the same order irrespective of the type of fault.)

Example 9.4 *A 33-kV source with infinite capacity feeds a distribution system shown in Fig. 9.10. Determine the fault current for a 3-phase fault at*

(i) Secondary side of the transformer 7.5 MVA
(ii) End of the 11-kV line
(iii) Secondary side of 100 kVA transformer

Fig. 9.10

The impedances are

7.5 MVA transformer: j0.07 pu

100 KVA transformer : j0.05 pu

11-kV line : 0.08 + j0.18 Ω

Solution Transformer (7.5 MVA) impedance referred to 11-kV side is

1. $$Z_T = \frac{(11)^2}{7\cdot5} \times j0\cdot07 = j1.13\,\Omega$$

fault current for 3-phase fault on 11-kV side $= \dfrac{V_{LL}}{\sqrt{3}} \times \dfrac{1}{Z_e}$

$$= \frac{11KV}{\sqrt{3} \times j1\cdot13} = 5\cdot62\text{kA}$$

2. Impedance of 11-kV line is $0.08 + j0.18\ \Omega$

$\therefore$ total impedance up to the fault $= 0.08 + j0.18 + j1.13$

$$Z_{Tr} + Z_{line} = 0.08 + j1.31 \approx j1.31\ \Omega$$

Fault current at the end of the line is $= \dfrac{11KV}{\sqrt{3} \times j1.31} = 4 \cdot 84\text{kA}$

3. Z_T of 100 kVA transformer referred to primary side

$$Z_T = \frac{(11,000)^2}{100 \times 10^3} \times j0 \cdot 05 = j60 \cdot 05$$

Total impedance referred to 11-kV side $= j1.31 + j60.05 = j61.36\ \Omega$

$\therefore$ fault current referred to 11-kV side $= \dfrac{11}{\sqrt{3}} \times \dfrac{1}{j61 \cdot 36} = 103.5$ A

Fault current referred to 400 V side $= \dfrac{11,000}{400} \times 103 \cdot 5 = 2846A = 2 \cdot 846\text{kA}$

Example 9.5 *Determine the sequence impedance of the distribution network and the fault impedances for (i) 3-phase fault (ii) L-L fault (iii) L-G fault at the fault positions indicated (1 and 2) in Fig. 9.11.*

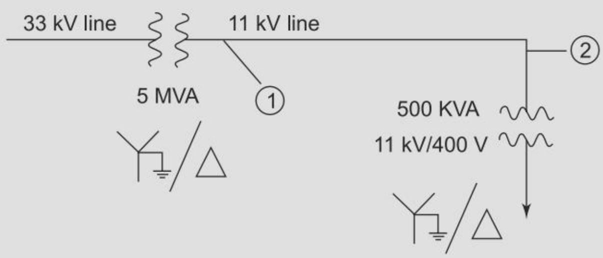


Fig. 9.11

33-kV line 5 MVA base	*5 MVA transformer*
$Z_1 = Z_2 = j6\%$	$Z_1 = Z_2 = j8\%$
$Z_0 = j4\%$	$Z_0 = j5\%$
11-kV line 1 MVA base	*500 KVA transformer*
$Z_1 = Z_2 = j5\%$	$Z_1 = Z_2 = 4\%$
$Z_0 = j8\%$	$Z_0 = 10\%$

Solution

At position 1 Only 33-kV line and 5 MVA transformer are included up to fault position

For 3-phase fault

Taking base MVA = 5

Base kV = 33

Total $Z_1 = j6\% + j8\% = j14\% = Z_2$

$Z_0 = j4\% + j5\% = j9\%$

Base impedance is $\dfrac{(V_{base})^2 (kV)^2}{S(MVA)} = \dfrac{(33)^2}{5} = 217 \cdot 8\ \Omega$

$\therefore$ total $Z_1 = Z_2$ in Ω is $j14\% = \dfrac{j9}{100} \times 217 \cdot 8 = j30 \cdot 5\ \Omega$

Z_0 in Ω = 9% is $\dfrac{j9}{100} \times 217 \cdot 8 = j19 \cdot 6\ \Omega$

$\therefore$ for 3-phase fault only Z_1 is included $= j30.5\ \Omega$

L-L fault

Fault impedance $= 2Z_1 + Z_f = 2Z_1 = 2 \times j14\% = j28\%$ ($\because Z_1 = Z_2$)

L-G fault

Since L-V side of transformer is Δ connected Z_0 is infinite. Hence, fault impedance is infinite i.e., L-G fault on 11-kV side does not reflect on primary side.

Fault at position: 2

The 11-kV line impedance is involved. The base is 1 MVA and 11-kV. Hence, converting it to 33-kV base and 5 MVA.

$$Z_{for\ \ new} = \left(\frac{V_{base}}{V_{base\ \ new}}\right)^2 \times \left(\frac{S_{base\ \ new}}{S_{base}}\right) \times Z = \left(\frac{33}{11}\right)^2 \times \left(\frac{5}{1}\right) \times Z = 45Z$$

for line $\% Z_1 = Z_2 = 45 \times j5\% = j225\%$

$Z_0 = 45 \times j8\% = j360\%$

Ohmic value of $= Z_1 = Z_2 = \dfrac{j225}{100} \times 217 \cdot 8 = j490\ \Omega$

$Z_0 = 3.6 \times 217.8 = j784\ \Omega$

$\therefore$ total fault impedance for 3-phase fault

Z_1 only included $= j490 + j30.5 = j520.5\ \Omega$

for L-L fault $2Z_1 + Z_f = 2 \times j520.5 = j1021\ \Omega$

For L-G fault only Z_0 of line is included.

hence fault impedance is $(Z_1 + Z_2 + Z_0)/3 = j1021 + j784 = j1805\ \Omega$ (on 33-kV, 5 MVA base)

9.4 OVERVOLTAGES IN DISTRIBUTION SYSTEMS

9.4.1 Lightning Overvoltage

Except for outdoor overhead lines and substations other distribution network in not exposed to direct lightning. In case a lightning strikes on a overhead distribution line, the surge magnitude is limited by the protective level of the lightning arresters placed at the substations or at line ends. The overvoltage due to lightning will be a steep front wave that can travel in both directions of the lines. As the surge travels, its magnitude is reduced or attenuated due to line losses and corona. Properly rated surge arresters will keep the surge voltage magnitude below the Basic Impulse Level of the system, i.e., the impulse voltage that should be with stood by the system insulation. For 33-kV it is about 140 kV peak (Impulse) and 70 kV rms for 50 Hz or power frequency. For 11-kV system it is about 45 kV impulse and 20 kV power frequency. Normally lightning does not directly strike the distribution lines but over voltage may come through the transformers or due to indirect lightning strokes. The current flowing in the lines due to lightning can be quite high and is limited by the surge impedance of the lines or cables which is equal to $\sqrt{L/C}$, neglecting the resistance. The lightning currents can be in the range 1000 A to 2,500 A in distribution lines. The lightning range over voltage may be of the order of 500 KV on 33-kV lines. The magnitude does not depend on the line parameters or configuration, but depends only on height of the line above the ground, the thunder storm activity and isokeruenic level in the area and vicinity of the line. Direct strokes are reduced or will not occur if the line is shielded by ground wires. But induced lightning voltages and transferred surges through the transformers connected to transmission lines can induce voltages. The duration of lightning voltages will be few microseconds. The rise time of the voltage will be or the order of 0.5 to 5 μ second. In India most of the 33-kV and 11-kV lines are unshielded and hence are subjected to lightning, mainly in rural areas, country side and forests.

The lightning voltage travelling into the substation causes over voltage on the connected apparatus like transformers, switch gear and metering equipment (PTs, CTs etc.). But all the electric apparatus insulation is designed to withstand voltages above BIL and sufficient margin for over voltages is allowed. Usually the insulation failure in apparatus is not only due to excess voltage but because of aggregate sum of total duration of such voltages. No device is available now which integrates correctly the cumulative effect. But the spark gaps and surge arresters provided, usually are sufficient to give protection.

9.4.2 Overvoltage Due to Switching Operations

Distribution systems have lines, transformers, inductive loads such as motors and capacitors. Hence the circuit is an R-L-C circuit. When ever a switching operation takes place such as closing or opening of a circuit breaker on load, a transient voltage appears. These switching voltages can be 2.0 to 4.0 times the peak system voltage. The different conditions that give rise to these transient voltages are

i. Sudden switching off of the loads
ii. De-energizing long cables, capacitor bank, etc.
iii. Energizing or re-closing of long lines and reactive loads
iv. Fault clearance
v. Ferro-resonance condition

The actual magnitude of switching transients is less than that of lightning over voltages but the duration is longer and hence contains more energy. These voltages have very different wave shapes and the total duration can be 1 ms to 10 ms are more. The rise time may be 0.1 ms to 1 ms. Very short duration over voltages occur with

i. Single pole closing of circuit breakers
ii. Interruption of fault current in L-G and L-L faults, when the faults are cleared
iii. Sparking of surge diverters at line ends when they limit the lightning over voltages
iv. Disconnecting the series capacitor compensated lines on load

In most cases the actual magnitude of the switching over voltage will be far less than that of lightning voltages and the surge arresters or spark gaps provided for protection will be sufficient. Further the apparatus designed for lightning over voltages, can withstand switching voltages.

With solid state drives and increased use of power electronic devices like controlled rectifiers, inverters etc., when they are in non-conducting mode give rise to local transient voltages given by $L\frac{di}{dt}$ where 'L' is the circuit inductance and $\frac{di}{dt}$ is rate at which current is switched off. This gives rise to very sharp over voltage pulses of 1.5 times the peak operating or system voltage. Addition of capacitors in the network mostly suppresses these transients.

To conclude both short circuits (faults) and switching operations present abnormal conditions in distribution networks. During faults, the current will be very large and can destroy or burn away the conductors in lines or power equipment connected to the lines. Over voltage will damage the insulation of the apparatus or equipment. Hence proper protection and protection schemes are needed.

Summary

In this chapter, different types of faults that occur in ac distribution systems(viz) Three-phase, line to ground, line to line, 3-phase symmetric and line to line to ground faults are discussed and analysed. Faults on single phase systems are also dealt with. Introduction to overvoltages that can occur in distribution systems are dealt with.

Keywords

Faults
Symmetrical components
LG, LL, LLG faults
Overvoltages
Lightning
Faults in single-phase systems

Review Questions

1. What are the different types of faults that can occur on distribution networks? Explain them with line diagrams.
2. Obtain the sequence impedance equivalent circuit for L-L and L-G faults. Compare the magnitude of fault current in both cases.

3. How is the equivalent impedance computed for a L-L and L-G fault occurring on distribution line with source impedance (Z_s), distribution line, transformer and a fault impedance of (Z_f)
4. What are the common faults in a single-phase 2-wire and 3-wire system ? Explain how fault current is computed with proper single line diagrams.
5. What are the different over voltages that can be impressed on a distribution network? Discuss their nature and origin

Problems

6. The per unit positive, negative and zero sequence impedances of a distribution network are 0.08 and 0.05 respectively. Determine the fault current for (i) L-L (ii) L-G faults.
7. The single line diagram of a distribution network is given in Fig. 9.12. Determine the sequence impedances up to fault point (i) fault at A, and (ii) fault at B.

   Source (132 kV) impedance on 10 MVA base (Z_1, Z_2, Z_0) 0.12j, 0.10j and 0.05j pu 10 MVA transformer on its own base and voltage 0.08j, 0.08j, 0.06j pu, 11-kV line 1 MVA base 0.03j, 0.03j, 0.05j, 1 MVA transformer on its own base 0.08j, 0.08j, 0.05j

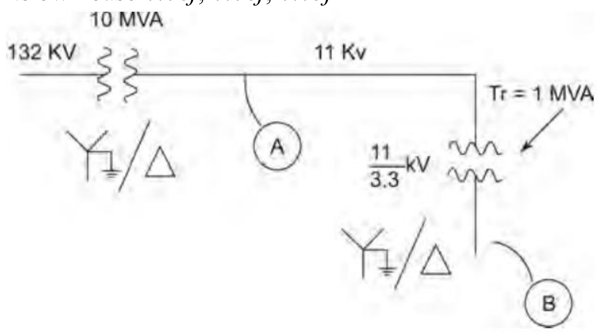


Fig. 9.12

8. Determine the fault current for a -3phase symmetrical fault and L-G fault for the distribution system shown in Fig. 9.13. The sequence impedance are (i) 11-kV line $Z_1 = Z_2 = 0.8 + j3.5\ \Omega$, $Z_0 = 0.5 + j3.0\ \Omega$ (ii) 100 kVA transformer on its own base $Z_1 = Z_2 = j0.05$, $Z_0 = j0.08$.

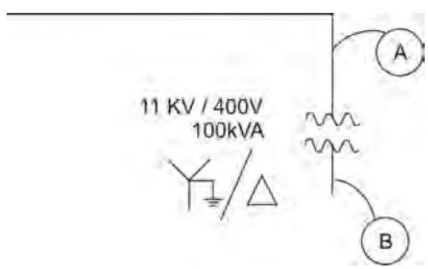


Fig. 9.13

9. What will be fault current for a line fault in single-phase 3-wire system shown in Fig. 9.14. Load (1) 10 kVA 0.8 p.f lag, Load (2) 8 kVA 0.09 p.f lag. Transformer impedance referred to 240 V side $0.1 + j0.4\ \Omega$, line impedance $0.1 + j0.05\ \Omega$ per conductor.

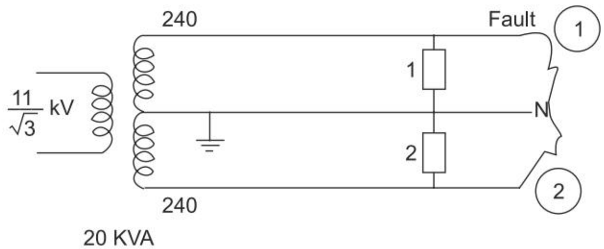


Fig. 9.14

10. In the Q. 9 if the fault occurs between line 1 and ground or neutral, what will be the fault current and fault kVA.

Multiple Choice Questions

1. Most severe fault in a power system is
   (a) L-G (b) L-L
   (c) L-L-G (d) 3-phase symmetrical
2. The fault current in L-L fault is __________ % 3-phase fault
   (a) 50% (b) 86.6% (c) 75% (d) 100%
3. For a L-G fault the sequence impedance are connected in
   (a) series (b) parallel
   (c) negative and zero sequence impedance are in parallel and positive sequence impedance in series with that combination
   (d) no simple connection
4. The transformation of fault current I_f from secondary side to primary side with V_1 primary side voltage and V_2 secondary side voltage is, I_1 =
   (a) $\frac{V_1}{V_2} I_f$ (b) $\frac{V_2}{V} I_f$ (c) $\left(\frac{V_1}{V_2}\right)^2 I_f$ (d) $\left(\frac{V_2}{V_1}\right)^2 I_f$
5. The common types of fault on single-phase distribution system (3-wire is)
   (a) line to ground (b) line to line
   (c) line to line to ground (d) none of the above
6. For static equipment like transformers which of the sequence impedance are equal?
   (a) $Z_1 = Z_2$ (b) $Z_1 = Z_0$ (c) $Z_2 = Z_0$ (d) $Z_1 = Z_2 = Z_0$
7. The magnitude of lightning voltages does not depend on
   (a) line height above ground (b) line parameters
   (c) shielding (d) all the above three
8. Switching overvoltages occur when
   (a) line is closed on load (b) ground or neutral gets disconnected
   (c) a fault occurs (d) a fault is cleared
9. A transformer is connected Δ / Y. If a L-G fault occurs on secondary side, the fault current on primary side is __________

(a) zero (b) maximum
(c) limited by primary impedance (d) cannot be found

10. The percentage probability of L-L-G fault is about ________ of the total faults.
(a) 90% (b) 50%
(c) 30% (d) 10%

Fill in the Blanks

11. A 400-V, 1000-kVA, 3-phase, *Y* connected generator has X_1 = 35%, X_2 = 25%, X_0 = 15% and feeds a line of $X_1 = X_2$ = 5% and X_0 = 10%. For 3-phase fault at line end, fault current is __________ % of full load current.
12. In Q.21, for L-G fault, fault current is ______________.%
13. Zero sequence current is measured ______________.
14. The magnitude of switching over voltage in distribution system will be of the order of ______________ p.u
15. % *Z* for new base MVA and KV is given by Z_{new} = ______________.
16. Overvoltage on an 11-kV distributor due to lightning will be about ______________.
17. 33-kV and 66 kV distribution feeders are protected against lightning using ______________
18. The common faults on a single-phase 3-wire system are ______________
19. A 33-kV / 11-kV transformer has a % impedance of 9 on LV side. Its % impedance on HV side is ______________.

    Transformer is *Y*/Δ connected and rated 5 MVA.
20. In Q.19, the impedance value in ohms is ______________

Answers

1. d	2. b	3. a	4. b
5. a	6. a	7. b	8. d
9. a	10. d	11. 250%	12. 316%

13. By connecting a CT and ammer in the neutral or connecting 3 CTs in the lines and measuring the sum of the three CT currents
14. 2 to 4 p.u
15. Z_{new} = (New base MVA / Previous MVA) × (Previous V / New base V) × Z
16. 45 kV
17. Ground wire
18. L-G and L-L faults
19. 9 20. 12.34.

Ten

Distribution system protection and protective devices are introduced. Fuses and their characteristics, fault sensors, i.e., relays and protective devices, circuit breakers, and their applications are also presented. Overvoltage protective devices, viz., spark gaps, surge (lightning) arresters, their characteristics and applications are discussed in this Chapter.

Protection

Introduction

Power system is subjected to the faults and transients. These will result in over currents and over voltages that can cause damage to conductors as well as insulation. The result is equipment loss and system failure. This chapter deals with the principles of protection of equipment and system in total by way of protective devices and their application. The engineering techniques of protective devices their co-ordination, maintenance and testing procedure are also outlined briefly.

In distribution systems, the main devices for over current or fault current protection are fuses and circuit breakers. In addition to the over current devices, for feeder lines graded protection is used known as "distance protection", which is time graded. For operation of the circuit breakers, the fault sensing is required. It is also necessary to distinguish between a very temporary fault or short circuit, like touching of a conductor with another due to wind etc. and the permanent fault. In case of a temporary fault automatic re-closing of the power circuit is desirable. These features are accompanied by "Relays" which sense and actuate the operation.

A presentation is made in this chapter regarding the protective devices i.e., fuses, circuit breakers, over voltage protective devices and relays. This discussion is limited to the distribution system only.

10.1 BASIC REQUIREMENTS

The basic requirements of the protective system is relative to the cost and flexibility to the extent the system is safe guarded against the possible damage and burning off. It is also required to give least or no disturbance to the normal operation and remove the fault and restore the system to normalcy at the minimum possible time. Protection is provided to (a) minimize or eleminate high current or overloading, (b) give safely against shocks, fire and other damages, (c) minimize interruption of power supply, and (d) to discriminate between overloading, short circuit and very temporary fault. Further the device must carry their normal or rated current continuously.

10.2 OVERCURRENT PROTECTION: FUSES

A fuse is an overcurrent protective device that melts directly and is destroyed when a current is excess of its capacity passes through it because of the heat generated. This is usually a metal conductor made of alloy that melts at low temperature. Fuses take a few milliseconds to seconds to melt depending on the thermal characteristics. The fuse clears the fault but makes that part of the circuit or device or completely disconnected from the supply source. Fuses are available in a wide range of ratings of voltage, current (interrupting rating, current limiting and non-current limiting) for indoor and outdoor applications.

10.2.1 Fuse Classification

Fuses are classified as follows:

(i) ***Low and Medium Voltage Fuses of Low Rating ≈ (100 A or less)*** These are metal or alloy wires and usually melt in 300 seconds or less at an r.m.s current of about 200% of its continuous rating. For higher ratings the time taken may be up to 600 seconds

(ii) ***Current Limiting Fuses or Power Fuses (or Power Cutouts)*** These are designed so that the melting of fuse element introduces high arc resistance in advance of the peak current of first half cycle of fault current. This restricts the fault current to a lower value than that would occur normally. These are mainly meant for use with motor starter contactors to limit the currents and are mainly used in circuits above 1000 V. The typical applications are with respect to potential transformers, small loads on high capacity circuits, etc. Typical time – current characteristic of a 125 A fuse is given in Fig. 10.1.

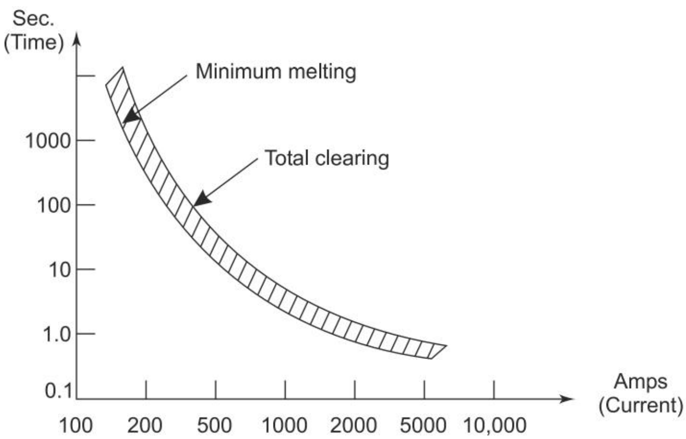


Fig. 10.1 *125 A power fuse characteristic*

(iii) ***Expulsion Fuses (HRC Fuses)*** These fuses are used in distribution systems for protection of power transformers, lines etc. To interrupt a fault current an arc quenching tube with a deionizing fibre lining and fusible element are employed. Arc interruption is done by release of pressurised gas within the tube which blows out the arc from open end of the tube.

The fuses are mounted in fuse holders in an insulating enclosure. The medium used for expulsion may be boric acid, silica sand or such other material. The fault current ratings can be typically 20 to 50 kA and voltage ratings up to 15 kV are available. The application for such type fuses is for line fault and over load protection on feeder circuits, capacitor bank fault protection and transformer primary side protection.

(iv) ***Cartridge Fuses*** These are one variety of fuses used in low voltage (<600 V) circuits which consists of a fusing element enclosed in a cartridge or tube containing arc quenching medium.

The fuses can be renewable or non-renewable. Renewable fuses can be dismantled and the fusible element is replaced.

Ratings and Selection of Power Fuses/cutouts

The rating and selection of fuse cutouts depends on, type of system, grounding scheme adopted, system voltage, maximum fault current expected and X/R ratio of the system, and maximum clearing thermal energy, X/R ratio being important for the expected transient over voltage after the fuse melts and interrupts and fault current. These features are in addition to the features mentioned in Section 10.2. The main operation characteristic of a fuse is the

$$\frac{K_1}{K_2} = \frac{V^2}{I_F^2} = K \cdot$$

which will be typical 8 to 20 or more.

The other important characteristic for fuses is I^2t. The speed of response in given by I^2t value, i.e., the product square of the current multiplied by the total clearing time, which is an index of thermal energy. This does not depend on the voltage rating of the fuse. The time delay for the fuse operation depends on I^2t and classification of fuses is based on I^2t only.

A fuse must be selected for minimum opening time at a specified over load value such as 125% or 200% of rating and for time delay co-ordination. It is also essential to have a co-ordination with other protective devices such as circuit breakers and other fuses.

10.2.2 Automatic Line Sectionalizers and Circuit Re-closers

Line Sectionalizers Automatic sectionalizers are overcurrent protective devices and used as backup of circuit breakers. Usually they are installed in a part or section of a feeder to isolate the circuit when a permanent fault occurs. It counts the number or interruptions and re-closers made (2 or 3) and after a preset time, opens the circuit. The operation of the sectionalizer is that

(i) If the fault is cleared while the re-closing circuit breaker is open, the sectionalizer will reset to normal position after the circuit is closed

(ii) If the fault persists when the circuit is closed the sectionalizer counts time for the next opening of the re-closer device

(iii) If the re-closing device is to go to locking position after a 3rd or 4th (as the case may be) the sectionalizer will be set to trip during the opening time of the CB

This device is mainly meant as a co-ordination device for primary circuit breakers.

