$$n^2 + n - 6 = 0$$

$$(n + 3)(n - 2) = 0, \qquad n = 2$$

Overall diameter of the conductor, $D = (1 + 2n)\, d = (1 + 4) \times 29 = 14.5$ mm

The *equivalent cross-section* of a stranded conductor is the area of cross-section of a solid conductor of the same material and length as the stranded conductor and having the same resistance at the same temperature. For convenience, the conductors are identified by their code names assigned by the manufacturers. Usually names of some animals, birds or flowers are used.

3.2 TYPES OF CONDUCTORS

Hard-drawn copper, hard-drawn aluminium, and steel-cored aluminium conductors are most commonly used. In addition to these, various other materials are used for making conductors but their use is limited. Some of the important types of conductors are given in the discussion as follows.

3.2.1 Hard-Drawn Copper Conductors

Copper for overhead lines is hard-drawn to give a relatively high tensile strength. It has a high electrical conductivity, long life, and high scrap value. Other properties of hard-drawn copper are given in Table 3.1 along with the properties of hard-drawn aluminium. Copper conductor is most suitable for distribution work where spans are short and tappings are more.

Table 3.1. Electrical and Mechanical Characteristics of Hard-Drawn Aluminium and Copper Wires

	Hard-drawn aluminium	*Hard-drawn copper*
Conductivity at 20°C IACS*	61	97.4
Resistivity at 20°C (microhm-cm)	2.8264	1.774
Resistivity temperature coefficient (microhm-cm °C)	0.0115	0.00681
Constant mass temperature coefficient of resistance per °C at 20°C	0.00403	0.00381
Coefficient of linear expansion per °C	2.3×10^{-5}	1.7×10^{-5}
Density at 20°C (gm/cm^3)	2.703	8.89
Ultimate tensile strength (kgf/mm^2)	16.21	35-47
Final modulus of elasticity (kgf/mm^2)	7000 average	12700 average

* International Annealed Copper Standard

3.2.2 Cadmium Copper Conductor

The tensile strength of copper is increased by approximately 50 per cent by adding about 0.7 to 1.0 per cent cadmium to it. The conductivity is, however, reduced by about 15 to 17 per

Combination of Eqs. (4.11.1) and (4.11.2) gives

$$g_x = \frac{V}{x \ln (R/r)} \text{ V/m} \qquad \text{...(4.11.3)}$$

The maximum stress will occur at the smallest radius, i.e., for $x = r$. The stress is a maximum at the surface of conductor, or in other words, the inner most layer of the dielectric is subjected to a maximum stress. The maximum stress is given by

$$g_{\max} = \frac{V}{r \ln \frac{R}{r}} \text{ V/m} \qquad \text{...(4.11.4)}$$

When $x = R$, the stress will be a minimum which indicates that stress has a minimum value at the sheath. The minimum value is given by

$$g_{\min} = \frac{V}{R \ln \frac{R}{r}} \text{ V/m} \qquad \text{...(4.11.5)}$$

Also, $$\frac{g_{\max}}{g_{\min}} = \frac{R}{r} \qquad \text{...(4.11.6)}$$

The electric stress in a belted cable cannot be calculated accurately due to non-uniformity of the dielectric and the distortion in the electrostatic field.

The present day tendency is to design high voltage cables on the basis of a fixed maximum value of operating stress. The stress is usually expressed in kilovolts per millimetre. Eq. (4.11.4) is then utilized to determine the thickness of insulation necessary for a given diameter of conductor. It is clear from Eq. (4.11.4) that greater the value of permissible stress the lesser will be the insulation thickness. It is desirable to choose a higher value of operating stress in order to have a reduced thickness of insulation and, therefore, a reduced size of cable. Since a smaller cable size affords more economy, there is a tendency to increase the operating stresses to their highest values without the failure to cable either under actual operating conditions or during its approval specified tests.

Considerably improvements have been made in developing high strength paper, conductor screening and manufacturing techniques to achieve the objective of operating the cable at maximum stress levels.