Automatic Re-closers This is a device which automatically trips on over loads or faults and recloses the circuit after a preset time. The number of trips and re-closures are fixed, usually 2 or 3. These are mainly meant to clear temporary faults and re-close the circuit. It isolates a permanent fault. These can be operated either manually or set for automatic operation. The number of trips and re-closures can be set and the time delay between the operations can be varied. The current ranges can be from 5 to 1000 A or more. The minimum pick up time can be varied and the time of operation can be as fast as 0.5 Hz. after the fault initiation. These are usually used in circuits with X/R ratio less than 5. Normally these are meant for light loaded or unimportant loads such as a rural feeder branching from an important main feeder or an urban feeder.

The above two devices, i.e., sectionalizers and re-closers are not generally used in India instead, a CB with ratio re-closer incorporated in it is used.

10.3 CIRCUIT BREAKERS

A circuit breaker is a device designed to

(i) open and close a circuit on LOAD either manually or automatically
(ii) open the circuit on a predetermined overload current without a damage to it self and other equipment in the circuit
(iii) interrupt and OPEN the circuit on short circuits or faults automatically upto the maximum short circuit rating within the duty time specified (2, 3 or more cycles time), as in (ii) above
(iv) automatically open or close with a time delay for preset number of times as in the case of a automatic re-closure

Circuit breakers are rated for low voltages (< 1000 V), medium voltages (over 1000 V but less than 7,200 V) and high voltages (≥ 7,200 V)

The circuit breakers used in the distribution systems are

(i) Air break CB,
(ii) Oil-circuit breakers (OCB),
(iii) Minimum oil CB, and
(iv) Vacuum CB.

The devices are available up to fault current ratings of 200 kA and continuous current rating of 3000 A.

In addition to the circuit breakers, for motor and other load applications, 'Load Break Switches' are available which can be closed or opened on loads.

When a large current is to be interrupted, the contacts of the switch or breaker separate. As the contacts move farther an arc is formed between them and an arc quenching or extinction medium is provided. The arc extinction is done by air, in air CBS, oil in bulk oil or minimum oil CBS and vacuum in vacuum CBS, (no medium). Special control means such as magnetic blow out or air blast or gas such as SF_6 can be employed. Circuit breakers are controlled by protective relays which sense the over load or fault and actuate the CBS.

Circuit breakers are rated on the basis of

(i) continuous normal operating current
(ii) rms symmetrical fault current
(iii) asymmetrical fault current
(iv) duty cycle i.e., number of breaks and makes when clearing a temporary fault
(v) the operating time (about 5 cycles time for distribution CBS)

10.4 PROTECTIVE RELAYS AND RELAYING

Protective relays are devices which sense an abnormal situation in the circuit such as (i) overcurrent, (ii) under or overvoltage, (iii) reverse current or power flow, and (iv) under or overfrequency, etc.

The relays or protective devices provide the intelligence and initiate action that enable the switching devices (CBS) to respond to the system condition and open the circuit. Relays can be electromechanical or solid state, the later being flexible, precise and quick acting.

The usual protection schemes in distribution systems are (i) overcurrent, (ii) distance protection for long feeders, and (iii) directional protection.

10.4.1 Overcurrent Protection and Overcurrent Relays

The common type of relay for large currents and short circuits is over current relay. Bimetallic elements can be used for thermal over loads. But they are slow and sluggish and are limited for motor protection in starters etc. The electromagnetic relay is the common one using either solenoid and plunger mechanism or attracted armature. Induction type over current relays use moving disc on a shaft with control spring for restraint. Pick up or operating current is adjustable when the current exceeds the given setting, the relay contacts close and initiate the CB tripping operation. The relays operate from the secondary current of the CTs mounted on the feeder lines or other apparatus to be protected.

The relays should not operate for very transient currents like motor starting or a brief over load. Hence they are given a time delay for operation. The overcurrent relays are classified as

(a) *Definite Minimum-time Relay* Having an operation time practically independent of magnitude of overcurrent.

(b) *Inverse-Time Relay* Time of operation is faster as the current increases called inverse or extremely or very inverse to fit the particular requirement. Typical time current characteristic of over current relays are shown in Fig. 10.2 A and 10.2 B.

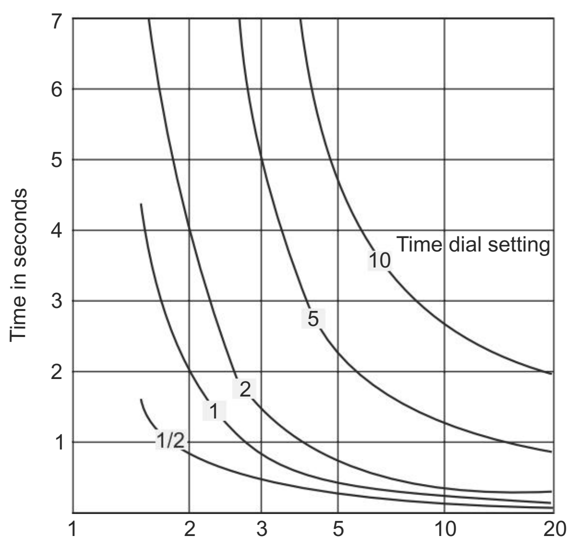


Fig. 10.2 (a) *Typical inverse time over current relay*

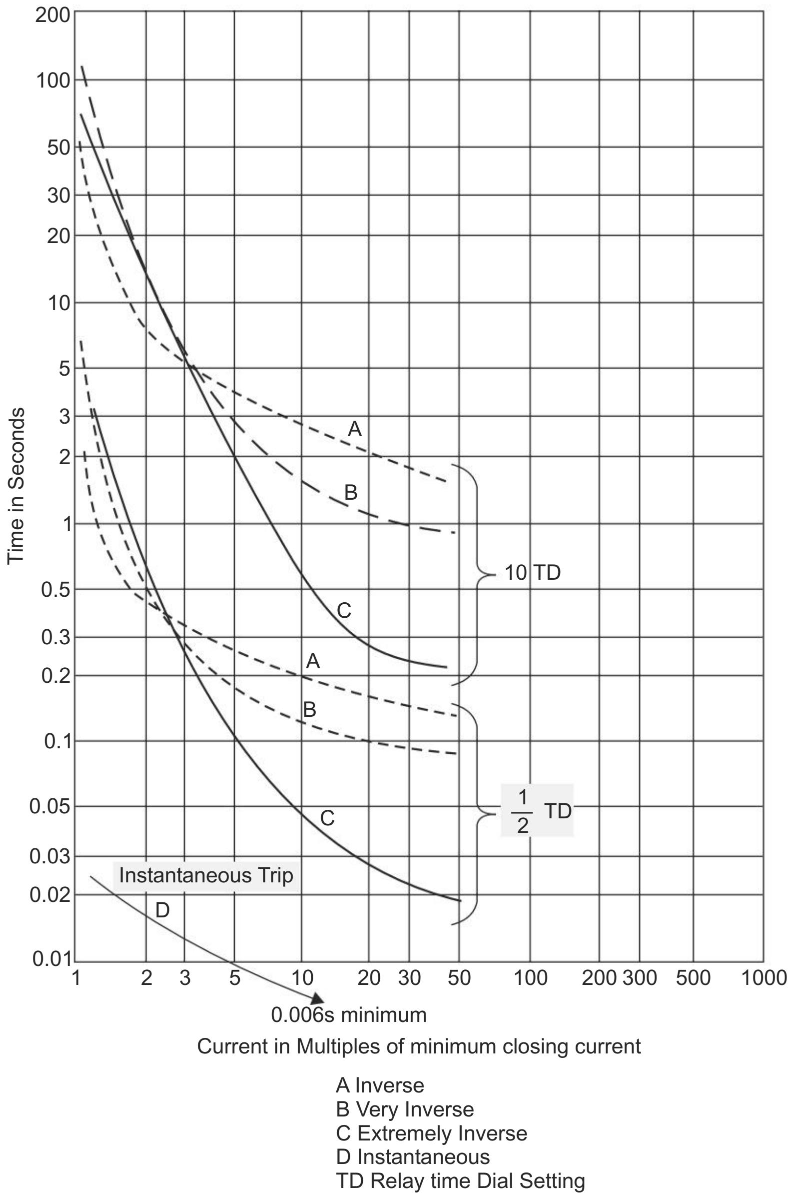


Fig. 10.2 (b) *Typical relay time-current characteristics for different TD*

From the characteristics it can be seen that the over current relay can be adjusted for operating time and for different time delays.

Sometimes overcurrent relays are accompanied by voltage restraint coils. When a over loading occurs voltage does not dip much, while for a fault, voltage dip will be high. This feature is incorporated in some relays so that they operate for faults and not on overloads of little higher value.

Directional overcurrent relays This is usually an overcurrent relay with a phase angle sensing. The phase angle between voltage and current is sensed and if this exceeds 90º (called the directional unit) the relay operates. The reference current or voltages is called 'polarization'. They operate only for the current flow and will be insensitive to the current flow in opposite direction. These are mainly used with generators to prevent motoring operation.

Solid state and electronic relays Since electromechanical relays are slow, bulky and require constant maintenance, they are nowadays replaced by electronic or solid state relays. They have the advantage of light weight, flexible and have adjustable characteristics, consume much less power. The reliability of the solid state relays, which was a constraint earlier has been much improved. Out of a variety of over current and impedance relays only few are discussed here.

Overcurrent relay A static overcurrent relay can be instantaneous, inverse time or directional relay. The input current is sensed through a CT, rectified and fed to a level detector. The output of the level detector which acts as a comparator, is amplified and fed to static switch that closes the trip circuit. The block diagram is shown in Fig. 10.3a.

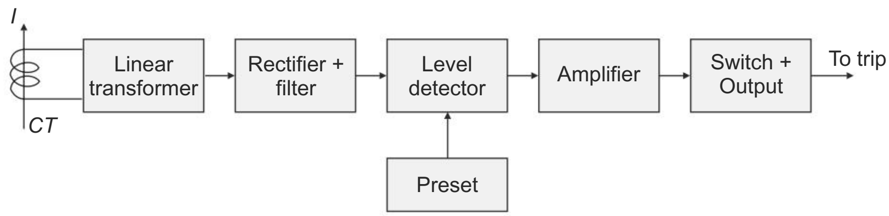


Fig. 10.3 a *Over current relay*

The linear transformer is a transformer with air gap in the core to give a linear output over a larger current range. The level detector is the comparator which compares the current signal with that of the preset value. The switch and output unit can be a thyristor or transistor switch which closes the trip coil circuit.

Definite time overcurrent relay For this type of relay, the operating time is constant irrespective of the magnitude of fault current. A simplified block diagram is given in Fig. 10.3 b.

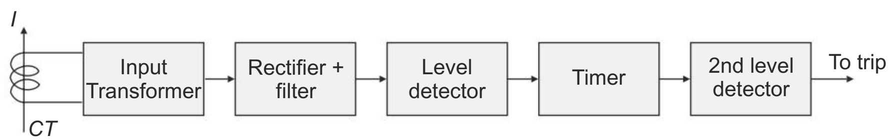


Fig. 10.3b *Define time over current relay*

The circuit and block arrangement are same as that of over current relay up to level detector. The output of level detector goes to a timer (an R-C charging circuit) or any other form which feeds a second level detector. When the voltage of the capacitor goes above the preset value of the 2nd level detector, it gives an output which closes the switch and makes the trip circuit 'ON'. The settings of level detectors can be adjusted to get the required time delay.

Directional overcurrent relay Directional overcurrent relays sense the direction of current or power flow i.e., the phase angle between I and V. When the phase angle exceeds a preset value (>90°) and the current is above the preset current, it closes trip circuit. The schematic block diagram is given in Fig. 10.3c.

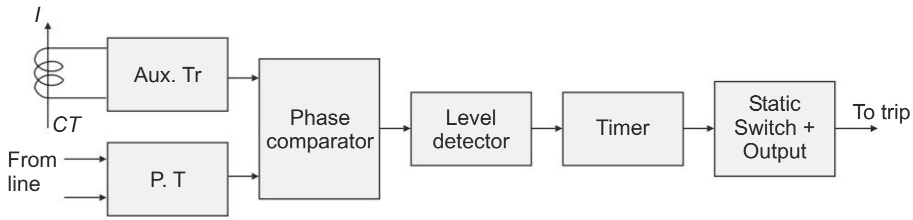


Fig. 10.3c *Directional current relay*

The current and voltage of the main circuit are sensed through CT and PT and fed to a phase comparator. Some times a phase shifter is added to the PT to give maximum output under fault conditions. The phase comparator gives the output proportional to $(I - V \cos \phi)$ and this is compared with a preset value at the level detector. The output of level detector, through an amplifier and static switch, is fed to the trip coil circuit. The comparators are mainly bridge rectifier circuits.

Directional ground relays For sensing of earth faults in power system with parallel circuits or loops the directional ground relays are used. In order to properly sense the direction of fault current flow, polarized relays are required and directional current relays can be used for this purpose.

Differential relays When over protection is to be given for internal faults as in transformer etc, a comparison of input and output current is required and whenever the difference exceeds a certain value, the inside fault is sensed. Fault conditions will cause a change of the compared values with reference to each other and the differential current will can be load to operate the relay. The differential relays are designed and adjusted such that they

(a) will not operate for the maximum error that can occur for a faulted condition, and
(b) will be sensitive to low magnitudes of faults inside the differentially protected zone.

To provide for the above conditions 'percentage differential relays are developed with special restraint'. They are applied for generators and motors and also for internal faults in the windings. Differential protection is used for (i) parallel feeder, (ii) bus bars, and (iii) transformer internal and earth faults in distribution systems.

10.4.2 Feeder Protection

Feeders are the most important entity of the distribution system and their protection and isolation under faults is a important and sensitive aspect. The various schemes for feeder protection are

(i) Graded time-lag systems
(ii) Differential protection (for parallel feeders, loops, etc.)
(iii) Distance protection in which the time delay in the relays is automatically made depending on the distance of the fault from the feeder

Graded time-lag Systems

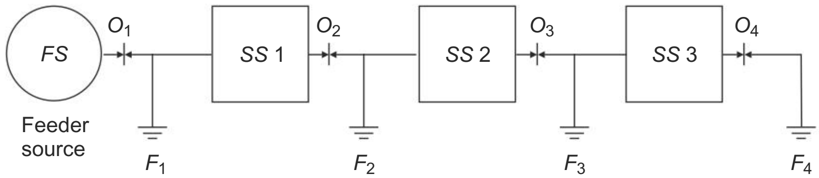


Fig. 10.4 *Series system with Time-graded protection*

When a feeder supplies load through several substations not connected in parallel, protection can be given by a series of over current relays which are arranged such that, farther the distance of the fault, greater will be the time taken for the relay to operate. This is illustrated in Fig. 10.4. *F*S is the feeder source which supplies power through a feeder and substations SS_1 and SS_2 and SS_3 are connected in series. If a fault occurs at F_4, over current relay (O_4) at SS_3 operates faster and the relays at SS_2, SS_1 and *FS* (O_3, O_2 and O_1) take longer time. As an example O_4 may take 0.3 second, O_3 0.6 second and O_2 0.9 second and O_1 1.2 second for their operation. Usually the time taken is graded as $t = \frac{A}{i^2} + B$, where *i* is the fault current. It may be seen that if fault occurs say at F_2, O_2 will operate first (faster and the fault current will be more) and if that fails then only O_1 operates at '*FS*' the source. This feature is obtained from the inverse characteristic shown in Fig. 10.2. When the protective system is made up of a series of overcurrent relays with graded operating times, it is essential that the current – time characteristics of all relays are similar and flatten in the same manner.

Protection of Parallel Feeders

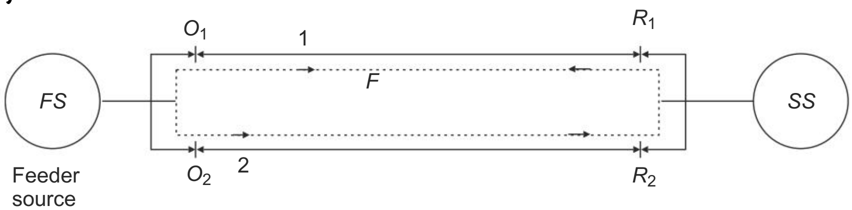


Fig. 10.5 *Parallel feeder protection*

Parallel feeders are provided to supply more load and provide an alternate means in case one fails to ensure continuity of supply. A parallel feeder arrangement is shown in Fig. 10.5 with two feeders to supply a substation *SS*. If fault occurs at *F*, fault current flows from *FS* to *F* in feeder 1 and from *FS* through feeder 2, *SS* and R_1, after O_1 senses the fault and switches of the feeder at O_1. Hence overcurrent relays O_1 and O_2 installed at *FS* and reverse current (or power) relays at R_1 and R_2. Since the current direction is reverse in feeder 1 from *SS* to fault position, reverse current (directional) or power relays are needed on feeders at *SS*. The feeder 1 is switched off first by the over current relay O_1 at (*FS*). The current flowing through feeder 2, *SS* and feeder 1 in opposite direction to the fault position will actuate the reverse power or current relay R_1 and *SS* and will switch off the feeder 1 at *SS*. Time delay will be introduced between the relay O_1 and R_1.

Distance Protection Using Impedance Relays The time grading of overcurrent relays for long feeders described earlier is not precise but arbitrary and unless the feeder is long and substations are spaced at large distance, it may not be effective. Hence distance protection scheme using impedance relays is preferred.

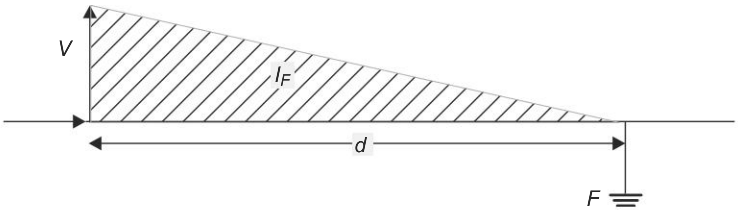


Fig. 10.6 *Feeder voltage drop from source end to fault on the line*

When a fault occurs on a feeder line at F (as shown in Fig. 10.6) the voltage falls to zero and the fault current I_F is given by V/Z where Z is the line impedance. But the impedance $Z \propto d$, the distance of the fault point from the source end. Hence I_F is proportional to the distance of fault position 'd'. The 'time delay' in operation of relays is to be proportional to 'd' or inversely proportional to the fault current.

Impedance Relay It consists of a combination of over current element and a voltage restraint element. In electromechanical relays, the arrangement is similar to that of an induction wattmeter or energy meter in which a disc rotates and closes the trip circuit. The driving force is obtained by the fault current and restraint is obtained by the voltage, thus the time of operation is proportional to Z. At the occurrence of a fault the over current element makes the disc rotate at speed depending on the magnitude of the current and starts unwinding the spring thus setting up a pull on the armature of the voltage element. When the pull is greater than the restraining magnet which is proportional to voltage, the armature leaves the face of the magnet and the contacts are closed A directional element or polarization can be added if required.

In solid state relays, the signals proportional to voltage and current are fed to a comparator which computes the ratio as well as phase difference between the two quantities 'V' and I. The comparator can act as an amplitude comparator or phase comparator or both depending on the application.

Static Impedance Relay A rectifier bridge comparator is used to realize the impedance relays as shown in Fig. 10.6a. The voltage and current signals are rectified and the output currents of the bridges are fed into a relay coil R. The output current I_0 of the bridge 1 is compared with I_r of the bridge 2 which acts as a restraint.

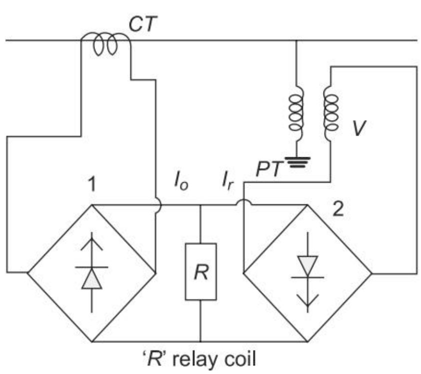


Fig. 10.6a *Bridge comparator as impedance relay*

Distance Protection Scheme

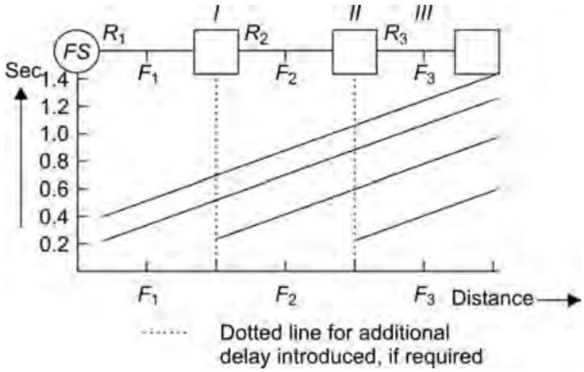


Fig. 10.7 *Distance protection scheme*

Distance protection scheme is illustrated Fig. 10.7. A feeder in this example is divided into 3 zones and fault can occur between source *FS* and I, I and II or II and III (positions F_1, F_2 and F_3). The operating lines for the relays R_1, R_2 and R_3 are shown. For a fault at F_3, the operating time for R_1 is about 1.4 second, R_2 0.8 second, and R_3 0.5 second. Thus only R_3 will operate and in case it fails R_2 will operate. For a fault at F_1 only R_1 will operate and will take 0.3 second. As seen from the schematic diagram for faults at farther ends, the relay nearer to that zone only will operate and others will act as back up.

Another scheme of distance protection is using step-graded definite time impedance relay. The time distance characteristic of such relays is shown in Fig. 10.8.

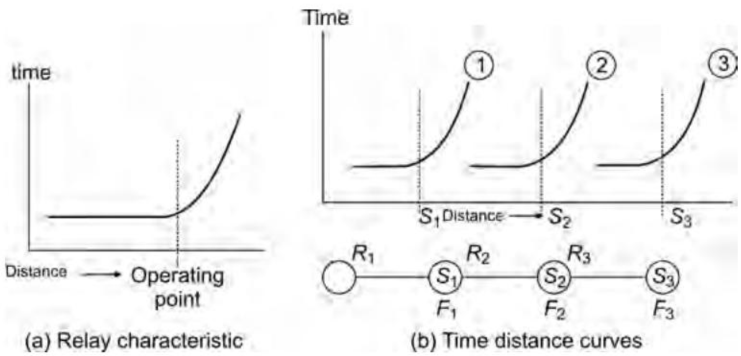


Fig. 10.8 *Distance protection using stepped characteristic of impedance relays*

Relays with operating characteristic of Fig. 10.8 a are used for stepped or time graded operation. The relay operating torque characteristic is given by

$$\text{Torque} \quad T = K_1 I_F^2 - K_2 V^2$$

Where I_F is the fault or feeder current. The relay will operate for $K_1 I_F^2 \geq K_2 V^2$ and limiting case is $\frac{K_1}{K_2} = \frac{V^2}{I_F^2} = K$. The closing time is almost instantaneous $K \geq K_1/K_2 \geq 0$. Hence for a fault F_3 only R_3

operates, fault F_2 only R_2 operates, etc. By adjusting the times R_2 and R_1 can be made to act as backups for R_3 in case it fails.

Distance protection is mainly used for feeders of length of 20 km or more. The protection scheme given to traction feeders (over head catenary wire feeding the engines) which runs to about 15 to 30 km from substations are protected by both over current and distance relays. Further radial feeders and feeders in ring distribution are also given distance protection. The distance protection scheme is further illustrated in the example given (See Example 10.1)

10.5 COORDINATION BETWEEN DIFFERENT PROTECTIVE DEVICES

A time-graded protective system consists of several protecting devices, each installed at one point, at intervals along a radial distribution feeder. These devices may not be inter connected and are not interconnected. For a fault, each device carries the same current. The problem is to obtain correct discrimination between several devices, so that the device nearest to the fault operates first. It is necessary to adjust their operating times (time grading) so that the device nearest on the source side clears the fault before any of the other ones operate. Time-graded protective system is in the form of fuses, miniature circuit breakers (MCB), etc. As such, the coordination between several devices is of importance.