Most Economical Size of Cable

Maximum potential gradient, $g_{\max} = \dfrac{V}{r \ln \frac{R}{r}}$

If V and R are constant and r is made variable the expression for $g_{\max}$ has a minimum value when $r \ln (R/r)$ is a maximum. This occurs when

$$\frac{d}{dr}\left(r \ln \frac{R}{r}\right) = 0 \; ; \qquad \frac{d}{dr}(r \ln R - r \ln r) = 0$$

$$\ln R - r \cdot \frac{1}{r} - \ln r = 0 \; ; \qquad \ln \frac{R}{r} = 1 = \ln e \; ; \qquad \frac{R}{r} = e = 2.718$$

4. Larger and stronger steel pipes are needed for bigger sizes of conductor. The pipes have to withstand gas pressures of the order of 1.725×10^6 N/m^2.

The pipe may as well be filled with oil, which although more costly than nitrogen gas, permits higher dielectric operating stresses than the cheaper gas filling.

4.28 COMPRESSED GAS INSULATED CABLES (GIC)

In a compressed gas insulted cable, high pressure sulphur hexafluoride (SF_6) gas fills the small spaces in oil-impregnated paper insulation and suppresses the ionization.

The conductors in gas insulated cables consist of hollow aluminium tubes rather than solid rods in order to have greater rigidity, lower electrical surface stress, and lower ac-dc resistance ratio. They are subject to severe mechanical, thermal and electrical stresses. It is, therefore, necessary to hold these conductors in position by spacers. Three types of spacers are used in rigid gas insulted cables. They are (a) disc type, (b) cone type, and (c) post type as shown in Fig. 4.27.

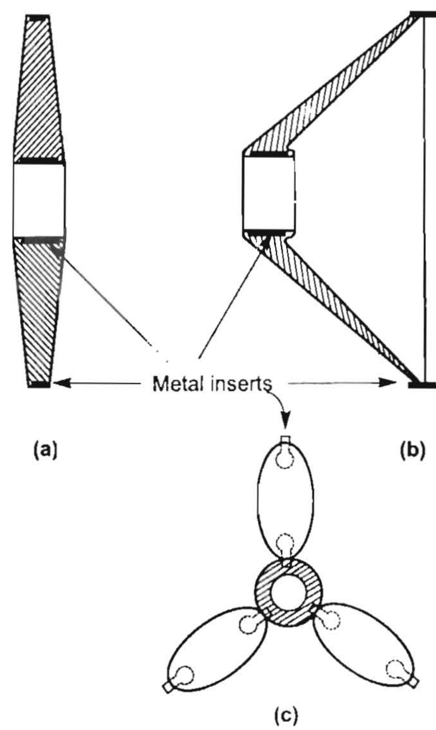

Fig. 4.27. Spacers used in rigid isolated phase gas insulated cables. (a) Disc, (b) Cone, (c) Post.

The spacers are made from epoxy resin insulating material. There are two possible configurations :

(a) Isolated phase GIC

(b) Single enclosure type three-phase GIC

In an *isolated phase GIC*, the three phases are enclosed in *separate enclosures*, filled with SF_6 gas at a pressure of 2 to 4 atmospheres (2×10^5 to 4×10^5 N/m^2) as shown in Fig. 4.28 (a). When all the three phases are put into the same enclosure (pipe or sheath), the configuration is called *single-enclosure three-phase GIC* [Fig. 4.28 (b)]. The enclosure is filled with SF_6 gas at a pressure of 2 to 4 atmospheres. The enclosure is made from an aluminium alloy for greater mechanical strength.

The choice between the GIC configurations is made on space and economic considerations. An isolated phase system requires (a) larger quantity of aluminium for enclosure pipes and (b) wider trenches. The rigid three-phase GIC system provide economies in metal consumption and trench width, but its current-carrying capacity is less than an isolated GIC system.

Most of the gas cables presently in use consist of three separate coaxial lines assembled from rigid pipes of aluminium alloy.

EHV/UHV lines insulated with sulphur hexafluoride (SF_6) gas are being used extensively for voltages above 132 kV upto 1200 kV.

GIC systems are very popular for short lengths, river crossings, and highway crossings, etc.

Solution

Let C represent the self capacitance of each unit. The capacitances of the link pins to earth and to the line will, therefore, be $0.2C$ and $0.1C$ respectively. The capacitances, voltages and currents are shown in Fig. 5.16.