In section 10.2 and 10.3 it has been mentioned that fuses, circuit breakers and circuit re-closures are used for protection purpose. When all such devices are used with certain time-current settings, they must be PRESET in a sequence to clear the faults so that least disturbance occurs in power supply. The PRESET SEQUENCE OF operation is known as COORDINATION. In this the device that is set to operate first is called “Main protective device” and the second one which is provided to operate in case the main protective device fails is called the backup. A properly coordinated scheme will

(i) eleminate service disconnection for temporary faults,

(ii) locate the fault area or point and hence minimizes or reduces the duration of service outage, and

(iii) also reduces the number of customers affected due to service interruption by disconnecting the supply with in the fault affected area.

A coordination scheme usually will have

(a) data pertaining to load currents, fault currents and location of protective devices

(b) maximum and minimum fault current for all types of faults and for the different possible locations

(c) time – current characteristics of the devices used

(d) the devices to be protected, i.e., transformers, feeder lines, substation equipment, etc.

The procedure followed will be

(i) the different devices used from the substation to the last point of the system is mapped

(ii) the composite time current characteristics (TCC) are made for a common voltage base if necessary

(iii) circuit diagram of the entire distribution circuit with details mentioned in co-ordination scheme are made

(iv) co-ordination of the different protective devices is arrived at

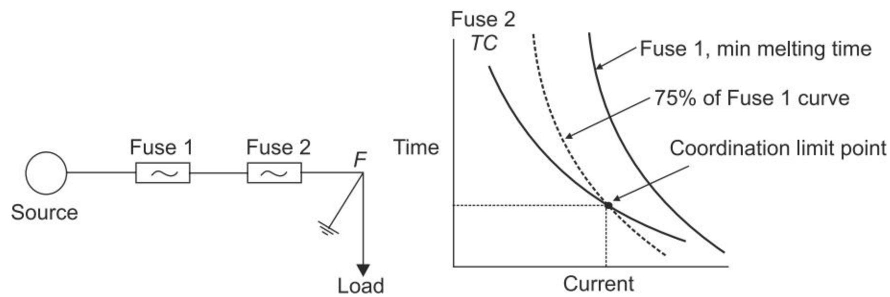
(v) the chosen or existing protective devices, current carrying capacity, interrupting capacity, minimum pickup rating, minimum time of operation, etc, are recommend and checked

When the last step is done, due consideration has to be given for (a) differences in TCCs and their tolerances have to be verified, and (b) changes that can occur due to ambient temperature, pre loading conditions, and other weather effects. Differences that can arise due to replacements, etc. have to be checked.

The different co-ordination arrangements needed are

(a) FUSE - FUSE
(b) FUSE – C.B
(c) FUSE-RE CLOSER, and
(d) RE CLOSER-C.B

10.5.1 Fuse–Fuse Co-ordination



(a) Schematic diagram of fuse protection (b) Coordination of Fuses using *TCCS*

Fig. 10.9

The schematic diagram of fuse protection of a load using two fuses 1 and 2 and their co-ordination using their TCCS is shown in Fig. 10.9 (a) and (b). Fuse 2 is the main fuse which protects the load and fuse 1 (which may include some other load also), is the backup or the protected fuse. The selection of fuse 2 is such that it provides adequate protection to the circuit beyond its location and is sufficiently selective. The TCC of the two fuses is shown in Figure 10.9b along with 25% margin i.e., 75% curve, For fuse B the melting characteristic is taken, where as for fuse A the total clearing time is taken. It may be seen that TC curve for fuse 2 is towards the left of fuse 1 but cuts the 75% curve of fuse 1 at the limiting point. This means that always fuse *B* melts and protects the load up to coordination point. The coordination implies that total clearing time of the protected fuse 1 is not to exceed the 75% minimum melting time of other fuse, i.e., fuse 2. Usually the manufactures give the data relating to coordination between fuses and proper types of fuses and their co-ordination have to chosen from the tables.

10.5.2 Fuse-CB Coordination

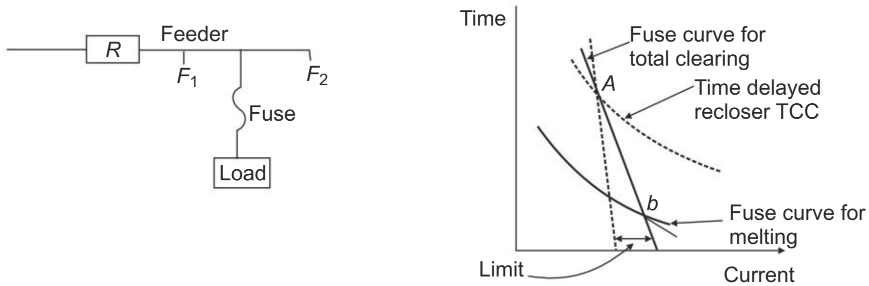
The fuse, CB, over current relay coordination is similar to the previous fuse-fuse coordination. Normally after a fault CB is automatically closed (or manually at times), where as fuse is to be replaced by switching off the supply by means of an isolator or load break switch, circuit breakers are closed after a few seconds. Hence the circuit breaker minimum closing time (together with relay operating times) is coordinated with minimum melting time curves of the fuses as described in Section 10.5.1. However when a fuse is used as back up protection device, the coordination is obtained only with relay operating time of about 150% of total clearing time of the fuse.

There are two cases to be dealt with (a) if CB is tripped instantaneously, it will clear the fault before the fuse acts. Hence the relay characteristics have to adjusted for all values of current up to the maximum value (b) if fuse is to clear the fault and CB acts as a backup, the circuit breaker and the actuating relay should have necessary time delay at all current values up to the maximum expected current.

10.5.3 Fuse Re-closer Coordination

Since re closers are meant for closing the circuit 2 or 3 times, time delay greater care and coordination is needed. Fuses are meant for protection against a permanent fault, where as re closers are to operate and close for transient and very short duration faults. This will save unnecessary cutoff of the supply, that would other wise occur, if only fuses are used. The fuses are thermal devices and will heat up with over current but will cool down when the re–closer opens the circuit. This has to be properly taken into account for fuse blowing off in case of permanent faults.

Consider a simple system with fuse acting for protection of a section of the system and RE-CLoSER to close, to protect the total feeder as shown in Fig. 10.10a.



(a) Feeder with fuse and re closer protection (b) T.C.C curves

Fig. 10.10

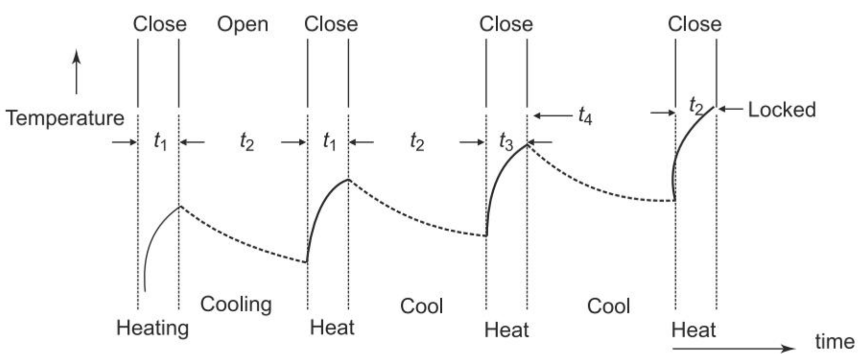


Fig. 10.11 *Heating and cooling curves for fuse with re closer*

The TCC of fuse for melting and total clearing of the fault is shown in Fig. 10.10b TCC along with re-closer TCC with time delay. For temporary faults the re closer opens and closes after a delay. Let the closer time be 't_1', open time t_2 and let the cycle change to t_3 and t_4 respectively for the next open and closing. While the re closer is closed, the fuse starts heating up and when open it starts cooling. The temperature time curves of the fuses is shown in Fig. 10.11. For temporary faults when re closer opens and closes the fuse should have sufficient 'thermal time constants', so that it does not melt. Hence the time delay for re closers should be sufficient as to act only after the limit duration indicated in Fig. 10.10. Fuse should only act for a permanent fault of the load and not for the other faults like F_1 or F_2 indicated in the Figure.

10.5.4 Re-closer–CB Coordination

This situation arises when a CB is used for protection of the main feeder and re-closers are used for sectional feeders or individual loads. A schematic diagram for such arrangement is given in Fig. 10.12.

Re-closers are used for each section of the loads (R) and CB is used for protection of transformer or total feeder. The relay 'OR' functions for re closing of 'CB' after a predetermined time delay (about 0.5 second or 1.0 second). Considering a fault F the re-close acts first, trips the circuit and re closes 2 or 3 times. The coordination should be such that for the fault current level, the relay characteristic of OR should be such that it gives sufficiently high delay. But if the fault is on feeder, the reclosers does not go into that zone and hence only CB acts and clears the fault.

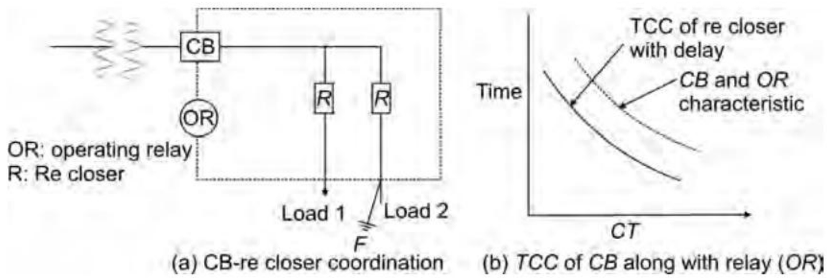


Fig. 10.12

It may be noted that in the distribution practices followed in this country, there are no separate reclosers. A main CB (oil or vacuum type) is used for feeder or large load protection. Air CB with automatic re closing is employed as recloser for important sections. Some times a CB to CB coordination is employed.

10.6 PROTECTION AGAINST OVERVOLTAGES

Whenever a line is suddenly closed or opened or a fault is cleared transient voltages appear in the system which can be of large magnitude and may last for few cycles. Further lightning over voltages directly induced into feeder lines or transferred through transformers also will be of concern. Normally, all apparatus like transformers, CB insulation, bushings, line insulation etc is designed and rated to with stand over voltages and the insulation level is called BIL (Basic Insulation Level) for that system voltage. For example a '11-kV' system apparatus has a withstand capability of about 35-kV power frequency voltage and 65-kV switching or lighting impulse voltage. But protection has to be given to divert higher voltages through some devices to the ground and safeguard the system. Further, both transmission lines and transformers and motor windings act as LC ladder networks for transients and hence large voltage builts up across the first few turns of the windings.

In few cases the over voltage is sufficient to cause corona on the lines and this limits the voltage level as well as the rate of rise of voltage i.e., $\frac{dV}{dt}\cdot$. Further the surge or transient voltages are controlled by using (i) spark gaps (ii) by shielding the overhead lines with ground wires (only for lightning voltages).

10.6.1 Spark Gaps (Rod Gap Protection)

A rod gap i.e., rods of circular section or square section spaced in air and mounted on a suitable insulated base acts as s protective gap. The insulation medium between the metal or conducting rods, sparks over when the voltage across the gap exceeds its spark over value. The spark overvoltage depends on ambient temperature pressure and humidity wave shape and polarity of the surge voltage but the variations that occur for the spark over is with in ± 15% of the standard values. The spark automatically stops as soon as the over voltages goes off and no power frequency current follows on sparking. During sparking, line voltage is reduces to zero but for a very short time (about 1 cycle time). Sometimes the spark gaps are connected in series with a non linear resistor to limit the current. Rod gaps are simple and cheap devices but do not meet all the requirements of protective devices. They may give rise to very high $\frac{dV}{dt}$ with impulse spark over on transformer windings which may lead to destruction of turn to turn insulation.

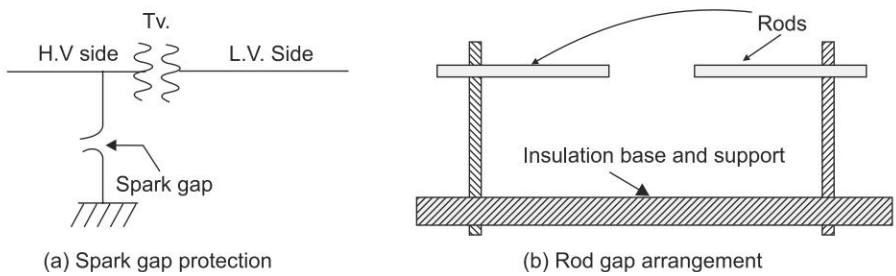


Fig. 10.13

10.6.2 Shielding of Overhead Lines

A ground or earth wire is run over the over head transmission lines and this will act as a shield for lightning over voltages. Normally, ground or shielding wires are run only for lines of above 33-kV rating and in areas where isokerauronic level (lightning activity) is very high. The presence of grounded conductor lessens the voltage gradient beneath them and hence the power line conductor do not get the induced lightning voltage or direct stroke (Fig. 10.14). Shielding is also used over sub-stations by running ground wires all over the metal structures and connecting all metal structures to ground. Further all metal poles and towers carrying the power line conductors must be earthed properly. This will reduce the rating and duty of the surge diverters used.

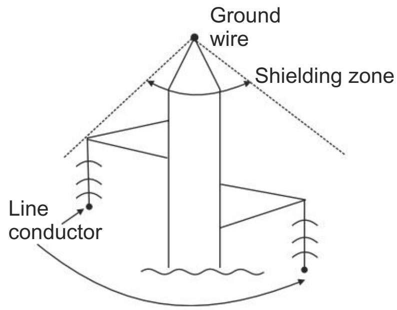


Fig. 10.14 *Line with ground wires*

10.6.3 Lightning Arrester or Surge Diverter

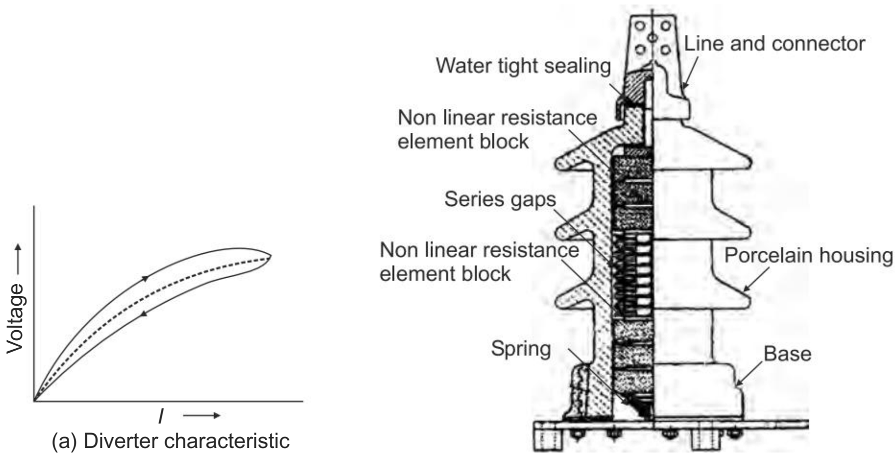


Fig. 10.15 *Surge Diverter or Lightning arrester and its characteristics*

Lightning arresters or surge diverters are nonlinear resistors in series with spark gaps which acts as a fast acting switch. The constructional features and characteristics are shown in Figure 10.15. The non linear resistor is either silicon carbide or zinc oxide and is made into discs. They are stacked one over the other and separated by spark gaps. The entire assemble is housed in a porcelain container with water proof housing.

The volt ampere characteristic (Static characteristic) is given by $I = KV^n$

where I = discharge current

V = applied voltage

K and n are constants depending on the material and dimensions of the disc. n is about 0.4 to 0.6 for silicon carbide 0.1 to 0.2 for zinc oxide (ZnO). Usually, ZnO discs are used for gap less arresters made for 100 kV or more.

The surge diverters are rated from 1.5 kA onwards up to 20 kA but in distribution circuits 1.5 kA, 2.5 KA or 5 kA rated surge diverters with voltage ratings for 400 V (600 V) upwards up to 22.5 kV (33 kV) are used.

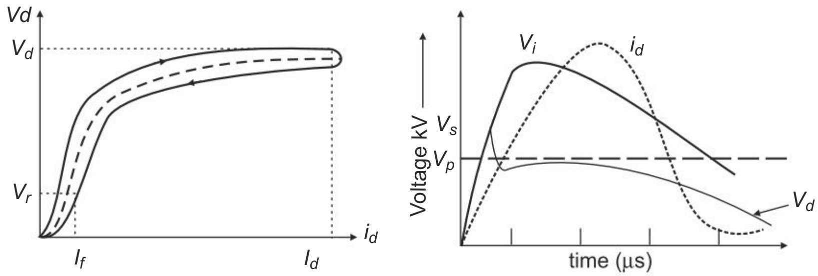


Fig. 10.16 *Characteristics of a surge diverter*

I_f – Power frequency follow on current at system voltage V_r

V_d – Maximum voltage across the diverter during discharge of surge current with peak value I_d

V_s – Spark overvoltage, V_p – Protective level, V_i – Surge voltage

i_d – Discharge current, V_d – Voltage across the diverter when discharge current i_d

The dynamic characteristic along with its operation is shown in Figure 10.16. When a surge voltage V_i is applied to the arrester it breaks down giving a discharge current. i_d and the voltage. V_d, across the arrester remains almost constant during the discharge. Hence it provides protection to the apparatus such as a transformer, bushing or a substation at a protective level = V_d.

Normally, when the surge or over voltage ceases, the spark gaps still remain conductive and current continues due to the follow on power frequency voltage. But the spark gaps can not remain conductive as the voltage will not be sufficient to maintain the current and the current stops at next current zero condition of AC cycle. Also the non linear resistors offer very large resistance for lower voltages.

The performance data of typical surge diverters is given in Table 10.1

Table 10.1 Performer data for surge diverters*

System Voltage	Arrester rating	Station type arresters		Line/Intermediate arrester	
		Spark over	Discharge voltage at 5kA (kV)	Spark over Voltage (kV)	Discharge voltage at 5 kA (kV)
3.3 KV	4.5 KV	12	8.5	12	10
6.6 KV	7.5 KV	24	17	24	19.6
11.0 KV	12.0 KV	45	32	45	36.5
22.0 KV	22.5 KV	72	55	72	63
33.0 KV	36.0 KV	105	100	108	100

(* Protective levels and performance data is given in I.S. 3070.)

10.6.4 Capacitors for Surge Voltage Control

Some times capacitors are used to control or limit the surges and decrease the rate of rise i.e., $\frac{dV}{dt}$ of the surge and making it flat. When a transient voltage is applied to a capacitor of value C, the current through the capacitor is $i_c = C\frac{dV}{dt}$ and this absorbs the energy in the surge as $\int \frac{1}{2}CV^2 dt$. When a steep fronted surge, i.e., $Vu(t)$ is applied to the capacitor through a line of surge impedance 'Z', the voltage across the capacitor will be $V_c = V(1 - e^{-t/cz})$ and hence the step voltage $u(t)$ becomes an exponentially rising voltage and $\frac{dV}{dt} = Ve^{-t/cz}$. As such a capacitor connected across an apparatus like a rotating machine will act as a surge absorber and will limit the voltage applied to the machine. The surge voltages can be delayed or flattened by 1 to 5μ seconds. Capacitance values of 0.25 to 1 μf are connected for motors rates to voltage of 11 kV down to 415 V.

Example 10.1 *A 33-kV distribution system feeder employs PTs of ratio 300:1 and CTs of ratio 20:1.*

The cable impedances per km is 1.05 Ω/ph. Determine the tripping time for distance protection scheme for feeder shown in Fig. E10.1. Line length = 20 km Take Max. Permissible time as 3 second. Fault occurs at F_1, 15 km away from the source.

(a) Distributor line

(b) A (Tripping time) relay time characteristic

Fig. E 10.1

Solution Tripping time in given by $t = K\frac{E}{I} = KZ$

(E supply voltage, I fault current Z = line impedance.)

The secondary side (relay side) impedance with PTs & CTs is

$$= Z_2 = Z_1 \times \left(\frac{CT\ ratio}{PT\ ratio}\right) = Z_1 \times \frac{20}{300} = \frac{Z_1}{15}$$

Relay constant $K = t/Z_2$

Cable impedance for line is (1.05) × 20 = 21 ohms

and relay side impedance $\frac{1\cdot 05 \times 20}{15} = 1\cdot 4\Omega$

$\therefore$ relay setting time $T = \frac{3}{1.4} = 2.15$ seconds

For the fault F_1 distant 15 km from R_1 relay tripping time is determined as follows. (refer Fig. 10.1 A)

1. Draw base line OS = 20 km for scale
2. Locate F_1 at 15 km from 0 on X-axis
3. Draw 2.15 second to scale on X-axis. Join TS_1
4. Draw parallel line to TS_1 though F_1 it cuts y axis at T_1. Measure 0 T_1 = 1.61 second

$$\text{Calculation: } \mathrm{OT}_1 = \frac{15}{20} \times OT = \frac{15}{20} \times 2.15 = 1.61\ Sec\cdot$$

Example 10.2 *For feeder line shown in Fig. E10.2. Compute relay setting times for R_1 and R_2 and time of operation for fault at F_2.*

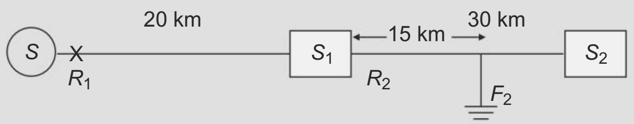


Fig. E 10.2 *Feeder line*

Relay setting time and operating time for fault adjacent to it be taken as 0.2 second (minimum operating time 10 cycles).

Solution Let the time for farthest point be set as 3.5 times the minimum operating time, i.e., 0.2 × 3.5 = 0.7 second. For the relay in the respective zone.

Referring to Fig. E 10.2 A the operating time lines for R_1 and R_2 are drawn to scale and extended to the other zone 0.2 second delay is for each relay to take into CB operation time i.e., (0.2 + 0.2 second = 0.4 second) operating time. The construction of operating lines is shown as in Example: 10.1. The thick line is for the relay operation and dotted line is for relay + CB operation. From the curves the relay operating times are as follows. With a vertical line at F_2 drawn, intersecting the characteristics at T_1, T_2, T_3 and T_4.

T_1 operating time of nearest relay in its zone (R_2) = 0.46 second

T_2 operating time of nearest relay in its zone (R_2) + the CB at R_2 = 0.66 second

Incase R_2 fails or CB at that location does not trip

T_3 operating time of back up relay R_1 = 1.06 second

T_4 operating time of back up relay R_1 and CB at that location = 1.26 second

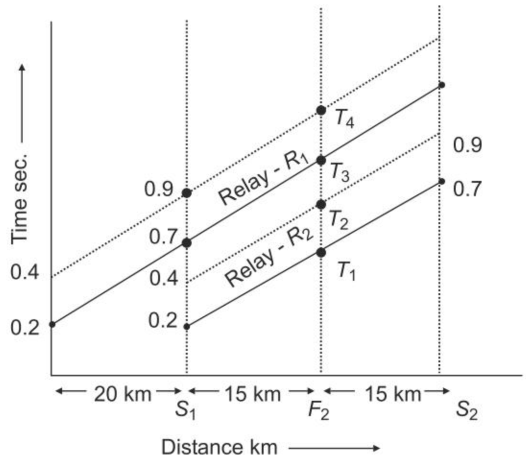


Fig. E 10.2 A

In the same manner, if reverse current relays are set, (in ring feeders or parallel feeders), their characteristic can be set and time of operation can be checked for co-ordination.