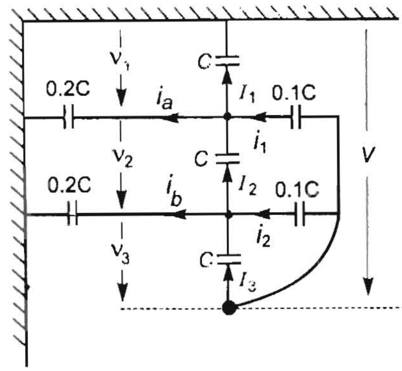

Fig. 5.16.

(a) We have

$$I_1 = v_1 (j\omega C),\ I_a = v_1 (j\omega)(0.2C)$$

$$i_1 = (V - v_1)\, j\omega (0.1C)$$

$$I_2 = I_1 + I_a - i_1$$

$$= v_1 j\omega C + 0.2v_1 j\omega C - 0.1(V - v_1) j\omega C$$

$$= j\omega C(1.3v_1 - 0.1V)$$

$$v_2 = \frac{I_2}{j\omega C} = 1.3v_1 - 0.1V$$

$$I_b = (v_1 + v_2) \times 0.2j\omega C = (v_1 + 1.3v_1 - 0.1V) \times 0.2j\omega C = j\omega C(0.46v_1 - 0.02V)$$

$$i_2 = v_3 \times 0.1j\omega C$$

$\therefore$
$$I_3 = I_2 + I_b - i_2$$

$$= j\omega C(1.3v_1 - 0.1V) + j\omega C(0.46v_1 - 0.02V) - 0.1\, j\omega C\, v_3$$

$$= j\omega C(1.76v_1 - 0.12V - 0.1v_2)$$

$$v_3 = \frac{I_3}{j\omega C} = 1.76v_1 - 0.12V - 0.1v_3$$

$$v_3 = \frac{1.76v_1}{1.1} - \frac{0.12V}{1.1} = 1.6v_1 - 0.109V$$

Also,
$$v_1 + v_2 + v_3 = V$$

$$v_1 + 1.3v_1 - 0.1V + 1.6v_1 - 0.109V = V$$

$$3.9v_1 = 1.209V, \qquad v_1 = \frac{1.209}{3.9}V = 0.31V$$

$$v_2 = 1.3v_1 - 0.1V = 1.3 \times 0.31V - 0.1V = 0.303V$$

$$v_3 = 1.6v_1 - 0.109V = 1.6 \times 0.31V - 0.109V = 0.387V$$

$$\text{String efficiency} = \frac{V}{3v_3} = \frac{V}{3 \times 0.387V} = 0.8613 \text{ pu}$$

(b) *With the grading ring*

The capacitance of the lower link pin now becomes $0.35C$ instead of $0.1C$. Therefore,

$$i_2 = v_3 \times 0.35\, j\omega C$$

and
$$I_3 = I_2 + I_b - i_2 = j\omega C(1.76v_1 - 0.12V - 0.35v_3)$$

Contents

Preface to the Fifth Edition v
Preface to the First Edition vii

1 Load Characteristics . . . . 1 – 15

1.1 Introduction *1*
1.2 Advantages of electrical energy *1*
1.3 Load *1*
1.4 Connected load *2*
1.5 Demand *2*
1.6 Demand interval *2*
1.7 Maximum demand (MD) or peak load *2*
1.8 Demand factor (DF) *2*
1.9 Average load or average demand *3*
1.10 Load factor *3*
1.11 Diversity factor F_D *3*
1.12 Load diversity *4*
1.13 Utilization factor F_u *4*
1.14 Plant factor or capacity factor *4*
1.15 Loss factor F_{LS} *5*
1.16 Load curve *5*
1.17 Informations obtained from load curves *5*
1.18 Utility of load curves *6*
1.19 Load-duration curve *6*
1.20 Procedure for plotting the load-duration curve *6*
1.21 Informations available from load duration curve *6*

2 Supply Systems . . . . **16 – 35**

2.1 Introduction *16*
2.2 Basic structure of an AC power system *16*
2.3 Distribution voltage level *16*
2.4 Subtransmission level *17*
2.5 Transmission level *17*
2.6 Layout of a power supply network *17*
2.7 System interconnection *18*
2.8 System voltage and transmission efficiency *19*
2.9 Working voltage *20*
2.10 Choice of the next high voltage *20*
2.11 Standardization of transmission voltages *21*
2.12 Classification of lines *21*
2.13 Comparison of conductor costs in various systems *22*
2.13.1 Criterion of equal maximum voltage to earth *23*
2.13.2 Criterion of equal maximum voltage between line conductors *27*

3 Conductors . . . . **36 – 54**

3.1 Introduction *36*
3.2 Types of conductors *37*
3.2.1 Hard-drawn copper conductors *37*
3.2.2 Cadmium copper conductor *37*
3.2.3 Steel-cored copper conductor (SCC) *38*
3.2.4 Copperweld conductor *38*
3.2.5 Hard-drawn aluminium conductor or all-aluminium conductor (AAC) *38*
3.2.6 Aluminium conductor steel reinforced (ACSR) *38*
3.2.7 Smooth body ACSR conductor *39*
3.2.8 Expanded ACSR conductor *40*
3.2.9 All-aluminium alloy conductor (AAAC) *40*
3.2.10 ACAR conductor *40*
3.2.11 Alumoweld conductor *41*
3.2.12 Phosphor-bronze conductor *41*
3.2.13 Galvanized steel conductor *41*
3.3 Resistance *41*
3.4 Skin effect *42*
3.5 Equivalent copper section *43*
3.6 Kelvin's economy law *43*
3.7 Modified Kelvin's law *44*
3.8 Graphical representation *45*
3.9 Economic current density *46*
3.10 Determination of losses *49*
3.11 Limitations of Kelvin's law *52*

4 Power Cables . . . . **55 – 92**

4.1 Introduction *55*
4.2 Cable construction *56*
4.3 Conductors *56*
4.4 Insulation *57*
4.5 Sheath *58*
4.6 Protective covering *58*
4.7 Belted cable *59*
4.8 Screened cable *59*
4.9 Cable impregnation *60*
4.10 Non-drained cables *60*
4.11 Dielectric stress *60*
4.12 Grading of cables *64*
4.13 Cable capacitance *70*
4.14 Charging current or capacitive current *70*
4.15 Capacitances in a three-core belted cable *70*
4.16 Measurement of C_c and C_s *72*
4.17 Insulation resistance *74*
4.18 Dielectric loss *75*
4.18.1 Conductivity of insulation *75*
4.18.2 Dielectric hysteresis or dielectric absorption *75*
4.18.3 Corona or gaseous ionization in cables *76*
4.18.4 Dielectric power loss *76*
4.19 Stress distribution in a HVDC cable *78*
4.20 Skin effect *79*
4.21 Proximity effect *79*
4.22 Current rating of cables *79*
4.22.1 Normal or safe current carrying capacity *79*
4.22.2 Over current rating *81*
4.22.3 Short-circuit rating *82*
4.23 Thermal breakdown *82*
4.24 Soil thermal resistivity *82*
4.25 Extra high voltage cables *82*
4.26 Oil-filled cables *83*
4.26.1 Advantages of self-contained oil-filled cables *85*
4.26.2 Advantages of oil-filled cables *85*
4.26.3 Oil for cables *85*
4.27 Gas-pressure cables *86*
4.27.1 External gas-pressure cables *86*
4.27.2 Internal gas-pressure cables *86*
4.28 Compressed gas insulated cables (GIC) *87*
4.29 Advantages of GIC over oil-filled cables *88*
4.30 Cross-linked polyethylene (XLPE) cables *89*
4.31 Power cable installation *89*

5 Line Insulators and Supports . . . . 93 – 122

5.1 Introduction *93*
5.2 Types of insulator *95*
  5.2.1 Pin type insulator *95*
  5.2.2 Suspension insulators *96*
  5.2.3 Strain or tension insulators *97*
5.3 V-strings *98*
5.4 Insulator materials *98*
  5.4.1 Polymer insulator *99*
5.5 Voltage distribution and string efficiency *99*
  5.5.1 Alternative method *101*
5.6 Improving voltage distribution *103*
5.7 Selection of insulation *112*
5.8 Line supports *113*
5.9 Wood poles *114*
5.10 Concrete poles *114*
5.11 Steel poles *115*
5.12 Supporting towers *115*
  5.12.1 Self-supporting towers *115*
  5.12.2 Guyed or stayed towers *115*
5.13 Vibration of conductors *117*
  5.13.1 Resonant vibration *117*
  5.13.2 Galloping *118*
  5.13.3 Dancing and steel-jump *118*
5.14 Effects of vibration on the transmission line *118*
5.15 Prevention of vibration *119*
  5.15.1 Armour rods *119*
  5.15.2 Stockbridge damper *119*
5.16 Spacing of conductors *120*