To conclude over voltage protection is very essential in distribution systems and more so for substations and over head lines. Other wise insulation damage and hence failure of system can occur.

Summary

In this chapter, protection of distribution lines and system against faults is covered using fuses and circuit breakers different types of fault sensors, i.e., relays are discussed and coordination of fuses and CBs is mentioned. Overvoltage protection using lightning arresters and lightning arrester characteristics are given. Distance protection of feeders using relays are cited through examples.

Keywords

Overcurrent protection
Fuses
Circuit breakers
Coordination of fuse and CBs
Relays
Overvoltages
Spark gaps
Lightning arresters

Review Questions

1. What are the objectives of a distribution protection?
2. What are the different protective devices used in the distribution system? Give comparison between them.
3. What are the different varieties of fuses used of protection? Give the features of HRC fuse and discuss its main advantages.

4. Give the diagram of an earth fault relay and discuss its function.
5. Explain the principle of a sectionaliser. How is it coordinated with a fuse?
6. Explain the coordination procedure between a fuse and a circuit breaker.
7. How is the coordination between main fuse and sectional fuse achieved?
8. What are the different protection schemes for a feeder ? Explain briefly.
9. What is distance protection in feeders ? Explain the scheme using an impedance relay.
10. How are feeder lines and transformers protected against over voltages or surges?
11. Explain how spark gaps can be used for protection of transformers and bushings against over voltages.
12. What is a surge diverter ? Explain its operation.
13. How does a surge diverter (lightning arrester) limits the over voltage and diverts surge currents?
14. A 25-kV electric traction system employs single-phase distributor with rail return and is 25 km with impedance $0.1 + j0.34\ \Omega$. If the PT and CT ratios employed are 200 : 1 and 100 : 1, determine the tripping time for distance protection taking maximum permissible time as 2.5 seconds when the fault occurs at 20 km away from the source point.
15. In Q.14, if the feeder is extended by another 20 km and two relays are employed, one at the source point and another 25 km from the source, compute the relay setting times for fault 20 km from the source as shown in Fig. Q.15. Taking minimum operating time of relay = 0.2 second

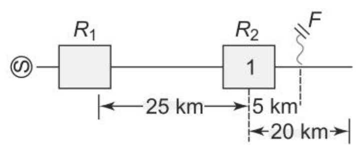


Fig. Q.15

Multiple Choice Questions

1. Fuse protection employed for current ratings of
   (a) less than 50 A (b) 50 – 100 A (c) 50 – 300 A (d) 5 – 300 A
2. Recloser is device used for
   (a) blowing of fuses
   (b) as a back up to fuses
   (c) for opening and automatically closing the circuit for temporary faults
   (d) replacement of CBs
3. Feeders of long distance are protected using
   (a) overcurrent protection
   (b) distance protection and overcurrent protection
   (c) only distance protection
   (d) reverse power and distance protection

4. Impedance or reactance relay is used for
   (a) distance protection (b) overcurrent protection
   (c) parallel feeder protection (d) none of the above
5. Type of CB used for primary feeders is (11-kV to 33-kV)
   (a) ABCB (b) MCB (c) MOCB (d) Vaccum CB
6. TCC of protective device is needed for
   (a) determining the ratings
   (b) knowing melting time
   (c) coordination with other protective devices
   (d) none of the above
7. Spark gap is used for
   (a) overvoltage protection (b) undervoltage protection
   (c) overcurrent protection (d) all the three above
8. Surge diverter consists of
   (a) spark gaps (b) non-linear resistors
   (c) thermal protection devices (d) non-linear resistors in series with spark gaps
9. Back-up device is one that
   (a) protects the equipment directly
   (b) acts when the primary protection fails
   (c) is kept as a unit for replacement of the primary device
   (d) used to switch off supply under fault condition
10. A relay is used in distribution circuits to
    (a) sense the fault (b) trip the circuit
    (c) act as a back-up device in protection (d) none of the above

Fill in the Blanks

11. Fuse is a device _______________.
12. Circuit breaker is a device _______________.
13. An expulsion fuse is a device meant for _______________.
14. Speed ratio of a fuse is defined as _______________.
15. A load break switch is a device meant for _______________.
16. Solid state relay has _______________ as the actuating or driving element
17. Impedance relay has _______________ as the actuating or driving force and _______________ restraining element.
18. Coordination between different devices is arrived at from _______________.
19. Spark gaps are used for protection against _______________.
20. The spark over voltage of a 12 kV arrester is ___________

Answers

1.	d	2.	c	3.	b	4.	a
5.	d	6.	c	7.	a	8.	d
9.	b	10.	a				

11. A thermal device used to protect apparatus against over currents
12. Device that automatically switch off the supply when a fault or over current occurs
13. Protection of low voltage (< 1000 V) circuits against faults and high currents
14. (Melting current for 0.1 second) / (melting current for 300 or 600 seconds)
15. Opening or closing a circuit under load (or carrying full load current)
16. Comparators
17. Current element, voltage element
18. TCC and total clearing time TCC of the protective devicces
19. Overvoltages
20. 45-kV

Eleven

Measurement of power, reactive power, kVA, p.f frequency and energy in distribution systems and electro-mechanical and electronic (solid state) meters used are introduced. Tariffs and billing for energy is also dealt with in this chapter.

Metering, Instrumentation and Tariffs

Introduction

In any distribution system it is essential to know the incoming power and energy and also the outgoing power or energy. The power and energy losses in the distribution system can be obtained only from these measurements. Power is the rate at which the energy is spent and energy is source for doing work. Usually in electrical measurement, it is easy to measure power and the total sum (integral) of power in a given time is energy. The basic unit for power is 'watt' and energy is 'joule' or watt second. Since watt-second is too small a unit, electrical energy is measured in kilowatt hours = 3600 kilojoules or 3.6 million joules.

Energy is measured using watt hour meters. For example, if a 2-kW heater is used for one hour, it consumes 2-kwh or 2 units of energy and the meter records 2 units.

The basic objective of metering and instrumentation is to give an indication to the operators and persons at the distribution stations, the information regarding the magnitude of loads, i.e., voltage, current, power energy and other characteristics like power factor, reactive power. Also the measurement of these quantities are needed for proper functioning as well as to detect the abnormal conditions. It is also necessary to ensure, in service, proper voltage, frequency and insulation condition.

A large variety of meters are available for this purpose such as (i) electromechanical meters, (ii) thermal instruments, and (iii) electronic and digital instruments. Of late, 'transducers' are also installed to get measurement of related quantities such as "temperature" coolant flow and condition of transformers, pressure of air or gas in circuit breakers etc. All the physical quantities are converted into either 'analog quantities' for display or as digital quantities for both display and telemetry purpose.

Since the voltage levels and currents (loads) are quite high, it is customary to use instrument transformers for voltage and current measurements. The standard voltage adopted for voltage or potential transformers on secondary side is 110 V or 100 V, while for current transformers it is 5 A or 1 A. With electronic and digital type meters, some times 0.5 A is also used.

11.1 MEASUREMENT OF POWER

All distribution systems are 3-phase 3-wire or 4-wire systems. It is well known from poly phase system measurements that in a '*n*' phase system "$n - 1$" phase metering is sufficient to measure power or energy, if it has 'n' lines or wires and '*n*' phase metering is required if it has 'n' phase wires and one neutral. Thus in a 3-phase 3-wire system TWO meters or TWO ELEMENT meter will measure power or energy and in 4-wire system, 3 meters or 3 element meter is required. At distribution substation end, both kW, KVA and power factor measurement is required. This means that only watt meter will not be sufficient, but "VAR" measurement and VA measurement is also needed.

Laboratory watt meters are usually dynamometer type where as industrial type watt-meters are panel board induction meters of class '*A*' or class '*B*' (± 1% or ± 2%) accuracy. These meters have the advantage of long scale (up to 300°) and robust, (Fig. 11.1). Usually a two element meter is used in 3-phase, 3-wire circuits. Previously, i.e., 25 years back, meters available for common use were either electromechanical driving gear registers for recording purpose or devices driving electronic registers. Later, after 1980 totally electronic or solid state devices have come and the previous devices are being replaced by electronic meters. Electronic meters can directly be connected to digital display (LED or LCD), consume less or almost "nil" power and hence do not form a load on the point at which measurement is done.

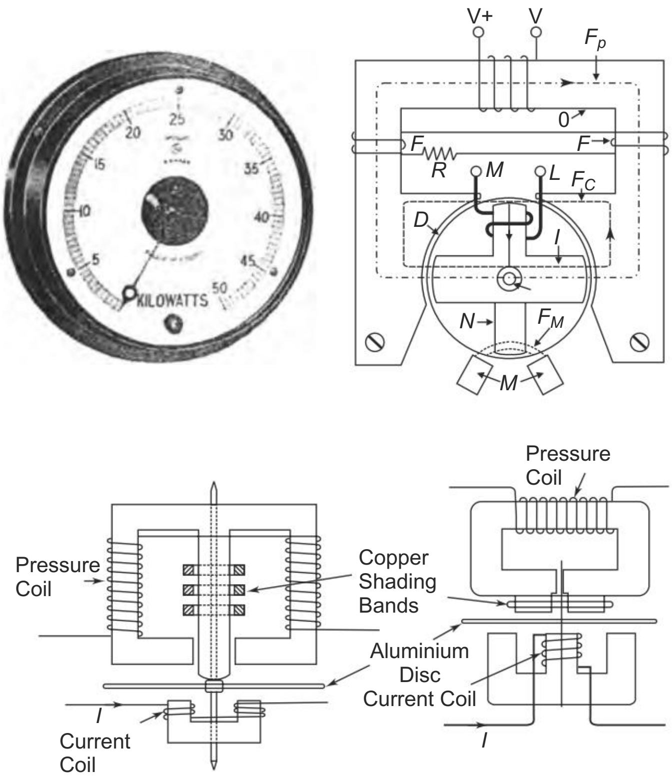


Fig. 11.1 *Induction wattmeters*

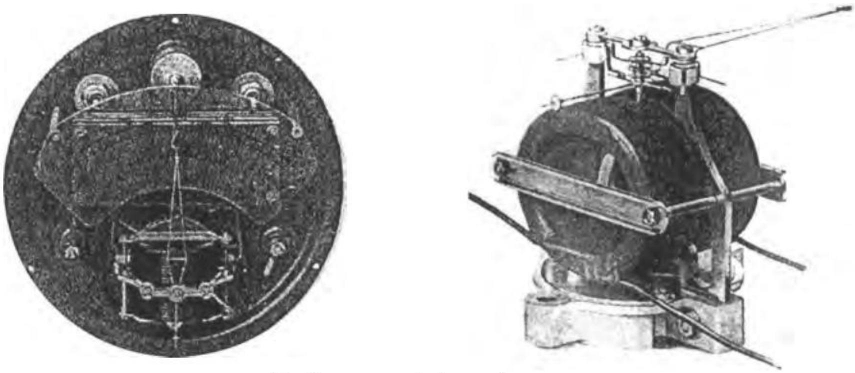
11.1.1 Measurement of Reactive Power: VAR Meters

A VAR meter is an instrument that measures the reactive power or 'VARS' directly. It is a modified wattmeter. The current coil of the meter is connected in series with the line or load and the voltage coil connected with a 90° shift from voltage across the circuits. Generally varmeters will have a centre zero scale with one side indicating lagging (to left of zero) and the other side leading. The var meters have an advantage over p.f. meters in that the scale in linear so that small variations can also be read.

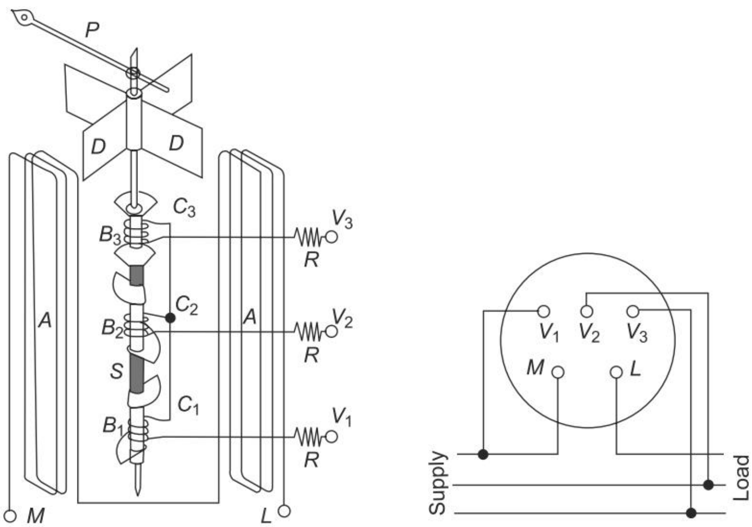
Measurement of reactive power in 3-phase, 3-wire balanced circuits can be done by using one wattmeter. The current coil is connected in phase 'Y' and voltage coil across phase R and B, so that the voltage applied to the voltage coil is $\sqrt{3}V_{ph}\underline{|90°}$. If the current is I_p with phase angle 'θ', wattmeter reads $(\sqrt{3}V_{ph}) \times I_p \times \cos(90 \pm \theta)$which given $\sqrt{3}\ V_{ph}\ I_p \sin(\pm\theta)$ and $(\sqrt{3})$ times wattmeter readings gives reactive power.

11.1.2 Measurement of p.f: P.f meters

Power factor meters are similar to wattmeters and indicate p.f directly. They will be single element meters for single phase and two or 3-element meters for 3 phase circuits. Some meters have circular scale of 360° with scale marked or calibrated as cos θ, p.f. The scale will be non linear. 360° instruments indicate both lag and lead, and the quadrant. Many commercial instruments, have 90° or 120° scale and calibrated 0.5 lag ~ 1.0 ~ 0.5 lead. A single phase and 3-ph. p.f meters are shown in Fig. 11.2.

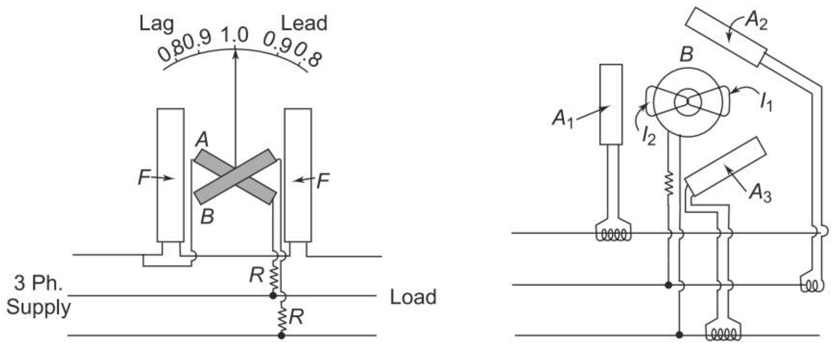


Weston power-factor meter



Moving iron power-factor meter

Fig 11.2 *p.f meters (Contd.)*



Dynamometer power-factor meter for a balanced three-phase loads

Westing-house three-phase power factor meter

Fig. 11.2 *Different types of power factor meters – industrial type*

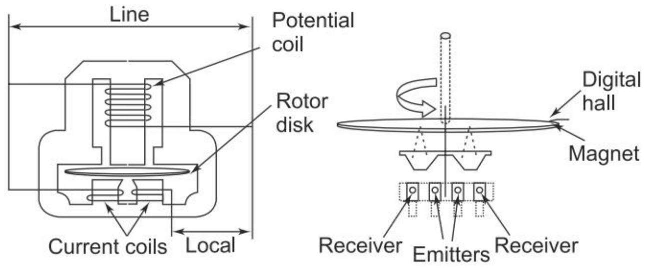
Usually in substations p.f meters are provided as panel meters to indicate average p.f of the system where p.f is obtained from an integrating meter (KWh and KVAR meters) as an average p.f during some duration (15 min) for billing purposes. The p.f meters installed are usually 3 phase moving vane type.

11.1.3 Frequency Meters

The supply frequency is directly indicated by frequency meters. These are similar to dynamometer instruments with crossed moving coils. There are usually made as indicating instruments of range 45 Hz to 55 Hz or 48 to 52 Hz. Vibrating reed frequency meters based on mechanical resonance of reed or strip were used earlier. Normally, they are made for operating voltages of 110 V, 220 V or 400 V. The electromechanical instruments are now-a-days replaced by electronic digital frequency meters.

11.2 MEASUREMENT OF ENERGY

Electrical energy is generated and sold to the consumers. As such both the producer or the generating source and the utility or customer needs correct measurement of energy. Energy is measured in kilowatt-hours and the common device is an electro-mechanical meter. A single element meter is used for measurement in single phase circuits, where as two or three element meter is used for 3-phase circuits. A two-wire induction type watt-hour meter consists of a stator with two electromagnets, one exited by the current and the other by the voltage coil connected across the supply. A moving (driving) disc, gets a driving torque proportional to the power $VI \cos \theta$. Thus the rotational speed is proportional to the power in the circuit. The number of revolutions made in a given time gives the energy consumed in that interval. The meter is calibrated and given the meter constant 'n' the number of revolutions per kwh. A typical 230 V, 5-A meter may have meter constant = 1500 rev. per kwh. The rotating disc drives a mechanism of gear trains so that the number of revolutions are directly indicated as the energy in units (kwhr). Meter reading is displayed on dials or recorded otherwise. A typical single-phase energy meter is shown in Fig. 11.3. Modern meters are provided with infrared sensors so that rotation of the disc is precisely sensed and counted. The display is done electronically with digital display.



(a) Stator of induction type energy meter
(b) Rotation measurement by infrared and Hall effect sensors

Fig. 11.3 *Introduction type electrical energy meter*

11.2.1 The Electronic Energy Meters

The demand for greater precision and complexity of measurement has led to the development of various type of electronic energy meters. They can perform multiple functions and indicate other quantities also if desired. The elimination of mechanical parts reduce the physical wear and tear and improve the reliability. Current sensors (like CTS) and voltage sensors (PTS) are often used directly to connect them for any voltage level or to high loads (current). Today a 250-V, 50-A meter is available with accuracy of ±0.2% or better at 50 Hz. They have a working temperature range – 40°C to + 85°C. Electronic meters are available for both single phase and 3-phase with direct connection on 440 V, 3-ph or 230-V single phase, 50 A and below. External CTS and PTS are required for other voltage and current ranges.

The Electronic and Digital Metering System

Although the traditional mechanical meters are still in use, the industrial and large consumers as well as the electrical supply concerns prefer a multifunctional metering that can go into more advanced instrumentation. The present day metering system is shown in Fig. 11.4.

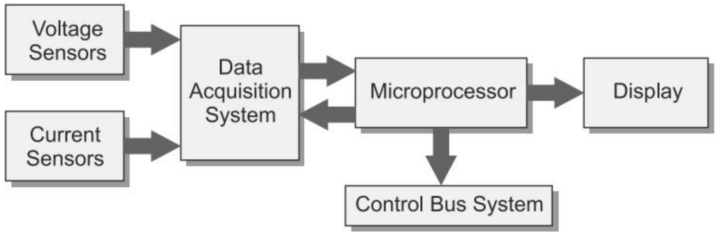


Fig. 11.4 *Scematic diagram of metering systems*

The above instrumentation also helps in getting the data relating to the distribution systems like all electrical parameters (voltage, current power, reactive power etc.) and can form a part of SCADA described in the next chapter (Chapter 12).

Usually individual consumer consumption is normally done with conventional electromechanical or electronic meters (<100 kW power or total 100 kVA loads), while bulk consumers (more than 100 kVA and HT consumers go with metering system shown in Fig. 11.4. Three phase meters have already come into market and many commercial and industrial users prefer electronic meters with voltage and current sensors/transducers and digitize the wave forms. A high speed, high performance microprocessor (or the digital signal processor, DSP) uses the digitized waveforms to calculate various quantities and information needed. A converter that interfaces directly with the voltage and current sensors instantly accumulates the kwh in a building block for computing the energy. This type of meters are providing low cost, high performance metering. Single phase digital energy measurement has been accepted widely and prepayment meters have come into market in western countries.

The term ‘digital meter’ implies that a time sampled signal is taken for processing. An analog to digital converter (ADC) samples the current and voltage from the transducer or sensor output at a very high frequency. Thus the analog waveform is converted into binary bits that are manipulated. The ADC’s resolution and speed, not only affects the duplication and quality of continuous time signals which vary at the fundamental (50 Hz) frequency, but also affects the microprocessor band width requirements for calculation.

When the voltage and current waveforms are once converted into digital form, they can be multiplied, filtered and integrated to extract any desired information. A fixed function DSP places values in registers that can be read by a low band width micro processor. But if power quality monitoring is needed then a programmable DSP is needed.

A fixed function DSP supported by few registers and capacitors may be sufficient for small, high performance, low cost display board. A typical digital power meter along with a electronic energy meter is shown in Fig. 11.4 a and b.

The advantages of digital energy meters are

(i) high accuracy and stability over a wide range; they are stable over a range of temperature (0° and 45°), voltage and frequency
(ii) very less cost of maintenance: periodic calibration as with mechanical meters is not needed and they are accurate over a wide range
(iii) these meters can be upgraded into communication networks; thus the two output terminals of the meter can be connected in series to a hub for data collection and central billing system

400/230V Three-phase 50 Hz (60Hz) 10 (40A)Class 1.0 Light-weight low power consumption highly stable meter

The microprocessor chip inside the meter

Fig. 11.4 *(a) Digital Ac power meter and electronic energy meter (b) Electronic three-phase 4 wire watt-hour meter*

11.3 MAXIMUM DEMAND AND TRIVECTOR METERS

In distribution and for large power consumers maximum demand or peak load is an essential parameter. Demand is defined as the average power (KVA) needed over specified time interval (it may be 15 min or 30 min). Demand is usually expressed in kW. However, applying the same criterion to the reactive power, apparent power or kVA is taken for billing purpose. Thus a customer's maximum demand may be both kVA and the p.f at which he draws the power. Maximum demand (kVA) is metered so that proper conductor size is chosen for the wires and the size of the supply transformer depends on the combined maximum demand of all the customers. By far the most common demand meters used are integrating demand meters. The mechanical meters used as demand meters are called "*Trivector meters*" which give the measurement of kW, RKVA and KVA and usually integrate the quantities and average out in 15 min or 30 min intervals.

Maximum Demand Indicators

The earlier mechanical type MD indicators were usually used along with in energy meter during a 15 min or 30 min intervals. A separate dial was fitted inside the instrument, the pointer of which was driven by the sprindle of the moving disc of the energy meter. After the dial has been with the gear for the above said interval, a mechanism comes into operation and brings the disc driving assembly to zero position. The pointer however does not comback and is held imposition. In the next interval if the drive is more than that of pervious one, the pointer moves a head, otherwise it stays at pervious position. The device for returning it to initial position at every interval of 15 min or 30 min is operated by a clock inside the meter (Fig. 11.5).

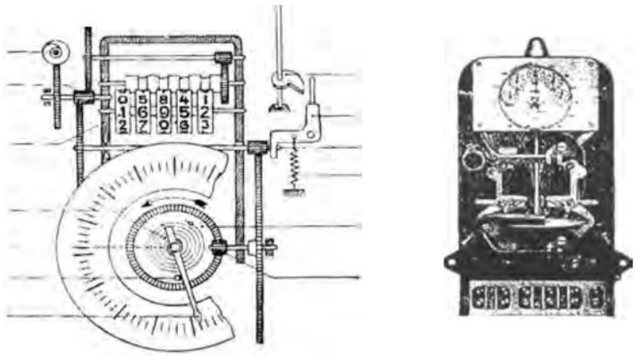


Fig. 11.5 *Maximum demand indicator*

Trivector Meter

An MD indicator gives the maximum kW but does not indicate either kVA or p.f. Hence for large power consumers the trivector meter measures KWh, KVARh and KVAh, so that p.f is calculated for billing. The tariff used is a two part tariff (refer Section 11.6). Measurement of above mentioned quantities is needed. The meter consist of two registering dials and wheels both which are operated for a given interval of time with MD indicators attached to them. The first one, i.e., KWh sensor drives the first wheel the second one is driven by RKVA (called the VI sin θ) drive. Both of them are engaged to a 3rd unit in perpendicular directions so that the resultant drive is equivalent to $[(VI\cos^2\theta + (VI\sin^2\theta)]^{1/2}$ or VI.