6 Sag and Tension . . . . 123 – 150

6.1 Introduction *123*
6.2 Sag and tension *123*
6.3 Parabolic method *124*
6.4 Catenary method *125*
6.5 Accuracy of results *128*
6.6 Loading on conductors *128*
6.7 Conductor clearance from ground *131*
6.8 Erection sag and tension *132*
  6.8.1 Factors affecting the sag *133*
6.9 Spans of unequal length *137*
6.10 Sag and tension charts *138*
6.11 Supports at unequal levels *139*
6.12 The sag template *144*
6.13 Preparation of the sag template *145*
6.14 Method of using the template *146*
6.15 Economic span length *147*

7 Line Parameters . . . . 151 – 212

7.1 Introduction *151*
7.2 Line inductance *151*
7.3 Inductance of a conductor *152*
7.3.1 Internal inductance *152*
7.3.2 External inductance *154*
7.4 Flux linkages in a group of conductors *155*
7.5 Inductance of a two-wire line *157*
7.6 Inductance of symmetrical three-phase line *159*
7.7 Inductance of unsymmetrical three-phase line *160*
7.8 Method of geometric mean distances *163*
7.9 Two-wire line *165*
7.10 Symmetrical three-phase line *165*
7.11 Inductance of unsymmetrical three-phase line *166*
7.12 Inductance of double-circuit single-phase line *169*
7.13 Inductance of double-circuit three-phase lines *170*
7.14 Special cases of double-circuit lines *172*
7.15 Inductance of bundled conductor lines *174*
7.16 Line capacitance *178*
7.17 Electric field of a long straight conductor *178*
7.18 System of conductors *179*
7.19 Capacitance of two-wire line *180*
7.20 Capacitance of the symmetrical three-phase line *182*
7.21 Capacitance of an unsymmetrical three-phase transposed line *183*
7.22 Capacitance of a three-phase single-circuit untransposed line *186*
7.23 Charging current *187*
7.24 Capacitance by GMD method *188*
7.25 Capacitance of double-circuit three-phase line *189*
7.26 Effect of earth on the line capacitance *190*
7.27 Effect of earth on capacitance of single-circuit three-phase line with transposition *193*
7.28 Capacitance of bundled conductor lines *195*
7.29 Shunt conductance *198*
7.30 Interference between power and communication lines *198*
7.31 Electromagnetic effect *198*
7.32 Electrostatic effect *199*

8 Per Unit Representation . . . . 213 – 237

8.1 Introduction *213*
8.2 Change of base *216*
8.3 Per unit impedance of a transformer *216*
8.4 Per unit quantities in three-phase systems *219*
8.5 Selection of base values *221*
8.6 Base quantities in terms of kV and MVA *221*
8.7 Per unit load impedance *222*

8.8 Advantages of per unit representation *224*
8.9 One-line diagrams *225*
8.10 Preparation of impedance diagrams *226*

9 Short and Medium Lines . . . . **238 – 265**

9.1 Introduction *238*
9.2 Classification of lines *238*
9.3 Short single-phase line *239*
9.4 Phasor diagram *240*
9.5 Short three-phase line *241*
9.6 Transmission line as a two-port network *242*
 9.6.1 ABCD constants of a short line *243*
9.7 Line regulation *243*
 9.7.1 Line regulation for short lines *243*
9.8 Line efficiency or transmission efficiency *244*
9.9 Line with transformers *248*
9.10 Medium lines *251*
9.11 Nominal T model of a medium line *252*
 9.11.1 Phasor diagram *253*
9.12 Nominal Π model of a medium line *254*
 9.12.1 Phasor diagram *255*
9.13 Calculation of transmission efficiency and regulation of medium lines *256*