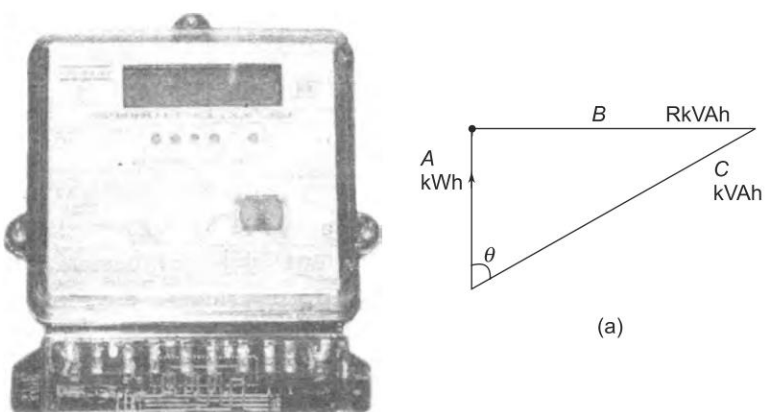


Fig. 11.6 *AC electronic trivector meter*

The movement of the above is schematically indicated in Fig. 11.6a. '*A*' corresponds to KWh drive and 'B' corresponds to RKVAh drive. 'A' registers the energy consumed while '*B*' corresponds to reactive power (energy consumed). '*C*' gives KVAh and the MD indicator attached to it gives the KVA for the time interval chosen (15 min or 30 min).

The trivector meter registers the true value of KVAh correct to about ±1%. Now-a-days the mechanical trivector meters are replaced by electronic meters (Fig. 11.6). These meters give the values of total real energy (KWh units), the maximum demand (MD) in KVA or KW as needed and total reactive energy KVRh. The average p.f is calculated from the KWh and KVARh readings.

The important features of modern electronic trivector meter are (i) automatic self-diagnostic check, calibration pulses for fast accuracy check, non-volatile memory for data storage and load profiles, MD computation and record load survey data. The parameters supported are

(i) energy meter KWh, KVARh lag, KVARh lead, apparent energy KVAh
(ii) MD indicating sliding window for KW, KVAR (lead or lag)
(iii) time of the day (TOD) registers for maximum and seasonal demand
(iv) p.f record : instantaneous p.f., average p.f, total p.f
(v) billing parameters KWh of demand for 12 months (FIFO based)
(vi) historical data record, 12 months KWh and demand
(vii) tampering features : display with data and time
   (a) missing phase (b) PT unbalance (c) CT reverse (d) CT unbalance
   (e) CT open/short (f) low p.f

11.4 SUBSTATION INSTRUMENTATION

In any distribution system or substation, metering of all electrical quantities is needed and should be displayed on the control board for monitoring and control purposes. Suitable voltage and current transformers installed at all feeder points, for each bus and transformer panel meters (electromechanical or digital/electronic) are installed, to indicate voltage, current, power, reactive power, KVA, p.f., incoming and outgoing power and energy. The trend now-a-days is to install a SCADA system in which the metering will be a part (refer Section 12.4. In addition to indicating, continuous recording of above quantities is done for further analysis.

11.5 TARIFFS AND BILLING

This is the most important commercial aspect in the distribution system. For small consumers, the energy is charged at a rate of Rs/KWh. For large consumers, if they draw more power or KVA for a given energy consumption the electricity concern has to have larger capacity. Hence charges are levied both on KVA demand as well as on energy consumed. Also extra charges are collected if the p.f is poor (<0.85) since poor p.f loads result in less voltage at consumer end and also larger current in power lines. For large consumers with bulk load, a telescopic tariff rate is given by some electricity concerns.

The two part tariff consists of billing for actual units consumed at a rate of Rs/KWhr + charges for maximum demand of rate of Rs/KVA. The consumer is billed for either the contracted KVA or the actual KVA if he exceeds the contracted demand. The following example will illustrate the tariff.

Further, since fuel like coal, gas etc have to be procured for generation of energy, fuel charges are added to consumer billing to account for variation of fuel costs.

Example 11.1 *In certain concern the meter readings are as follows. Prepare the bill for electrical charges:*

(A) *KWh :* *98.600 units*

KVARh : *58,000 units*

KVA : *181 contracted demand = 150 kVA*

Billing charges : *Rs. 4.25/unit*

Demand charges : *Rs. 250/kVA*

Extra charges for low p.f : Rs 1000 per 0.01 of p.f when p.f is less than 0.85

Solution Bill for units 98,600 × 4.25 = Rs. 4,19,050

Bill for demand 180 × 250 = Rs. 45,250

$$\tan\theta = \frac{REVAh}{KWh} = \frac{58,000}{98,600} = 0.5882$$

$$\cos\theta = 0.8619$$

since p.f is more than 0.85 no extra charge

Hence total bill is Rs 4,64,300.

(B) *The reading in the next month are as follows :*

KWh = *76,600*

KVARh = *51,600*

KVA demand = *145, Prepare the bill*

Solution

Bill for units: 76,600 × 4.25 = Rs 3,25,550

Bill for demand: 150 × 250 = Rs 37,500

(kVA demand is less than 150)

$$\tan\theta = \frac{51,200}{76,600} = 0\cdot 6684$$

$$\cos\theta = 0.8314 \text{ (p.f is less than 0.85)}$$

Difference = 0.85 – 0.8314 = 0.0186 ≈ 0.02 (rounded off)

$$\text{Extra charge for poor p.f} = \frac{0.02}{0.01} \times 1000 = \text{Rs. } 2000$$

Total bill : Rs. 3,25,550 + Rs. 37,500 + Rs. 2000 = Rs. 3,65,050

11.6.1 Two-part Tariffs : Billing Rules

The following are some of the rules for billing for bulk consumers with 50 kW / 67 HP or more and draw power at high distribution voltages (11 kV or 4.6 kV).

(i) Billing Demand

(a) Billing demand will be on the MD recorded during the month or 95% or connected demand which ever is higher

(b) When there is a demand cut of 25% or less the above rule is applied and when there is a demand cut of more than 25%, the billing demand is on MD recorded or 75% of restricted demand which-ever is higher

(c) At any time the maximum demand exceeds the connected demand during restriction period the consumer has to pay at 1.5 times the normal rate provided the excess demand is 1.2 times or less than the contracted demand. Otherwise the penalty is 1.8 times the normal rates

(ii) Power Factor

(a) All HT consumers have to maintain a p.f of 0.9. If it is less, corrective measures are to adopted by installing capacitors

(b) If the p.f goes less than 0.90 a surcharge of Rs. 0.05 per unit consumed is levied for every reduction of p.f by 0.01 below 0.9 p.f. The p.f is determined for 3 decimals and rounded off to two decimals.

For example, 0.8849 is made as 0.88 and 0.8851 is made as 0.89

With electronic trivector meter, the recorded average p.f over the billing period is considered. Rebate is given if the supply is taken at higher voltages like 33 kV or above and special tariff is given for seasonal loads and connections.

(iii) Some electricity concerns add an extra amount as fuel charges based on the units consumed.

Summary

Basic objectives of the metering and instrumention for substations is presented. Different electromechanical meters for power, VARS, KVA, frequency, p.f, energy and maximum demand are explained. Digital meters and metering system is introduced. The chapter concludes with need of tariffs and billing together with an example on calculation in billing.

Keywords

Measurements · *Watt meters* · *VAR meters* · *p.f meters*
Frequency meters · *MD and trivector meters* · *Electronic meters*
Digital metering system · *Tariffs* · *Billing*

Review Questions

1. What are the different parameters and quantities in power distribution that are to be measured in substation?
2. Discuss the type of meters used for measurement of power and p.f in industries

3. Give the line diagram of modern electronic metering adopted in the industry or substation and discuss its features
4. How is measurement of energy done ? Give the type of meters used in single and 3 phase systems
5. What is a MD meter ? Why is it needed in power system ?
6. What is a trivector meter ? Why is it needed ?
7. Give the two part tariff system and illustrate how the billing is done
8. Give the features of an electronic trivector meter. What is its advantage over conventional meter ?
9. A consumer has a choice to opt for one of the following tariffs. (a) Rs 4.50 / KWh (b) Rs 1000 + Rs 5 / KWh. At what consumption is the second tariff preferrable

(Ans $\geq$ 400 units)

10. A consumer has the following record for his consumption :

Contracted demand:	250 kW
MD recorded:	225 kW
Units recorded:	1,15,000 units
KVARH recorded:	70,000
Tariff : MD charges:	Rs 160/- kW
Unit charges:	Rs 5.50/ Kwh
Penalty for low p.f (<0.85):	Rs 1000/- for 0.01 of p.f
Prepare the bill to be paid	[Ans : Rs 6,72,500]

11. What will be the bill in Q.10 if
    (i) MD recorded is 280 kW and
    (ii) KVARH recorded 1,00,000

    Penalty for excess MD taken : Rs 500 / kW [Ans: Rs 6,97,500]
12. A residential accommodation is given the following tariff by the owner to the rentals. The rent is Rs 15,000 per month. The monthly consumption is 800 units
    (a) fixed charge of 5% of the rent
    (b) units rate : 0 – 100 Rs 4.50 per unit 100 – 200 : Rs 5.50 per unit 200 – 500 : Rs 6.50 per unit; more than 500 : Rs 7.50 unit. What will be the monthly bill for the rentals?

[Ans: Rs 5,200]

Multiple Choice Questions

1. Maximum demand is measured by
    (a) trivector meter
    (b) watt meter
    (c) p.f and VAR meter
    (d) none of the above
2. Commercial p.f meters installed in industries are
    (a) single-phase moving-coil type
    (b) 3-phase moving-coil type
    (c) 3-phase moving vane type
    (d) any one of a, b or c

3. Modern digital electronic meters that measure energy have the following input quantities :
   (a) power and time (b) voltage and current
   (c) voltage, current and phase angle (d) any of the three above
4. Commonly used energy meter on 3-phase balanced systems are
   (a) dynamometer (b) moving coil (c) moving vane d) induction meter
5. Digital Ac meters can measure
   (a) voltage and current (b) voltage, current, power, KVA and p.f
   (c) frequency, phase angle and energy (d) none of the above
6. Two-part tariff charges are for
   (a) units consumed (b) units and power factor
   (c) units and power (d) units + maximum demand KVA
7. In two-part tariff, penalty is levied if
   (a) excess units are consumed
   (b) if max. demand exceeds contracted demand
   (c) excess maximum demand and for poor p.f (p.f lower than a minimum value)
   (d) both a and c
8. The present electronic meters read
   (a) power, p.f and KVA
   (b) power, KVA and historical record
   (c) KWh, KVAH, RKVAh, MD and past data for about 12 months
   (d) none of the above
9. Digital metering has the following advantage :
   (a) high accuracy and stability
   (b) high accuracy, stability, less maintainance cost and can be upgraded into communication networks for central billing
   (c) low-maintainance cost, accurate over wide range but cannot be connected for central billing
   (d) can be connected to central hub for data collection and billing only
10. Substation metering and instrumentation includes
    (a) metering of all electrical quantities like voltage, power, p.f., etc. and displaced on the central control board
    (b) metering and displaying only voltage power and p.f of incoming and out going feeders
    (c) to install a SCADA for continuous record and display
    (d) connecting suitable PTS, CTS and sensors for measurements purpose only

Fill in The Blanks

11. Energy in 3-phase, 4-wire system is measured with __________ element meter
12. Commercial p.f meters have range usually from __________ to __________

13. In two-part tariff billing is based on __________ and __________.
14. A trivector meter measures __________
15. In two-part tariff penalty is levied if __________
16. A voltage sensor is usually __________
17. A current sensor is usually __________
18. In modern electro mechanical energy meters __________ are used for precision measurements.
19. A two element meter is usually suitable for __________
20. In an electronic meter __________ is used for computation and display of the quantity measured

Answers

1. a	2. c	3. b	4. d
5. b	6. d	7. c	8. c
9. b	10. a		
11. 3-element	12. 0.5 lag – unity to 0.5 lead		

13. Units consumed and maximum demand kVA
14. KWh, KVARh and KVAh
15. p.f. is less than 0.85 or 0.9 as the case may be
16. A potential transformer
17. Current transformer
18. Hall elements with infrared beam
19. 3-phase 3-wire balanced or unbalanced load
20. A micro processor

Twelve

Voltage control in a distribution and how the feeder voltage is maintained within limits is discussed, and voltage-controlling units are explained in this Chapter. Distribution planning, automation, SCADA and substation automation are also presented.

Voltage Control: System Planning and Automation

Introduction

The aim of electrical supply service is to provide continuous, uninterrupted supply to the consumers and the service provided should maintain voltage levels at consumer point or premises with the stipulated limits ($\leq \pm$ 5%) of nominal rated value. It is highly impossible to maintain a constant voltage of nominal value and therefore a common practice is to maintain voltage levels within the range of variation for satisfactory operation of the different equipment or apparatus as per the regulations within the 'Electricity Act'. The Electricity Act 2003 and the Electricity rules 2005. Neither, too high nor a too low voltage is be maintained. A high voltage reduces the life of the apparatus such as electric devices, bulbs or motors and too low voltage causes reduced illumination level, difficulties in motor operation and some times over loading and improper heating of heater appliances etc. Hence, it is important to control the voltage level of the distribution network as the load changes occur. Typical voltage profile on a rural feeder at the peak load is presented in Fig. 12.1.

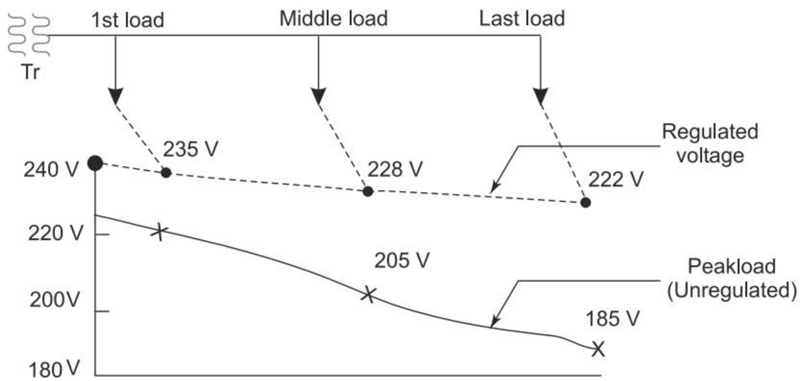


Fig. 12.1 *Voltage profile on a rural feeder at peak load*

The voltage at transformer point was 225 V instead of 230 V and at last load point 185 V, the voltage regulation was very poor. The well maintained and regulated feeder voltage profile is shown as dotted line. (This data is taken from a load survey conducted.)

12.1 BASIC DIFINITIONS

In order to have clear understanding and meaning of the terminology used, definitions of few quantities are given.

Nominal voltage (V_b) The voltage that is assigned to the system or apparatus specified, in given voltage class or level.

Rated voltage The voltage at which the performance or output and the operating characteristics of an apparatus or appliance is specified.

Service voltage The voltage measured between the two lines or supply points or ends of the service entries or connection of the appliance, for example, at the terminals of the motor or at the output points of the main switch, etc.

Base voltage The reference voltage of the system, for example, 230 V, single-phase, 400-V, 3-ph line voltage, etc.

Maximum voltage The largest average voltage sustained for 1 minute or 5 minutes.

Minimum voltage The lowest average voltage sustained for 1 minute or 5 minutes.

Voltage spread The difference between maximum and minimum voltages, considering any transient dips or over voltages due to a motor starting or fault clearing, etc.

Voltage drop The difference between sending end and receiving end voltage of a line or feeder. This may be from transformer point to the service connection point of the consumer.

Voltage regulation The percentage voltage drop of a line or transformer.

$$V_r = \frac{|V_s| - |V_r|}{|V_b|} \times 100 \quad \text{or} \quad = \frac{|V_s| - |V_r|}{|V_r|} \times 100$$

V_s = Sending end voltage, V_b = Nominal voltage of line or system

V_r = Receiving end voltage

12.2 VOLTAGE CONTROL

In order to keep the voltage of a distribution line within the permissible limits some correction and control be provided in the system. The usual means of control in distribution systems are

(i) Incorporating voltage regulating devices such as induction regulators, buck-boost transformers, line drop compensators, etc.

(ii) Applying of power factor correction and improving power factor and thus regulation of the line

(iii) Relocation of loads on the feeders such as (a) balancing the service connections on the 3 phases equally, (b) increasing the size of feeder conductors, and (c) transferring loads to new feeders, etc.

(iv) Erecting new lines or substations for increased loads or increasing the voltage levels of the feeders.

Out of the different methods mentioned, the first one will be discussed here. Other methods are already mentioned and discussed in the earlier chapters.

12.2.1 Feeder Voltage Regulators: Induction Regulators

Induction regulators are similar to the three phase or single induction motors in construction, but are static devices. The rotor is held stationary in position but can be adjusted either manually or automatically. The primary winding or output is connected to the line whose voltage is to be controlled. In a three phase regulator, the stator generates a rotating magnetic field of constant magnitude and the rotor gets induced voltage in the secondary. The phase of the secondary voltage can be varied depending on the rotor position. The rotor voltage is added to the stator or line voltage and depending on the phase position, the net voltage becomes more or less. In Fig. 12.2 the voltage phasor of one phase along with the output voltage is shown.

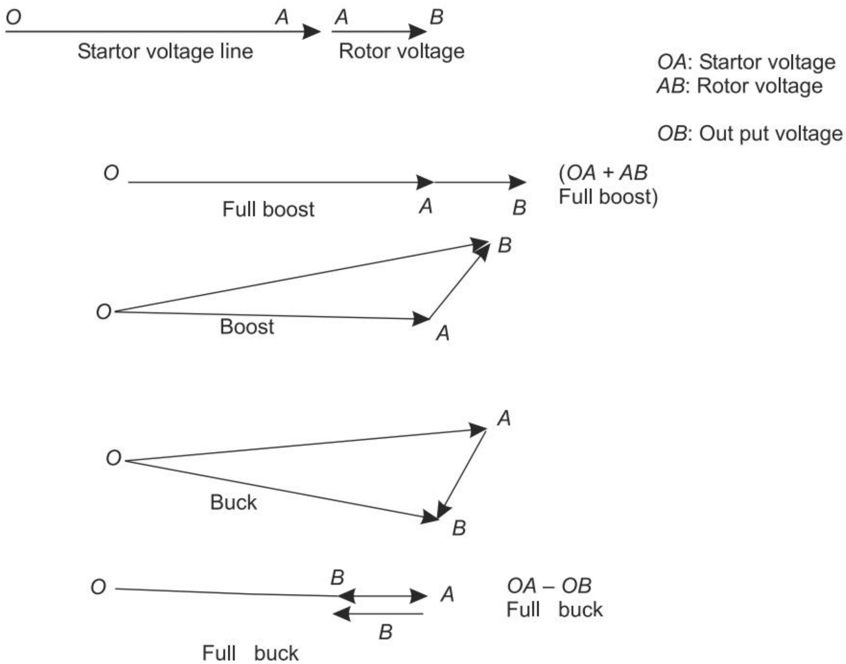


Fig. 12.2 *Phasor diagram of induction regulator*

Induction regulator is convenient for single feeder lines or for a single load at the feeder end or load point. It can boost or buck (reduce) the voltage up to 15% or more. The voltage variation is continuous. They are available from 400 V, 3 ph up to 33 kV, 3 ph in power range of 25 kVA to 2 MVA or more. Now-a-days these are not used as they are costly and un-economical and maintenance is also high.

12.2.2 Transformer Tap Changing

This is the most common method used every where. Transformer tap changing can be either off load or on load. On-load tap changing is used in 66 kV and above substations and rarely in 22 or 33-kV substations. 11 kV and below rated transformers usually have off load tap changing arrangement. Schematic diagram of tap changer is shown in Fig. 12.3. One phase of the HV side winding of the transformer is shown. Since the number of turns are more on HV side, tap charger is installed on HV side only. Further it will be at neutral end for star connection and at the middle of the winding for delta connected windings of the transformer Tap 3-3′ is normal position and in the present example only two taps up, to increase the voltage (1-1′ and 2-2′) and two taps down to reduce voltage (4-4′ and 5-5′) say for ±5% and ±10% are shown. If the number of turns increases, voltage ratio increases, output voltage reduces (buck). The tap changing operation for ON LOAD tap changing is as follows.

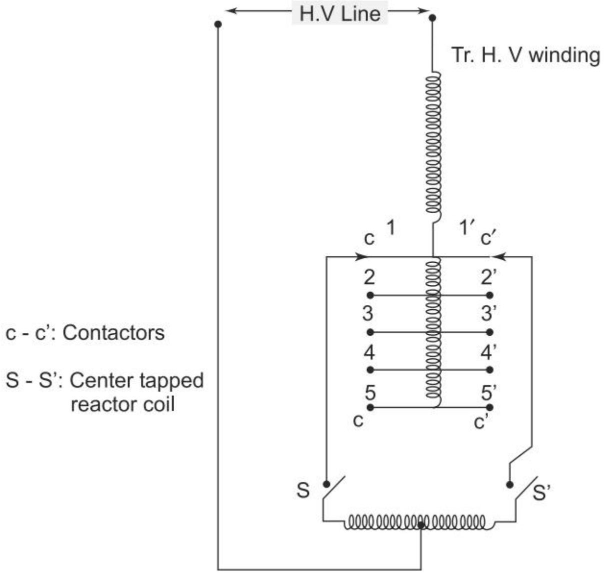


Fig. 12.3 *Transformer tap changer*

When the tap is changed on no load, the circuit is disconnected and large current is to be interrupted without breaking the circuit or short circuiting the winding. For this, a single winding (another coil) with a centre tap is connected at the conductors 1, 1′ etc., shown in Fig. 12.3 and the connection and transfer of tapping is done through it. It is desired to change the tapping 1-1′ to 2-2′. The switches S and *S*′ are closed with contactor *C*-*C*′ on 1 and 1′. The operation of tap changer is as follows.

(a) First *S* is opened and contactors *C* is moved from tapping 1 to 2. The circuit is closed through 1′- *C*′-*S*′ and reactor coil.

(b) *S* is closed and *S*′ is open. This means that circuit is closed through 2 – S – C′ and reactor coil.

(c) C^1 is moved to 2^1 and *S*′ is closed. The contactors *C* and *C*′ are now on 2 and 2′ with *S* and *S*′ closed.

The additional equipment fitted for on-load tap changer are

(i) Transformer winding with required tapping points on the high-voltage side
(ii) Center-tapping reactor
(iii) Two tapping switches
(iv) Two contactors or CBS
(v) Opening and closing mechanism with timing schemes for opening in a sequential manner

A better and simplified arrangement for sequential operation with movable contactor and switches is shown is Fig. 12.4.

The tap changer movable contactor is at step 5 and let it be required to be changed to position ‘4’. The switch of the contactor will be initially closed at position 5 and open at position 4. Then the switch is closed to position 4. This makes tap position 5 and 4 short circuited. But the impedance of moving contactor is such that the short-circuit current flowing and the load current put together are not too high. Next the contactor switch at position 5 will be opened. Thus the contactor is now shifted to position completely. The intermediate shorting between 5 and 4 is necessary to see that load current is not disrupted and is maintained without break.