10 Long Transmission Lines . . . . **266 – 282**

10.1 Introduction *266*
10.2 Exact solution of a long line *266*
10.3 Physical interpretation of the long line equations *269*
10.4 Propagation constant *270*
10.5 Wavelength and velocity of propagation *271*
10.6 Characteristic impedance Z_0 *271*
10.7 Hyperbolic form of line equations *272*
10.8 Evaluation of ABCD parameters *273*
10.9 Ferranti effect *278*
10.10 Surge impedance loading (SIL) *279*

11 General Network Constants . . . . **283 – 310**

11.1 Introduction *283*
11.2 Cascaded networks *284*
11.3 Relations between ABCD constants *286*
11.4 Output in terms of input *287*
11.5 Typical transmission networks *288*
 11.5.1 Series impedance circuit *289*
 11.5.2 Shunt admittance circuit *289*
 11.5.3 Half T-network *289*

11.5.4 T-network *290*
11.5.5 Π-network *291*
11.5.6 Ideal transformer *292*
11.5.7 Actual transformer *292*
11.5.8 Transmission line *293*
11.5.9 Transmission line with transformers at both ends *294*
11.6 Networks in parallel *296*
11.7 Equivalent networks *298*
11.8 Equivalent T-network of a line *298*
11.9 Equivalent Π networks of a line *299*
11.10 The nominal T- and Π-equivalent network of a line *299*
11.11 Experimental determination of ABCD constants *300*

12 Power Circle Diagrams . . . . 311 – 330

12.1 Introduction *311*
12.2 Receiving-end voltage phasor diagram *311*
12.3 Phasor volt-amperes *312*
12.4 Receiving-end power circle diagram *312*
12.5 Analytical method *316*
12.6 Sending-end voltage phasor diagram *318*
12.7 Sending-end power circle diagram *318*
12.8 Analytical method *321*
12.9 Power transmitted over a line *323*
12.10 Per unit value circle diagrams *324*
12.11 Receiving-end per unit circle diagrams *324*
12.12 Sending-end per unit circle diagrams *326*
12.13 Universal power circle diagrams *327*
12.14 The use of universal power circle diagrams *328*

13 Control of Voltage and Reactive Power . . . . 331 – 353

13.1 Introduction *331*
13.2 Methods of voltage control *332*
13.3 Tap-changing transformers *333*
13.3.1 Off-load tap-changing transformer *333*
13.3.2 On-load tap-changing transformer *333*
13.4 Shunt reactors *335*
13.5 Shunt capacitors *335*
13.6 Series compensation *336*
13.7 Location of series capacitors *337*
13.8 Protective schemes for series capacitors *337*
13.9 Problems associated with series capacitors *338*
13.10 Series capacitor versus shunt capacitor *339*
13.11 Synchronous phase modifiers *339*
13.11.1 Rating of a phase modifier *340*
13.12 Static VAr systems (SVS) *347*

13.13 SVS schemes *348*
13.14 Thyristor controlled reactor (TCR) *348*
13.15 Thyristor switched capacitor (TSC) *348*
13.16 FC-TCR type VAr compensator *349*
13.17 TSC-TCR scheme *350*
13.18 Advantages of SVS *351*
13.19 Applications of SVS *351*

14 Load Flow Analysis . . . . 354 – 383

14.1 Introduction *354*
14.2 Load flow problem *354*
14.3 Bus admittance matrix Y_{bus} *356*
14.4 Static load flow equations (SLFE) *363*
14.5 Methods of load flow solution *364*
14.6 Gauss-Seidel method using Y_{bus} *364*
14.6.1 Computation for load buses *366*
14.6.2 Computation for PV buses *367*
14.6.3 Acceleration factors *368*
14.7 Newton-Raphson (NR) method *368*
14.8 Newton-Raphson method for load flow solution *371*
14.9 Computational procedure for Newton-Raphson method *374*
14.10 Power flow through lines and slack bus power *376*
14.11 Decoupled load flow methods *376*
14.12 Fast decoupled load flow (FDLF) method *377*
14.13 DC load flow method *378*
14.14 Comparison of load flow analysis methods *379*