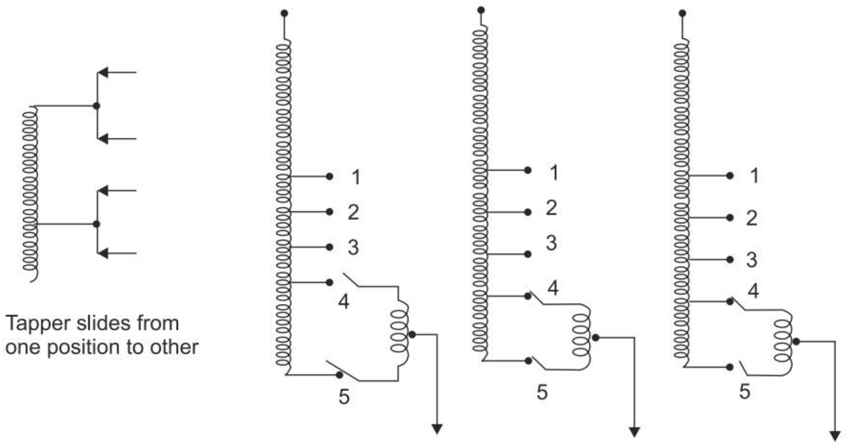


Fig. 12.4 *Tap changing with reactor coil. Tap shifted from position 5 to 4*

12.2.3 Step Voltage Regulator

A step voltage regulator is an auto transformer with a load tap changer. The voltage rise or lowering is obtained by changing the tappings of the series winding connected with the autotransformer. The arrangement is shown in Fig. 12.5.

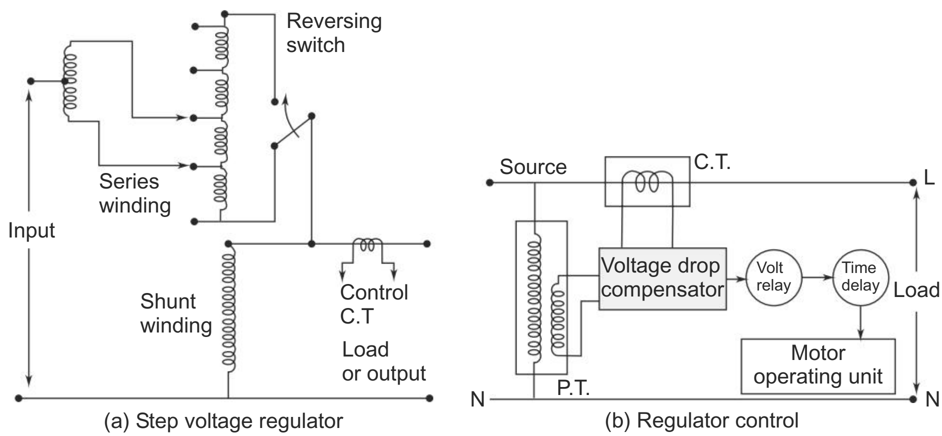


Fig. 12.5 *Voltage step regulator and its regulator unit*

The series regulator is provided with approximately 30 to 32 steps for voltage boost or buck. Each step will be about 0.5% of the nominal phase voltage and total variation obtained will be about ±10%. The desired voltage is set and the output terminal of the regulator is controlled locally or at a remote place.

The regulator control unit will have CT and PT to sense the line voltage and current. These signals are fed to the line voltage drop compensator. The allowable variation in the load voltage is obtained from the voltage set level (say at 235 volts for a 230-V single phase system). A time delay is set to disallow any transient voltage variations and also allows time for the tap changer operation times. The line drop compensator computes the voltage drop that can occur in the line due to load current at that p.f and corrects for the voltage drop.

After the time delay if the voltage deviation is more than the set value, the motor control (operating unit) gets signal which will move the auto transformer tap to the next position and also operates the reversing switch forward for boost and backward for back (lowering) operation.

12.2.4 Line Drop Compensator

When load current flows through feeder lines voltage drop occurs in the line resistance and reactance. As the current varies, the voltage drop also varies. In order to keep load end voltage constant, voltage proportional to (IR) and (IX) are injected into the line with the circuit energized by current from the secondary of CT. A simplified diagram of the arrangement is shown in Fig. 12.6.

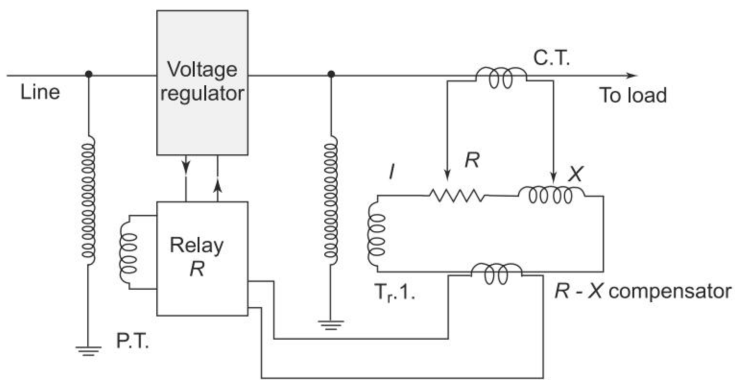


Fig. 12.6 *Line drop compensator*

The voltage regulator shown may be an induction regular or 'ON' load tap changer of the supply transformer etc. The line conditions, i.e., voltage and current are sensed by PT and CTs. When the voltage is too low or high the relay operates and closes the circuit of the relay *R*. The load current is sensed through the CT and adjustment for (IR drop) and (IX) drop is controlled by the *R* and *X* provided. Transformer 1 gives supply to the compensator circuit. The relay which is a differential relay actuated by *R*-*X* compensator and restrained by P.T., operates the voltage regulator. The incoming supply voltage plus the line voltage drop is balanced against the regulator output voltage and thus necessary compensation for voltage drop is given.

12.2.5 Voltage Boosters

A booster is device used to increase the voltage of a feeder line proportional to the load current. It is mainly used in such feeders as 'TRACTION' lines at a convenient point. A simplified diagram of the booster transformer for 'one phase' is given in Fig. 12.7.

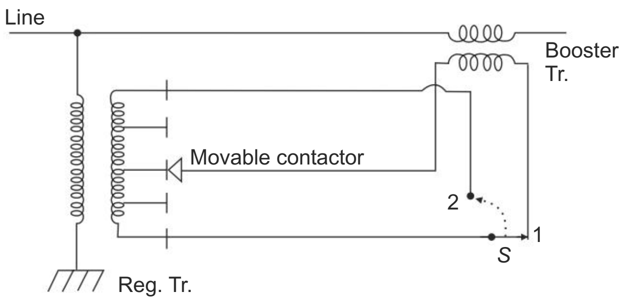


Fig. 12.7 *Line voltage booster*

Booster are small transformers, of output voltage rating, not more than about 3000 V. It consists of a main unit, the regulating transformer and booster unit, the primaries of both are connected in series like an auto transformer. The line voltage is sensed and fed to the regulating transformer. The secondary will be having taps and its voltage is fed to the booster. The switch (*S*) is closed to position 1 for normal boosting. When the voltage is to be changed, it is closed to position 2, contactor change is made and again put back to position 1. The voltage of booster transformer is added to the line voltage. The secondary of the regulating transformer is designed to withstand the short-circuit while tap position is changed. The advantage are

(a) it is separate from the source transformer and hence can be put at any point on the feeder
(b) it can be isolated from the supply without interrupting the main feeder for maintenance
(c) it is simple, reliable and can be worked with any feeder, but regulating transformer and booster are more expensive than a transformer with tap-changing unit.

12.3 DISTRIBUTION PLANNING

Distribution system planning is a difficult and important task in power planning schemes. It has to go in line with growth of population, industrial growth and master plan of a given area. It is also linked with state or country power growth plans. Planning process involves

(a) feasibility studies regarding, power available, financial and other resources and alternate schemes
(b) the immediate, short-term and long-term requirements
(c) formulation, policies adopted, regulatory measures, acts and other legal implications
(d) technical aspects

The technical and basic principles are

(a) the generating stations and transport of power (bulk) to the area concerned and cost per kw or kw hour

(b) losses and voltage regulation
(c) substation locations, land acquisition
(d) labour, material and equipment cost
(e) energy management, billing, market selection, alternate sources, bilateral contracts, etc.

The planning is normally done such that minimum or least amount is spent for either a new system or expansion of the existing system, sometimes this results in higher losses, poor voltage profile, frequent failure of supply and no scope for future expansion. A better method of distribution planning is to

(i) reduce the losses and improve the voltage regulation and go for cost-effective planning, this is sometimes referred as conservation of energy program. Energy saved is energy generated
(ii) redistribution of power demands, load shifting and improved management techniques
(iii) going for demand side planning, i.e., conducting cost effective screening, going for efficiency measures, go in for evaluating programmes, etc.
(iv) economical apprisal of alternate plans, using load research facility to identify customer loading, research facility to identity customer loading requirements and load duration demands, etc.
(v) taking into account demographic aspects and factors

Technical Planning

The technical planning involves determination of optimum sizes and expansion possibilities for

(i) substation locations
(ii) transformer and its associate equipment, their sizes and ratings
(iii) feeder sizes, number, routes to supply the given loads
(iv) system development : sub transmission level (132 kV, etc.) to L.T (400 V – 415 V) level
(v) service area identification
(vi) consideration of alternate sources of energy like solar, wind power, micro hydel generation (on existing canals, etc.)

To conclude, a proper distribution network planning and implementation for both short-term and long-term will save lot of energy and costs and will be reduce the energy deficiency experiences today.

12.4 DISTRIBUTION AUTOMATION

Distribution automation is control aspect in power system with large and complex power network. The system requires most efficient transmission and distribution (T & D) of electric power. It includes control supervision, monitoring and protection of the system. Further load management and remote metering and control is required.

Distribution automation is a diverse topic and depends on the particular utilities. In India most of the distribution system is within the state electricity authorities or their distribution companies. The distribution automation has come up due to

(i) introduction of new technologies in the areas of communication, PLC, RTU and computer systems
(ii) introduction of microprocessor based and computer-based controls
(iii) strategic benefits due to better planning from better information, optimization of capital expenses, reduced outage times, elimination or reduction of labour charges, human errors and manual controls, etc.

In understanding distribution automation focus is on preceeding information regarding various alternatives available to engineers for an electrical concern. Automating distribution system is highly desirable but can not be accepted and attainable due to

(i) size and magnitude of the distribution system infrastructure and facilities
(ii) cost of communicating and control establishments needed.
(iii) the local and central control establishments needed.

The elements of distribution automation are broadly divided as

(i) SCADA
(ii) DMS (data management system and applications)
(iii) TMS (trouble management applications), all the above require computer services and application servers

The data required for distribution automation is

(i) all electrical parameters, i.e., voltage, current, power, p.f energy, frequency, etc.
(ii) equipment operation condition like transformer or substation load, inflow, outflow, feeder loadings, etc.
(iii) service conditions like number of feeders in service, routing of power, failure or other wise of equipments, etc.

This information is usually obtained from SCADA. (the supervisory control and data aquisition system). DAC (distribution automation and control) supervises and oversees the system including loads. The aim of this complex procedure is to

(i) improve overall efficiency, reduce losses and hence save capital and energy
(ii) reduce the reserve requirements or utilize the existing source to the best. The second feature is India's present requirement
(iii) to increase the reliability of the power system and power distribution

Distribution automation is done using a computer system and requires several hardware, software and communication systems. Consumer information and metering should also form as a integral part. Several factors that are to be integrated into distribution automation are

(i) peak loading and peak demand pricing; this involves premium rate to customers who require power at that time and is not done in India
(ii) load-shedding or power cuts : proper scheduling, and dropping and switching off certain unimportant loads or limiting them
(iii) load reconfiguration and rerouting – this is a part of load despatch units and allows for relief at peak loads
(iv) load switching and load management – this involves direct control of loads from remote points. It requires remote control of substations and load centres
(v) transformer load management (TLM), feeder load management (FLM) and reactive power control – this is a part of substation control but done from remote points

Apart from the above, several other factors and data pertaining to them have to be fed to the distribution automation control (DAC) centres.

12.4.1 SCADA (Supervisory Control and Data Acquisition)

SCADA is a computing and communication system which collects the necessary information regarding the entire distribution system. It can be implemented for a substation, group of substations and feeders or for the entire electric power system.

At every substation or load points, the required data, i.e., voltage level, current, power, kVA, pf frequency, power flow direction etc. are sensed or measured and converted into digital or analog data. The data is stored in computer system on line continuously and sent to the controlling centre. A work station installed at the 'SCADA' centre collects and computes the data. The system involves computers connected in WAN (wide area network) servers for the particular stations, communication (power line carrier or optical fibre) system along with other peripherals, I.O. devices, etc.

The work station or supervisory control computes the necessary information and gives direction for operations such as load flow pattern, capacitor inclusion or switching off as the load changes, instructs for load shedding, rescheduling of loading in case of feeder failures, transformer failure/maintenance etc. SCADA is now implemented in many transmission and distribution system but supervisory control is not automatic in India.

SCADA technology consists of (i) a control centre with (a) server workstations, high end PCS, operating system (b) fault redundant computing and application knowledge, and (c) graphic user interface for display and interaction. The work stations operate through a communication network that may consist of a microwave link, optical fibre leased lines or may be a wireless system of UHF, VHF or VSAT mode. Since the information or data relating to the system is needed, it is obtained through field devices. The instrumentation and field devices consists of transducers and sensors like PTS, CTS i.e., relays, which pickup the required quantities in electrical form (voltages) and the signals obtained are processes through a signal conditioning unit through the Remote Terminal Units (RTU) to the work station. The SCADA server maintains the data sent by the remote terminals (RTU) and application server provides for the specific analysis of the data. The specific application may be for contingency analysis, optimal power flow through the feeders, short-term load force casting, voltage-reactive power optimization, etc. In distribution system applications, it is used for

(i) load management like load shedding, scheduling power cuts, etc
(ii) remote metering
(iii) load survey and energy accounting
(iv) fault localization and load balancing
(v) trouble call management service (TMS), etc.

Schematic diagram of SCADA and its arrangement in distribution control centres is shown in figures of SCADA. (Fig. 12.8 and Fig. 12.9).

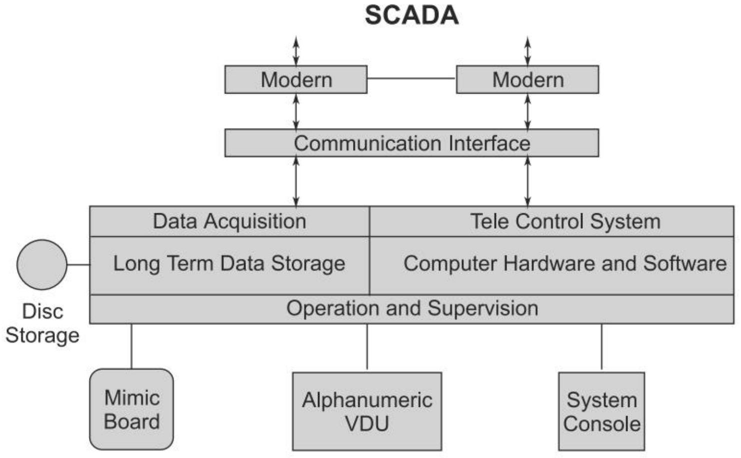


Fig. 12.8 Distribution SCADA: Block diagram

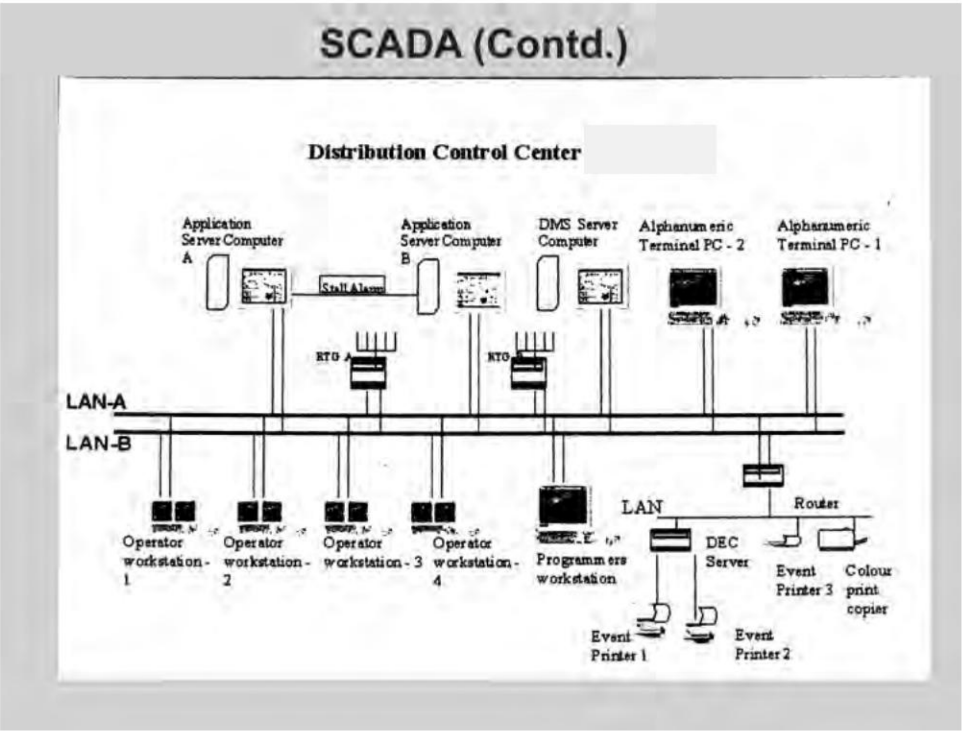


Fig. 12.9 SCADA for Distribution control centre

12.4.2 Distribution SCADA

The distribution SCADA system primary function is to support distribution telemetry operations, giving alarms when need, event recording and remote control of the field equipment. The main elements in the system are

(i) host equipment comprising of host server network based communication front end nodes, graphic user interfaces and rational data base servers

(ii) communication infrastructure comprising of serial communication to field devices like copper wire cables, fibre, radio links or telephone circuits. The coverage area can be typically 30 to 40 km and be effective from remote point to field points

(iii) field devices are a broad range of control and operating devices and include such devices that provide (a) record for power quality, (b) fault detection, and (c) status indicating sensors, they provide real-time data for both day to day operations and also for system planning and future expansion

A TMS application gives the prediction and analysis for call made or trouble indicated. It provides for (a) case management, (b) maintenance or service crew arrangement and management, (c) customer callbacks, and (d) accounting and reports.

12.4.3 Analog Data Acquisition

For automation purpose the distribution substation has to aquire power system performance parameters such as voltage, current power in watts, reactive power 'VARS' the transmission or distribution lines (parameters) transformer banks, buses, feeder lines, energy input and output (usage) in kW hour and KVA hours. A few other parameters like temperature of transformers, gas pressure in CBS, transformer tap positions etc. are also to be sensed and transmitted as analog data. These values are entered into the substation automation data through IEDS transducers and other sensors. All the transducers, sensors etc. are provided in the power equipment itself along with proper instrument transformers, The output of these sensors will be AC or DC voltages or currents and may be converted into digital values which can be accepted by a SCADA RTU or SA controller.

The economy of the data acquisition system (DAC) lies in weighing the cost of the DAC against the data quality and the service automation to suit the particular job. The overall accuracy of the measured quantities is affected by a number of factors like, instrument transformer errors. IED or transducer performance, A/D conversion. The accuracy of the system is not readily predicable. Significant measuring errors occur which are to be corrected or compensated. High accuracy metering involves ±0.25% or better accuracy for 'IED' and transducers, but usually will be better then ±1%. When substation automation provides information for telemetry purpose many of the above said elements have less accuracy and overall error under these conditions for the entire system will be 2 to 3% for voltage, current and power (watts) and less than 5% for reactive power and p.f.

IEDS (Intelligent Electronic Devices) as Analog Data Sources

IED is a device that incorporates one or more processors with capability to receive or send data from or to an external source or device. Nowadays electronic meters are used for measurements and hence regulators and reclosures even form as data sources. IED measurements are directly converted into digital forms. In order to use an IED it is required to assure that the performance characteristics fit into the requirements of the system. Usually they do not have low load (low value < 0.1 of full scale) accuracy overload capacity and sufficient resolution capability. Sometimes they do not meet the measuring standards set for distribution automation system.

Status Monitoring

This is required for power circuit breaker position, switches, reclosures, motor operated and remote controlled disconnect switches and other ON – OFF functions in a substation. Hence "STATUS " points are to be provided with status memory (for changes) for in between scans time scheduling sequence of events (like fault initiation, breaker operating, disconnect switch opening etc.) interposing relay contacts may also be used for this purpose.

Control functions Supervisory control function provide both for emergency switching and routine operation capability for all equipment. This is provided for CBS, reclosures, voltage regulators etc. but difficulties occur when an equipment like a transformer is changed. Usually provision is made for both momentary timed control outputs and latching type with blocking of certain operations (auto reclosing of breakers, etc.)

12.4.4 Distribution Automation and Control

Objective

(i) effective control and management of distribution system with reduced staff
(ii) reduced outages, service restoration time and line losses
(iii) low voltage (voltage sag) problems and reactive power management, better voltage management and quality of power
(iv) improved revenue collection

The distribution automation data consists of continues analog data from feeders, transformers, etc., such as (i) electrical parameter data, (viz.), voltage, current p.f., frequency power (MW, MVA, MVAR) and (ii) non-electrical parameters like oil temperature, winding temperature, CB gas or oil pressure in the tank, etc., other data like 'CB' positions, isolator and load break switch status. Transformer tap position will be in digital form and data regarding total units (MW Hr, MVA Hr) can form accumulated data. Display of a few of them in graphic mode will also be done, (viz.), real-time values of the above may be displaced and a few abnormalities may be notified by alarms.

Distribution automation applications will be for

(i) load management for assisting the supervision or operators for load control, scheduled power cuts, emergency load shedding, etc
(ii) for load relief requirements at substations sensing under frequency and give load shedding based on under frequency
(iii) reactive power management for controlling switching on or off the capacitor banks, transformer tap changing and to improve voltage profile
(iv) trouble call management for received complaints, register them and pass on to the maintenance/ trouble management crew
(v) remote metering like customer meter reading check for multiple tariff and detect meter tampering and theft
(vi) generating reports and giving auto metering, mapping of dynamic information, scrolling and pausing and provide historical data on the devices and equipment.
(vii) facilitate energy auditing at substation feeder and distribution transformer level. Determining high loss areas, under and non-billing areas and non-accounting areas. Calculating technical and commercial losses for all levels of the network

(viii) data acquisition from various sources like consumer billing, spot billing or PDA. Schematic arrangement of distribution system management is shown in Fig. 12.10 and 12.11

Some of the benefits of distribution automation are

(i) compilation of accurate data for analysis and future planning
(ii) facility for better voltage, reactive power and quality of power and their management
(iii) improved revenue collection
(iv) effective and efficient monitoring of system
(v) quick fault localization, service restoration and redressal for consumer complaints
(vi) faster decision making

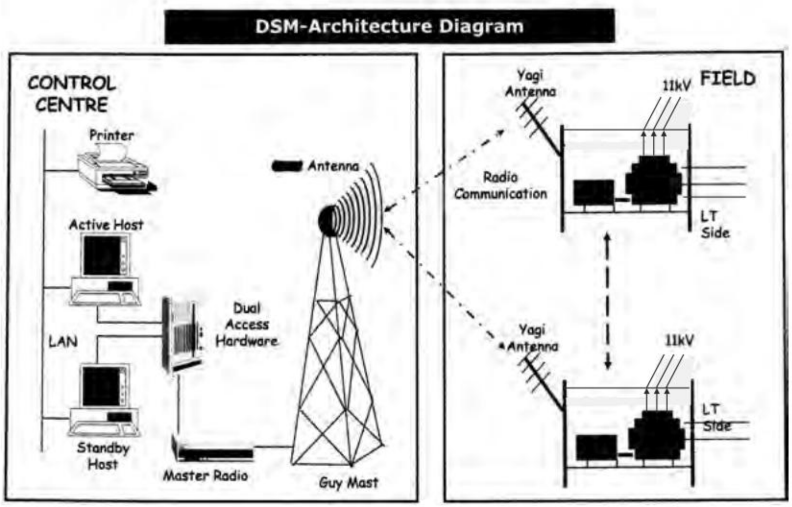


Fig. 12.10 Distribution system management

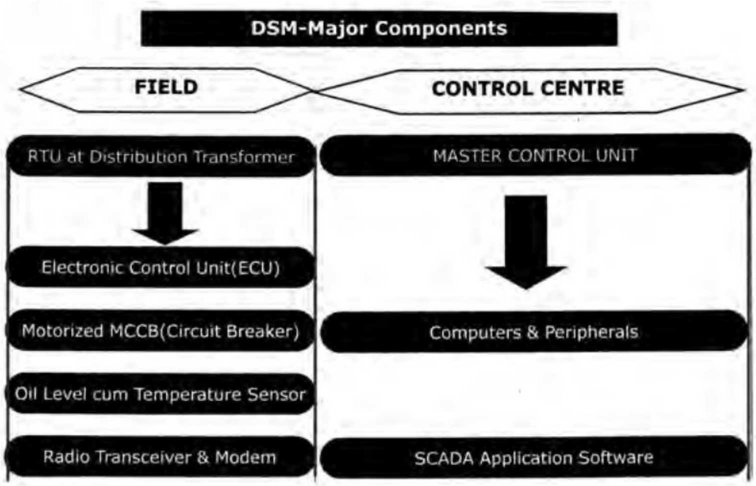


Fig. 12.11 Distribution system management block diagram major components

12.4.5 Substation Automation

This may be defined as deployment of all substation and feeder operating functions and applications ranging from SCADA, alarm processing, operation and maintenances, management of capital assets and optimize them. In a “open” system each function is done separately and manually co-ordinated by authorities concerned. Substation automation employs a “computer system” which performs the above operations automatically, thus minimising the manpower and mechanical control and operations. There are many and several levels over which the operations are done. As mentioned in Section 12.4.2, the system contains the following:

MBC – metering, billing, collection management is shown in Figures 12.12 and 12.13.

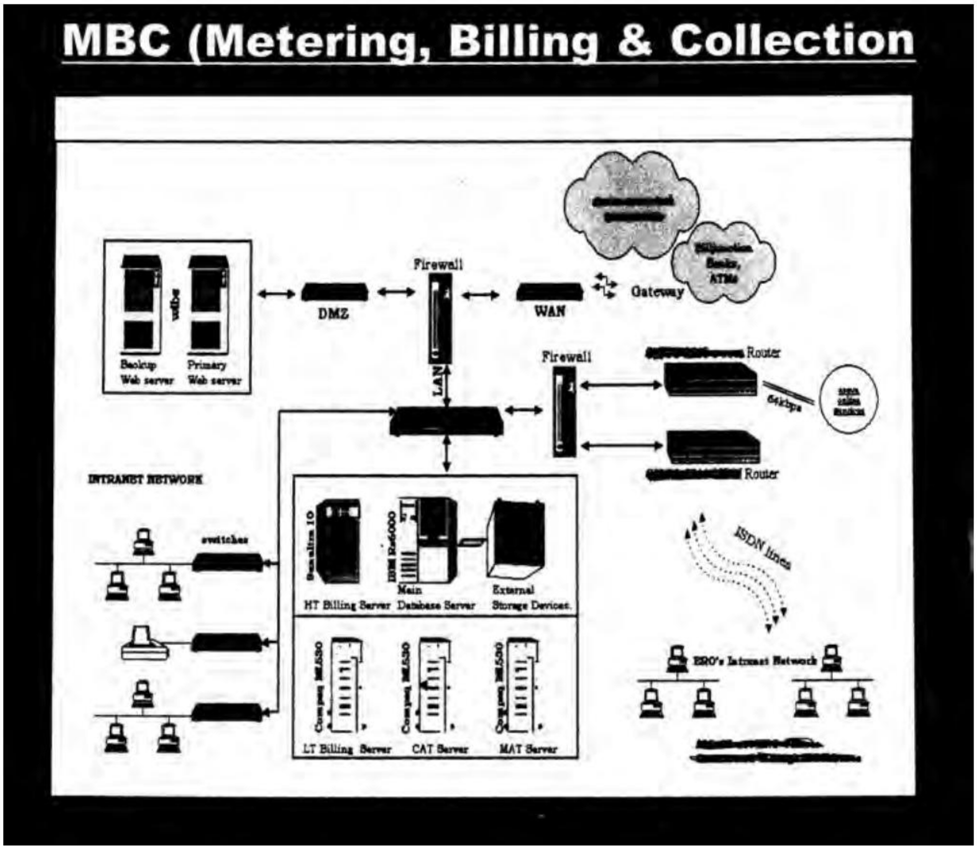


Fig. 12.12 *Automatic billing and metering*

Fig. 12.13 *Automatic billing unit (hand set)*

(i) *Field devices* This provides the data and sequence of events. The data is typically stored in a FIFO queue and record maintained.

(ii) *Data concentrator* This pools and arranges for analog values and status changes at fixed intervals typically 2 to 10 seconds. This is a local data base.

(iii) *Data warehouse* All data required for operational purpose will the communicated to the SCADA system via communication links (mentioned in Section 12.4.2). Other data required for non operational purpose is stored in data warehouse. This is necessary to support a main frame or client-server architecture between the system and corporate users over a WAN.

(iv) *Substation host processor* This is a computer system based on industrial standards and will have networking ability to support open architecture. An industrial accepted type data base (RDB) with SQL capability is provided. A full graphic user interface should also be provided. The substation host processor should be flexible, expandable and transportable to other platforms like PCS, etc.

(v) *Substation local area network* The substation should have a LAN that is applicable to the environment, incorporating substation noise immunity, isolation and interfacing capability to process-level equipment. The LAN should support peer to peer communication capability for high speed protection functions, file transfer supports for IEDS and PLCS.

(vi) *User interface* The substation system must have interfacing devices to ensure effective use of the system with minimal confusion. An efficient and precise display hierarchy is essential with as few displays as possible. There should be a common look-feel established in all displays.

In addition to the above the substation automation should and is to be effectively connected to the control DAC (Distribution Automation and Control) that controls all the substations, transmission and feeder lines and loads. Schematic distribution automation system is shown in Fig. 12.15

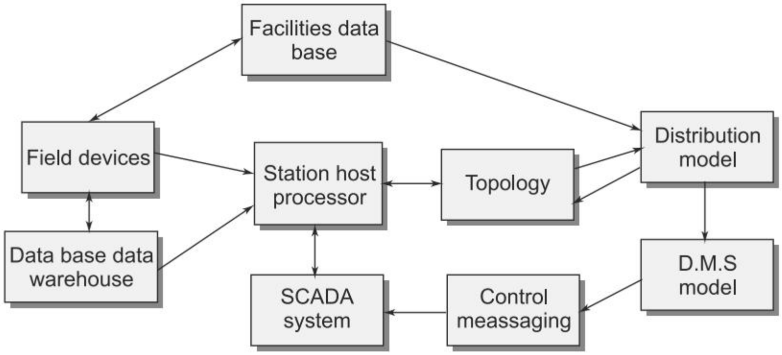


Fig. 12.15 *DMS platform with SCADA*

Data management system (DMS) applications give

(i) state estimation
(ii) load flows
(iii) fault isolation and service restoring
(iv) voltage and reactive power management
(v) energy saving and loss reduction

The substation automation consists of monitoring and measurement of parameters and condition of different equipment in the substation and control the equipment. The apparatus usually seen are (i) incoming and outgoing feeders, (ii) CBS, isolators other switches and relays, (iii) transformers, (iv) capacitor banks. The information and control is obtained through (a) IEDS / RTUS (b) field transducers and relays (c) communication equipment (d) front end processors / MMIS and high-speed LAN and data storage servers. Equipment status, power flow parameters, current and past events, real-time trend, safely interlocking is continuously observed and controlled.

The typical benefits obtained as reported in international and national reports are

(i) reduction in losses and maintenance ≈ 5%
(ii) reduced tripping and customer ≈ 10% outages
(iii) new construction costs, equipment ≈ 25 to 30% costs and capital expenditure

12.5 DISTRIBUTION OPTIMIZATION

Optimization of any equipment or system is to minimize the cost, save power and energy and give the best possible design or operation taking into account CERTAIN CONSTAINTS AND RESTRICTIONS. Here the capacity of the system, operating cost and utilization should be best for given real conditions existing. Optimization in distribution system involves the following technical and economic aspects.

(i) Selection of Voltage Levels

The number of voltage levels and upgrading to higher levels : This involves the power demand, load density, area to be covered. A large city or industrial belt can have a load density of 10 MVA/km^2, while a rural area can have only 100 kVA/km^2. Further the site available for substations, route, etc., may also be a constraint. The choice goes between adopting standard voltage levels like 6.6 kV, 11-kV or 33-kV etc. or plan for new level if it is cost effective. The usual thumb rules are shown in Table 12.1.

Table 12.1 Voltage level for different loads

Load	*≤ 100 kVA*	*100 kVA to 1 MVA*	*1 to 5 MVA*	*> 10 MVA*
Voltage Level	400 V	11 kV	33 kV	132 or 220 kV

But selection of voltage level is to be done based on other parameters like feeder length and load location.

(ii) Lines, Transformers and Substations

Section of transformer and its rating, feeder lines and substation involve the following parameters.

(i) Cost of equipment and installation
(ii) Maintenance costs
(iii) Other recurring costs like salaries, repair costs, etc.
(iv) Future load increase and expansion

Cost economics is worked out between the standard ratings available and going for higher ratings than required taking into account for expansion.

(iii) Feeder Networks

Optimum number of feeder lines conductor size, main feeder length, lateral feeders, voltage regulation and power losses are the factors that are to considered. Initial optimization may start with the existing lines or from a sub transmission network. Synthesis of optimum line network is the usual problem solved taking all factors into account.

(iv) Economic Loading of Transformers and Distribution Lines

The life of power transformers and feeder lines depends on the loading pattern, temperature rise and insulation conditions. Hence overloading will give rise to early failures, where as under loading makes them uneconomical from revenue point.

Hence a optimal loading pattern should be decided using the usual methods and techniques.

There are other aspects like overall operating cost minimization, worst case loading management etc. in distribution optimization.

To conclude, distribution system planning, operation, maintenance and control is the heart of power system. If this is weak and unhealthy, poor performance and unsatisfactory operation will result in.

Example 12.1 *A 33-kV / 11- kV 5 MVA substation has two 3 MVA transformers with impedance 0.025 + j0.06 p.u. There are four feeder lines of length 15 km each with uniformly distributed load of 50 kVA / km and a concentrated load of 0.5 MVA at feeder end. If the voltage is to be maintained at 11-kV at feeder end. (i) What is the voltage boost needed at substation? (ii) The transformer has taps of 2% of normal voltage. What is the tap setting to be used? Line impedance is 0.8 + j0.6 Ω/km and load p.f may be taken as 0.8 lag. (Fig. 12.1)*

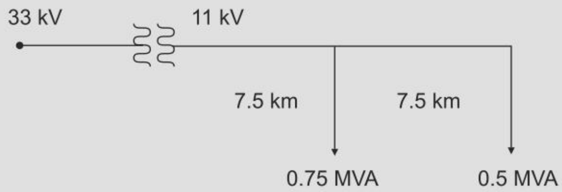


Fig. Q. 12.1

Solution

Uniformly distributed load on feeders = 50 × 15 = 750 kVA and is taken at the middle of line.

Total line impedance = 15 (0.8 + j0.6) = 12 + j9 Ω

$$\text{current for 0.75 MVA load is } = \left(\frac{0\cdot 75\times 10^3}{\sqrt{3}\times 11}\right) = 39.4 \text{ A}$$

$$\text{current for 0.50 MVA load is } = \left(\frac{0\cdot 5\times 10^3}{\sqrt{3}\times 11}\right) = 26.2 \text{ A}$$

Assuming two feeders are connected to each transformer load on each one is 2 × (0.75 + 0.5) = 3 MVA

$$\therefore \quad \text{current of each transformer } = \left(\frac{0\cdot 3\times 10^3}{\sqrt{3}\times 11}\right) = 131.28 \text{ A}$$

Impedance of each transformer, taking Y connection per phase is

$$\text{p.u. } = \frac{11}{\sqrt{3}}\times\frac{1}{131\cdot 28}\times 10^3 = \frac{19\cdot 05}{131\cdot 28}\times 10^3 \approx 48\cdot 4\Omega$$

Transformer impedance = 48.4 (0.025 + j0.06) = 1.21 + j2.9

Voltage drop in transformer

$$= I\,(R\cos\theta + X\sin\theta) = 131.28\,(1.21\times 0.8 + 2.9\times 0.6) = 355.5 \text{ V}$$

Since the p.f is the same for both loads

Voltage drop up to 0.75 MVA load (1/2 line length) = 65.6 (6 × 0.8 + 4.5 × 0.6) = 492 V

Voltage drop in rest of the line 26.2 (6 × 0.8 + 4.5 × 0.6) = 196.5 V

Voltage drop in line 492 + 196.5 = 688.5 V / ph

Total voltage drop= 355.5 + 492 + 196.5 = 1044 V / ph

(i) Voltage to be maintained at transformer end = (11,000 + $\sqrt{3}\times$ 688.5) = 12192.5 V.
Voltage boost needed for line (688.5) $\sqrt{3}$ = 1192 V

(ii) Transformer tap is 2% = 0.02 × 11000/ $\sqrt{3}$ = 127 V

Tap position needed to take into account transformer voltage drop = 1044 / 127 = 8.2 or 8th tap

Voltage at that position = (11000 / $\sqrt{3}$ + 8 × 127) $\sqrt{3}$ = 12760 V.

Summary

In this chapter, the voltage control and regulating the feeder or supply voltage within the limits is discussed. The voltage regulating equipment such as induction regulators transformer tap changing and line voltage boosters are explained. Distribution automation, planning and SCADA are introduced.

Keywords

Voltage control
Voltage regulators
Induction regulator
Transformer tap changing
Line boosters
Distribution planning
SCADA
Data acquisition
Substation automation
Distribution optimization

Review Questions

1. What are the different methods for voltage control ? Briefly explain them.
2. Explain the use of Induction regulator in voltage control. Can it be used for large powers ?
3. What is a line drop compensator ? How is it used along with tap changer of transformer for voltage control ?
4. Explain the basic function of booster transformer? How does it increase the line voltage?
5. What are the various factors that affect the distribution system planning?
6. Discuss the objective of system planning. How does is distribution automation done?
7. What is SCADA ? How does it help for distribution automation?
8. Discuss the different components of distribution system that require optimization.
9. What is a step voltage regulator? Compare the step voltage regulators with other types used for voltage correction
10. Why is distribution automation needed? Discuss the different elements with their functional role in distribution automation.
11. A 33-kV / 11-kV substation has two 5 MVA transformers with (3.0 + j7.5)% impedance. There are four feeders, each of line length 12 km, with 100 kVA transformers connected at 1.5 km intervals (8 nos) and a concentrated load of 0.8 MVA at the line end. If the feeder (11-kV) line impedance is 0.5 + j0.3 Ω/km, what is the voltage boost needed to maintain 11-kV at feeder end? Take p.f of load as 0.8 lagging.
12. In the above problem, if one of the lines has a uniformly distributed load of 75 KVA / km and a concentrated load at 10 km from the substation. What is the tap setting to be set on the transformer, so that 11-kV is maintained at 10 km point. Transformer has tapping of 2%

Multiple Choice Questions

1. Voltage control means
   (a) boosting the feeder voltage
   (b) reducing the line voltage under overvoltage conditions
   (c) keeping the voltage level within the allowable limits
   (d) tap changing of transformation
2. Voltage spread is
   (a) difference between normalize voltage and actual voltage
   (b) difference between maximum voltage and minimum voltage over a period
   (c) difference between peak and rms values of voltage
   (d) none of the above
3. A 11-kV system has at its load end 10,300 V between lines. What is the voltage boost required to make the voltage within limits of nominal voltage (±5% limit)
   (a) 150 V (b) 700 V (c) 850 V (d) 1250 V
4. Line drop compensator corrects for
   (a) Line drop lagging p.f (b) voltage at leading p.f
   (c) transformer voltage drop (d) voltage drop in the feeder lines
5. Optimum loading for 33-kV line is
   (a) 1 to 5 MVA (b) less than 1 MVA (c) 5 to 10 MVA (d) more than 10 MVA
6. With step voltage regulator, voltage is
   (a) boosted (b) can be reduced
   (c) can be boosted or reduced in steps (d) can be boosted or reduced continuously
7. For a load of 750 kVA, the distribution line voltage choosen will be
   (a) 400 V (b) 6.6 kV or 11 kV
   (c) 11 kV or 33 kV (d) 33 kV or 132 kV
8. DATA acquisition from substation requires
   (a) host equipment (b) communication network and infrastructure
   (c) field devices (d) all the three in a, b and c
9. DAC is mainly meant for
   (a) data acquisition
   (b) automatic control
   (c) supervision and control of the distribution system including loads and substations
   (d) reducing revenue requirements and improve reliability
10. TMS in substation automation is
    (a) trouble management system
    (b) transformer management and supervision
    (c) total management system
    (d) all the above three (a, b and c)

Fill in the Blanks

11. Maximum voltage of a system is ______________.
12. Service voltage is ______________.
13. Most commonly used voltage control in substations is ______________.
14. DAC is meant for ______________.
15. Mention two important factors for distribution automation
16. With induction regulator the voltage can be ______________ or ______________.
17. Selection of voltage level for distribution network depends on ______________.
18. Field devices in SCADA are ______________.
19. TMS application provides for ______________.
20. Distribution optimization means ______________.

Answers

1. c	2. b	3. a	4. d
5. a	6. c	7. b	8. d
9. c	10. a		
11. and	12. Ref. definitions	13. Transformer tap changing	

14. Control, supervision and monitoring of distribution system
15. (i) Improve over all efficiency and reliability (ii) reduce reserve capacity
16. Boosted or reduced
17. Load density, power to be transmitted and feeder length
18. Sensors located to collect real time data
19. Case management and customer service
20. Minimization of costs, saving power and energy and giving best and most suitable designed service.

Appendix 1

Definitions and terminology in distribution systems with brief explanations

AAC All Aluminium Conductor, does not contain any steel wire (core). High grade and higher Strength conductors are called AAAC (All Aluminium Alloy Conductor)

ACSR Aluminium Conductor with Steel reinforcement. Normally used for long spans, Contains Steel strands as core over which Aluminium conductors are spun as several Layers. Ex 37/.118 conductor has 1 + 6 conductors of Steel as Central Core over which 12 + 18 aluminium conductors are used in two Layers. Diameter of the aluminium conductor is .118 cm

A C B Air Circuit Breaker, It Interupts the current in air as medium.

Air Switch Make and Break Switch is air medium. Can be used for closing or opening of circuit

Arcuing Time (of Fuse) Time taken form the instant the Fuse starts burning to the final interruption of **Base Load** (Minimum load) on the System over a given interval of time (15 min, 30 min,etc.).

BIL Basic Impulse level. The minium withstand Voltage of an Apparatus or equipment (rated for particular system voltage) for 1.2/50 Impulse Wave (Lightning) for Eg: for 132 kV System, it is 650 kV,

Breakdown Disruptive or flashover through an insulation medium

Bus A conductor or a group of conductors that serves as a common connection to more than one circuit in switch gear or transformer assembly

Cable An insulated conductor with either solid or stranded conductors. It can have one or more insulated conductors again covered with insulation and protective cover. Conductor is usually called core, 3 core conductor refers to 3 insulated conductors in the cable

Capability Maximum current carrying capacity or load expressed in kVA or MVA under specified ambient and working conditions

Capacitor Bank Location of a number of capacitors in one unit with a given inter connection, eg: for a 3 phase unit, sometimes it refers to complete installation including protective gear and switching units.

Capacity Factor The ratio of average load to rated value of the apparatus, equipment, etc, over a given period of time or interval

Circuit Breaker A device that interupts the circuit under fault or abnormal condition without damage to itself or to the components of the circuit

Coincidence Factor The ratio of maximum coincident total demand of a group of loads consumers, etc, to the sum of individual maximum demand, both taking supply from same source and at the same time

Coincident Demand Any demand that occurs simultaneously with other demands

Condenser Another term for capacitor

Conductor A wire, or device that allows free flow of electrons or other charge carriers. It permits flow of current when a potential difference is applied across it

Contactor A power switch designed for frequent operation and is not operated manually

Contracted Demand The load or demand a consumer agrees to take from the supply authorities

CT Current transformer, a device used in power circuits to isolate from the supply potential and give a low output proportional to the current in the main circuit

DAC Distribution automation and control, it is a computer and control system installed to have supervisory control and display of the entire distribution system

DMS Distribution management system: An advancement of DAC which will also collect data, calls from customers, analyses and presents to the service personal to rectify the same. Sometimes this term is meant for Data management system also

Demand Load (power in kw or kVA) at the receiving or consumer terminal over a given or specified time.

Demand Factor Ratio of maximum coincident demand to the total connected load of the system.

Demand Interval The time period over which the electrical supply (energy) is summed up or integrated for dermining the demand

Disconnect (Isolator) Switch A mechanical device that isolates or switches off the equipment from power supply

Disconnecter *A.* switch intended to be operated only after a load is switched off, i.e, under no load condition for isolating the equipment from supply source and to provide a safe means for open circuiting.

Distribution System The part of the electric supply system which delivers power or energy from Tansformation (transformer) point / bulk power station to the consumers or utilities

Distribution Transformer Transformer used for transfer of energy from a distribution station to the utilities or consumer at service points. Usual ratings 10 to 500 kVA. Load on this can vary from zero to maximum rating. It will normally have low impedance, very low constant (core) losses and high energy efficiency.

Effective Ground Good connection to earth with low impedance. The Voltage built up under fault or short circuit to earth will not be dangerous to the equipment or personnel.

Electric System Loss Total energy wasted is the power system. It includes energy loss is lines. transformers and other equipment and also at all points in electric power system.

Feeder A set of power conductors originating from a substation or distribution centre and supplies power to other substations, distribution points and normally do not have a tapped load.

Fuse An over current protective device which melts and opens the circuit or equipment that is protected. It is a thermal device, a wire or other material with low melting temperature.

Fuse Cutout An assembly or holder that can house the fuse and support it.

Ground or Earth The connection between soil and electrical power equipment, frame or point to be maintained at zero potential.

Ground Wire A conductor with ground or earth connection at both ends and at regular intervals. It is also the zero potential wire run on the Transmission / Distribution poles over the live conductors to shield them from lightning.

Interruption Loss of power supply or service to the consumer. This is due to failure of one or more components in the system.

Lateral (Conductor) A wire, cable, or connection extending from feeder pole to service point. This may be a overhead conductor or an insulated cable.

Lightning Arrester (Surge Diverter) A device used in power system to reduce or divert the over voltage and current through it when a transient or surge appears. It is mainly used to protect against lightning. It automatically restores itself after the surge duration.

Line Drop Compensator A regulating device to regulate or correct the line voltage as the load increases. It compensates or adds for the voltage drop in the line due to its impedance.

Load Centre The point location at which the load of a given area in assumed to be concentrated or to exist.

Load Duratioin Curve The graph of load plotted in decreasing order of magnitude Vrs time - intervals of specified value or period.

Load Factor The ratio of average load to peak load occurring over a period.

Loss Factor The ratio of average power loss to peak load power loss during a period specified.

Maximum Demand The largest value of the particular type of load or demand occurring in a given specified time duration.

Maximum Demand The smallest value of the particular type of load or demand occurring in a given specified time duration.

Non-Coincident Demand sum of all the individual demands regardless of time of occurrence during a specified period of time.

Normal Rating Capacity of the equipment or apparatus connected to the supply.

Outage The state of component when it is not available for operation / (usage) of its purpose due to an event that occurred to the component. An outage may or may not cause disconnection of power supply. An outage of transformer may result in cut off of the supply.

Outage Duration The period over which an equipment is out of service from the initiation of outage till it is connected to perform its duty.

Outage Rate The average number of times a component / equipment is out of service per unit exposure of time per component.

Over Load The loading in excess of the rated value, for example, for a 10A rated motor 11 A is an over load.

Overload Protection Interruption of the current in excess of the rating or demand (current), provided by a device meant for it. It can also bring back or reduce the excess current by switching off of the faulted portion.

Peak Current The maximum value of the current (in A.C. it is the maximum of the sine wave).

Percent Voltage drop(%**VD**) The ratio of value of voltage drop in a circuit (net work) to that of voltage available at that location expressed as percentage.

Phase Angle Phase difference between two quantities (voltage and current, or two voltage values etc.) expressed in angular form.

Primary Feeder feeder or line operating at the voltage level of the primary distribution system. It is the portion of conductor system between point of supply and centre of distribution system.

Primary Distribution Network The circuit or network portion of the system consisting of the primary mains. The supply system,i e, the MAIN portion distribution network from subtransmission substation or genarating station to the primary side of distribution transformers.

Protective relays The device that detects an abnormal condition / defective condition of lines, apparatus or any device which may be dangerous or other wise and intiate control on that portion of the circuit.

Power The Rate at which energy is transformed or consumed (watts or kWs).

Power Factor Ratio of active (real) power to apperent power (product of V & I) in AC system.

Power transformer transformer that transfers electrical power from generating station, transmission system to the distribution network. It is usually loaded nearer to its full capacity, has more percentage or per unit impedance and core losses comparatively than distribution transformers. The maximum power efficiency will be at load of 75 to 100% of its full load rating.

P.T (Potential Transformer) Used as a measuring device for voltage. It reduces the line value to (110 V or 220 V) for measurement and gives isolation between supply lines and meters.

PU Per unit value

Radial .System It consists of single transmission circuit, a single substation, and a single distribution line to each load. There may be several single lines supplying the loads. A radial distribution system is one which has several single simultaneous lines or paths for power flow to the loads.

Recloser A timing device which can be set to act fast to prevent down line protective devices like fuses from blowing.

Recloser Device A control device that initiates reclosing of the circuit after it (Switch) is opened by a relay.

Recloser Fuse A combination of two or more fusing devices or links, inter locked so that one only can be connected into the circuit at a time. The function of that fuse is to automatically connect the next one into the circuit permitting the restoration of the supply without manual replacement.

Recloser The automatic closing of the circuit breaking device following a tripping. It may be instantaneous or with time delay, single time or multiple operation as has been set.

SCADA Supervisory Control and Data Acquisition system installed in distribution system to sense all parameters and collect data.

Secondary Feeder A feeder operating at the secondary voltage level of the distribution network.

Secondary Network A network or portion of supply system connected to the secondary side of distribution transformers and the consumer service mains or points. In supply systems in India it may be the low voltage (400V) or 6.6 kV or 11 kV network supplying loads.

Secondary Banking A system in which one or more transformers supplied from single primary feeder or distribution feeder, operated or connected in parallel through a secondary mains and supply the loads together.

Sectionlizer A device used in secondary distribution network similar to reclosers but does not have the circuit interrupting capacity. They may be oil insulated or other wise and operated manual or automatically. These are not used much in India.

Service Area The area or territory in which supply system is available to the consumers. These will be right for the concerns to supply electric power in that locality.

Stranded Conductors A conductor composing of a group of wires twisted together and arranged in a circular or any other geometry

Substation An arrangement or assembly of apparatus, equipment or devices for the purpose of transmission of electrical energy in large quantities for the purpose of switching or regulating it.

Switch A device for making or breaking or changing connection in a circuit.

Switch (isolating) secondary or auxiliary device for isolating the circuit after the circuit is opened. It is operated only after the circuit is opened or other wise.

Switch gear It is a combination of all switching devices, control devices, protective, metering and all associated equipmentmeant, for circuit interruption and closing.

Switching time The time period required to, from the instant the switching operation starts, till the circuit is closed or the switching is completed.

Voltage, Base A reference value which is used as common denominator to the nominal voltage ratings in Transmission and Distribution systems. '

Voltage, Maximum The greatest of the 5 minutes average value of the supply voltage.

Voltage, Minimum smallest of the 5 minute average value of the supply voltage.

Voltage, Nominal A value assigned to the system of a given voltage class for purpose of reference.

Voltage, Rated voltage at which the performance characteristics, normal operation of the equipment or apparatus is referred. Example: If a motor is rated at 400 V, the name plate, technical performance mentioned is referred at 400V.only and is not assured at 380 V or 410 V.

Voltage Dip A voltage change (reduction) that occurs due to starting of motor or other heavy loads.

Voltage, Service Voltage measured at the terminals of the equipment, machine etc. at the entrance point of supply

Voltage Drop The difference in voltage between the sending end and receiving end of a line, feeder or cable or service connection.

Voltage Regulation (The percentage voltage drop of line, transformer etc. with reference to the receiving end voltage.

$$\% \text{ regulation } = \left(\frac{|V_s| - |V_r|}{V_r}\right) \times 100$$

V_s = sending end voltage (Input)

V_r = Receiving end voltage (output)

In distribution systems, the nominal voltage 'V' is used in the denominator instead of V,

Voltage Regulator An induction or electronic device in shunt or parallel with the supply that is suitably adopted and arranged to control voltage, phase angle or both in the output or regulated circuit.

Voltage spread The difference between maximum and minimum voltage that occur in the system during a period.

Note: The definitions and explanations given are adopted from those given in different standards and not Legal. Explanation is added to certain terms.

Appendix 2

Representation of feeder lines with genaralised circuit constants (A, B, C, D parameters)

In distribution feeder analysis for computer studies, some times it is desirable to express line quantities interms of its generalised constants A, B, C, D.

Let the receiving end voltage = $V_r\underline{|0}$

current = $I_r\underline{|-\theta}$

and power = P_r

Let the corresponding sending end voltage = $V_s\underline{|\delta}$

and power = P_s

The matrix equation for the quantities mentioned is

$$\begin{matrix} V_s \\ I_s \end{matrix} \quad \begin{matrix} A & B \\ C & D \end{matrix} \qquad \text{...(A1)}$$

(i.e) $$V_s = AV_r + Bl_r \qquad \text{...(A2)}$$

Let $$A = A_1 + jA_2, B = B_1 + jB_2 \qquad \text{...(A3)}$$

and $$V_r = V_r + j0;\ I_r = I_r(\cos\theta - j\sin\theta) \qquad \text{...(A4)}$$

$$V_s = V_s\,[\cos\delta + j\sin\delta]$$

$$= (A_1 + jA_2)V_r + (B_1 + jB_2)(I_r)(\cos\theta - j\sin\theta)$$

equating real and *j* parts

$$V_s \cos\delta = A_1\, V_r + I_r[B_1 \cos\theta + B_2 \sin\theta] \qquad \text{...(A5)}$$

$$V_s \sin\delta = A_2\, V_r + I_r[B_2 \cos\theta - B_1 \sin\theta] \qquad \text{...(A6)}$$

V_s^2 is obtained by squaring and adding equations A5 and A6. ...(A7)

The receiving end power $P_r = V_r I_r \cos\theta$

reactive power $\quad Q_r = V_r I_r \sin\theta = P_r \tan\theta$ ...(A8)

and $\quad I_s = \dfrac{P_r}{V_r \cos\theta}$

$V_s \cos\delta$ in terms of P_r will be $= A_1 V_r \quad \dfrac{B_1 P_r}{V_r} \quad \dfrac{B_2 P_r \tan\theta}{V_r}$

$$= A_1 V_r + \frac{P_r}{V_r}[B_1 + B_2 \tan\theta] \qquad \text{...(A9)}$$

$$V_s \sin\delta \quad A_2 V_r + \frac{B_2 P_r}{V_r} \quad \frac{B_1 P_r \tan\theta}{V_r}$$

$$A_2 V_r + \frac{P_r}{V_r}[B_2 \quad B_1 \tan\theta] \qquad \text{...(A10)}$$

$$\tan\delta_r \quad \frac{eq\ A10}{eq\ A9} \quad \frac{A_2 V_r^2 + P_r(B_2 \quad B_1 \tan\theta)}{A_1 V_r^2 + P_r(B_1 + B_2 \tan\theta)} \qquad \text{...(A11)}$$

$$V_s^2 = [A_t V_r + I_r[B_1, \cos\theta + B_2, \sin\theta]^2 + [A_2 V_r + I_r[B_2, \cos\theta + B_1, \sin\theta]^2$$

Substituting for I_r

$$V_s^2 = [A_1 V_r + \frac{P_r}{V_r \cos\theta}(B_1 \cos\theta + B_2 \sin\theta)]^2$$

which simplies into $\quad + \ A_2 V_r + \dfrac{P}{V_r \cos\theta}(B_2 \sin\theta \quad B \cos\theta)^2$ ...(A12)

$$V_s^2 = A^2 V_r^2 + B^2(1 + \tan^2\theta)P_r^2/V_r^2 + 2P_r[(A_1B_1 + A_2B_2) + (A_1B_2 - A_1B_2)\tan\theta] \qquad \text{(A13)}$$

or $\quad V_s^2 = 2P_r[(A_1, B_1 + A_2B_2) + (A_1B_2 - A._2B_1]\tan\theta = AV_r^2 + B(1 + \tan^2\theta)P_r^2/V_r^2$ ...(A14)

For a given sending end voltage V_s L.H.S of equation A 14 is constant if P_r is specified. Therefore V_r can be obtained by solving the equation.

$$AV_r^2 + (B \sec^2\theta)\ \frac{P_r^2}{V_r^2} \quad K. \qquad \text{...(A15)}$$

the RHS of the equation on A14.

For short lines $\quad A_1 = A = 1.0, \quad (A_2 = 0)$

$B = B_1 + jB_2 = R + jX = Z\underline{|\phi}$ the impedance of the line.

$C = 0$ and $D = A$

Hence the above equation A14 or A15 is solved easily by substituting for A, B, C, D.

$$\text{(i.e)} \quad \left.\begin{aligned} V_r^2 + (Z\sec^2\theta)P_r^2/V_r^2 = K \\ where\ \ K = V_s^2 - 2P_r R \end{aligned}\right\} \qquad \ldots\text{(A16)}$$

Normally, receiving end power 'P_r' '$P.F$' and sending end voltage 'V_s' will be known. Hence equation A 16 can be solved easily.

In distribution line design, knowing $I_r (= I_s)$, and V_s (only magnitudes) V_r is to be estimated and checked for regulation and line losses.

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Index

Plate 1 *Pole mounted substation 11,000 V/415V*

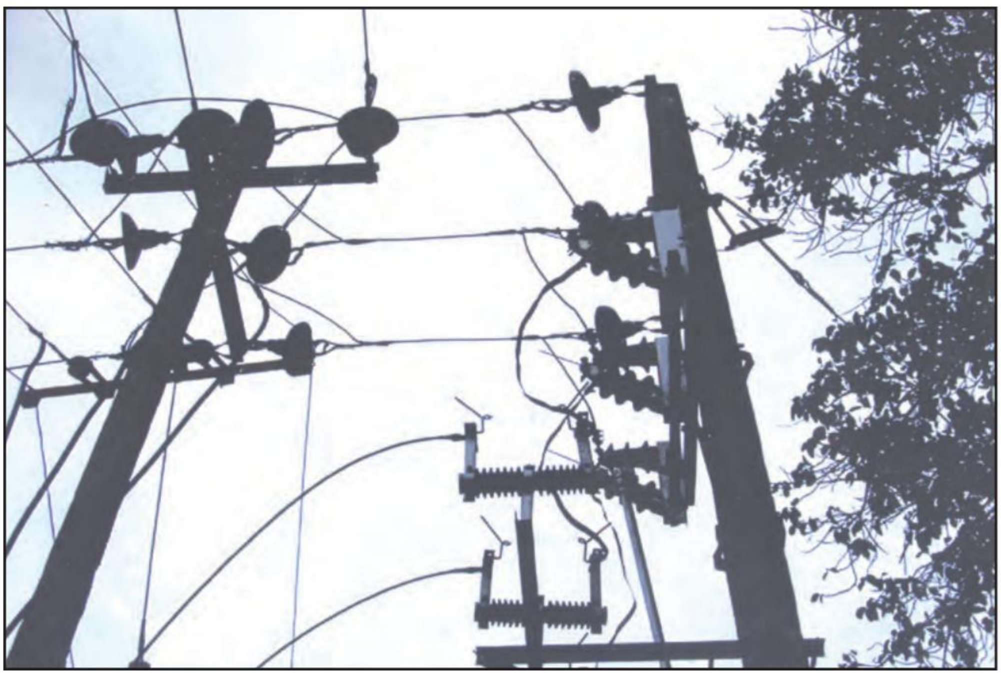


Plate 2 *11 KV Isolator switch and surge diverter, Horn gap fuse mounting for the substation in Plate 1*

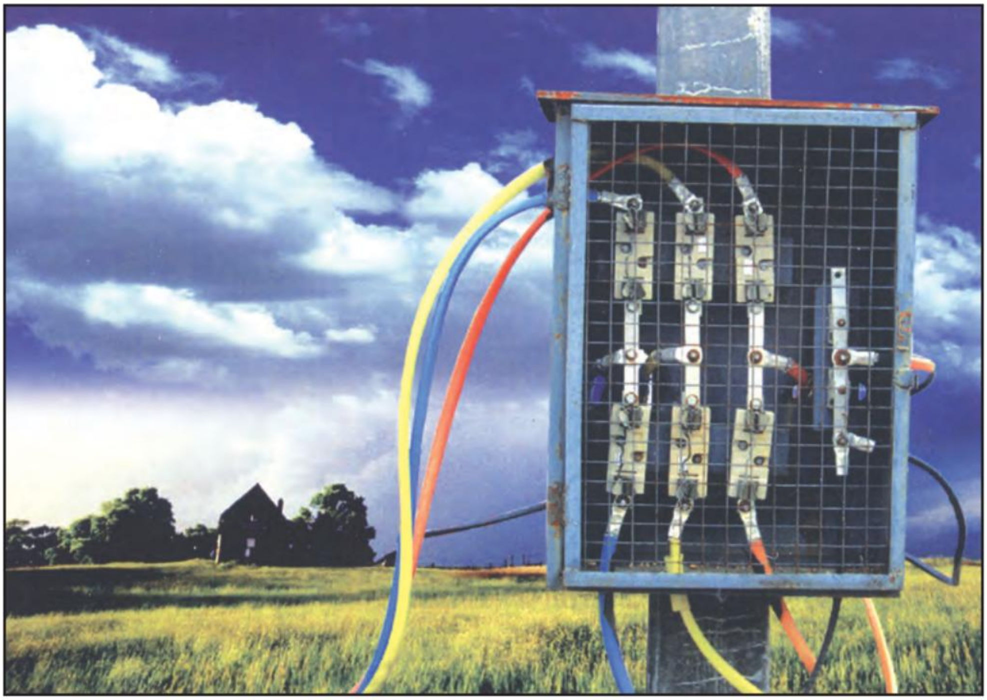


Plate 3 *400 V Fuse Mounting with 3-phase wires and neutral connection*

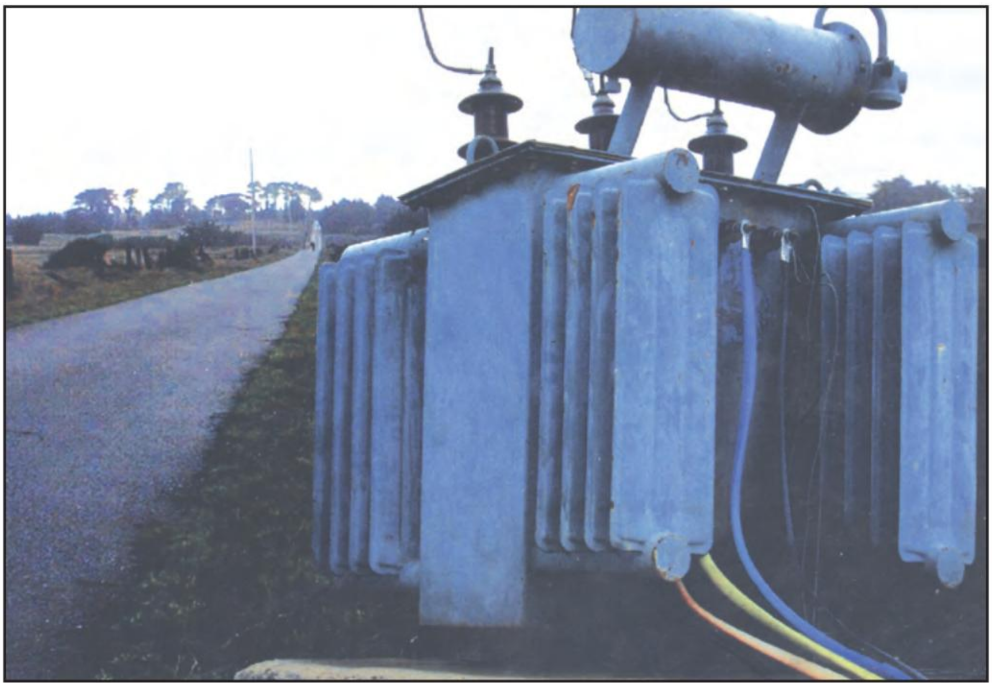


Plate 4 *Distribution transformer 11,000 V/400 V, 250 KVA*

Plate 5 *33/11 KV substation: 33 KV MOCBS isolator switches and bus CTS*

Plate 6 *33/11 KV substation bus bar arrangement, air disconnector switches, lightning arresters, mocers amd bus CTS*

Plate 7 *33/11 KV Power transformer (5MVA)*

Plate 8 *KV bus bars, outgoing feeders with CB & isolators*

Plate 9 *11 KV feeder control and metering cubicle*

Plate 10 *11 KV voltage control capacitor bank with vaccum [BSC on Top]*

Plate 11 *11 KV capacitor bank arrangement with control panel [2 MVAR]*
[1 phase arrangement of Plate 10]

Plate 12 *11 KV side of 33/11 KV substation with outgoing feeders [4 numbers & voltage control capacitor bank [Plate 10]*

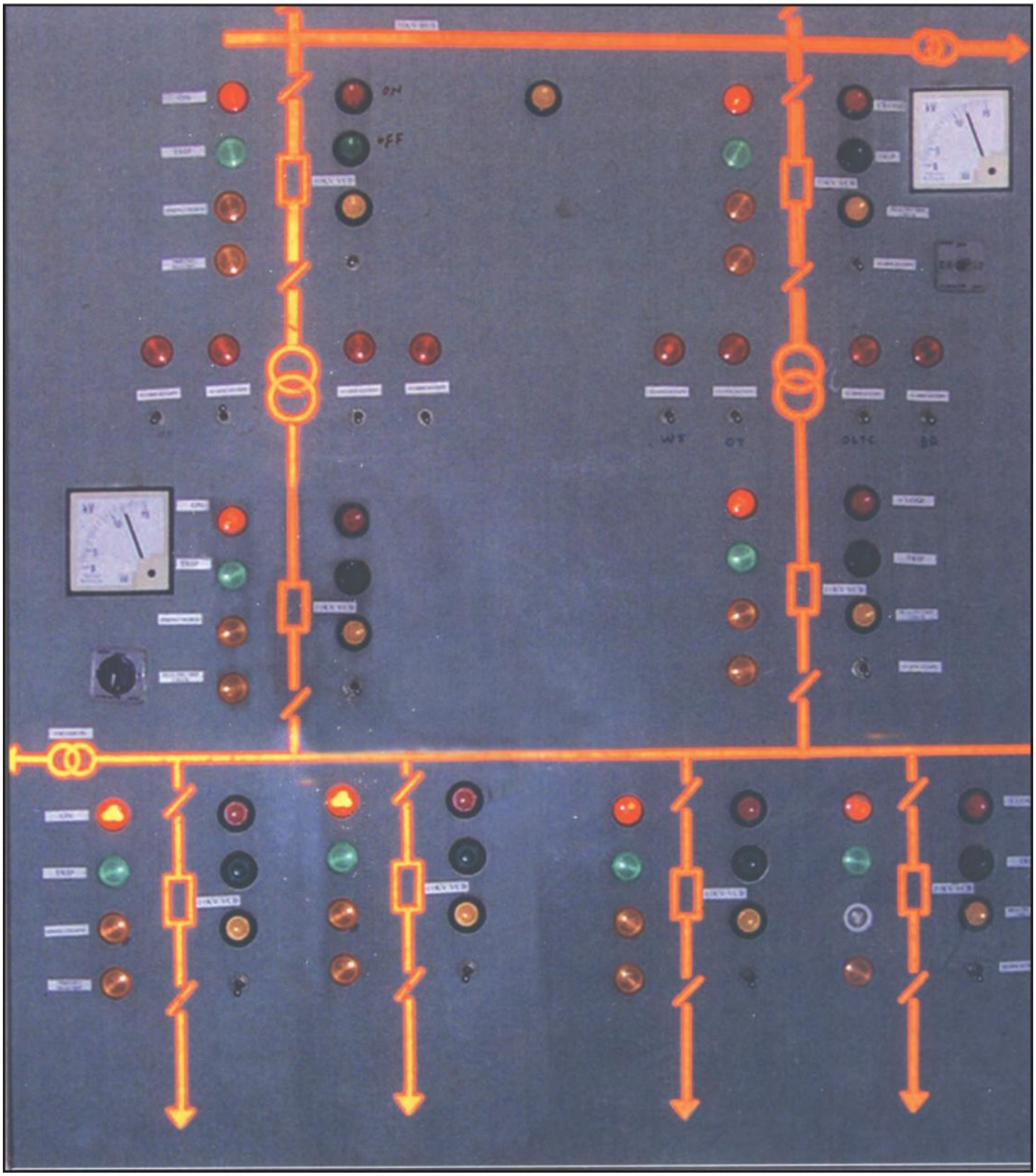


Plate 13 *Single line diagram of 33/11 KV substation shown in Plates 1 to 12*

Voltage transformer of GIS

Gas insulated SS

Plate 14

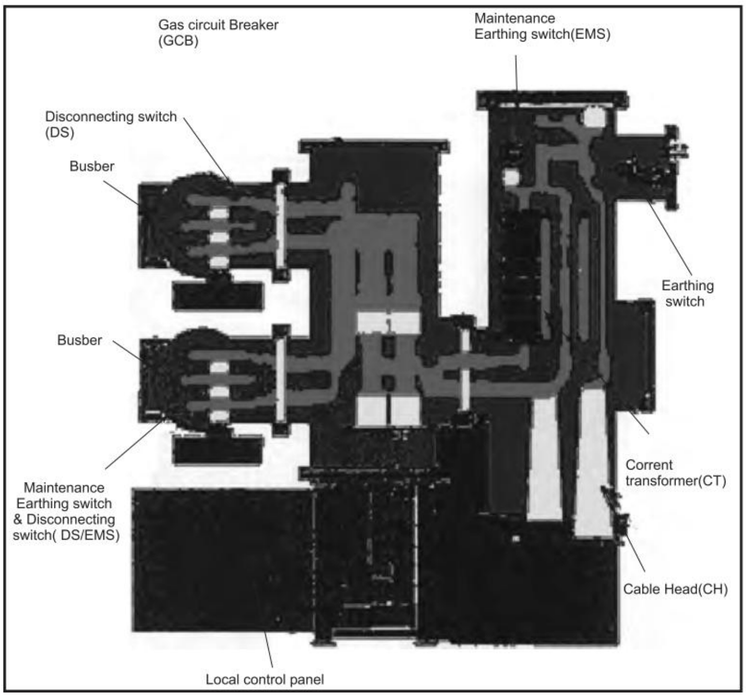
Compact GIS for 15 kV

GIS bus duct

Plate 15

High-voltage GIS

Plate 16



Typical construction of 69 to 132 kV

Plate 17