15 Economic Operation of Power Systems . . . . 384 – 403

15.1 Introduction *384*
15.2 Incremental fuel cost *385*
15.3 Economic dispatch neglecting transmission losses *386*
15.4 Transmission loss as a function of plant generation *391*
15.5 General loss formula *393*
15.6 Optimum load dispatch considering transmission losses *394*
15.7 Iterative method of solving coordination equation *398*

16 Symmetrical Faults . . . . 404 – 430

16.1 Introduction *404*
16.2 Effects of faults *405*
16.3 Purpose of fault analysis *405*
16.4 Simplifying assumptions *405*
16.5 Thevenin's equivalent circuit *406*
16.6 Short-circuit capacity, SCC *406*
16.7 Procedure for calculating short-circuit voltamperes and short-circuit current *408*

16.8 Star-delta and delta-star transformations *408*
16.9 Transient in a series *R-L* circuit *409*
16.10 Sudden short-circuit at the armature terminals of a three-phase generator *411*
16.11 Consideration of prefault load current *416*
16.12 Current-limiting reactors *417*
16.12.1 Construction of reactors *417*
16.12.2 Location of reactors *417*
16.12.3 Rating of reactors *419*
16.13 Short-circuit MVA in a tie-bus system *419*

17 Symmetrical Components 431

17.1 Introduction *431*
17.2 Fortescue's theorem *431*
17.3 Phase sequence *431*
17.4 α-operator *432*
17.5 Symmetrical components of an unbalanced three-phase system *432*
17.6 Component synthesis *433*
17.7 Component analysis *434*
17.8 Graphical method of determining sequence components *436*
17.9 Symmetrical components of current phasors *436*
17.10 Zero-sequence components of voltage *437*
17.11 General nature of zero-sequence currents *438*
17.12 Power in terms of symmetrical components *443*
17.13 Potential of neutral *447*
17.14 Phase shift in star-delta transformers *448*
17.15 Sequence impedances *449*
17.16 Sequence networks for fault calculations *450*
17.17 Sequence impedances of a transmission line *451*
17.18 Sequence impedances of synchronous machines *454*
17.19 Sequence networks of synchronous machines *455*
17.20 Zero-sequence networks of transformers *457*
17.21 Assembly of sequence networks of a power system *459*

18 Unsymmetrical Faults 463

18.1 Introduction *463*
18.2 Assumptions *464*
18.3 Sequence voltages of a generator *464*
18.4 Sequence voltages at a fault point *464*
18.5 General procedure *465*
18.6 Single line-to-ground (LG) fault *466*
18.7 Line-to-line fault *469*
18.8 Double line-to-ground (LLG or DLG) fault *471*
18.9 Balanced three-phase fault *474*
18.10 Comparison of single line-to-ground and three-phase fault currents *480*

18.11 Open conductor faults *482*
18.11.1 One conductor open *482*
18.11.2 Two conductors open *482*

19 Power System Stability . . . . 486 – 536

19.1 Introduction *486*
19.2 Stability limits and power transmission capability *487*
19.3 Infinite bus *487*
19.4 Synchronous generator connected to an infinite bus *488*
19.5 Power-angle curve *489*
19.6 Representation of a T-circuit with a series circuit *490*
19.7 Power-angle relations for general network configurations *491*
19.8 Transfer impedance *492*
19.9 Power-angle characteristic of a salient-pole synchronous machine *498*
19.10 Steady-state stability criterion *501*
19.11 Transient stability *502*
19.12 Swing equation *502*
19.13 Swing curves *504*
19.14 *M* and *H* constants *504*
19.14.1 *M* constant *504*
19.14.2 *H* constant or per unit inertia constant *505*
19.14.3 *H* constant on a common base *506*
19.15 Equivalent system *506*
19.16 Equivalent *M* constant of two machines *506*
19.17 Equal-area criterion of stability *509*
19.17.1 Application to sudden increase in mechanical power input *511*
19.17.2 One of the parallel lines suddenly switched off *515*
19.18 System fault and subsequent circuit isolation *518*
19.18.1 System fault, circuit isolation and reclosing *521*
19.19 Numerical solution of swing equation (point-by-point solution) *525*
19.20 Methods of improving stability *530*

20 Travelling Waves . . . . 537 – 573

20.1 Introduction *537*
20.2 Wave equation *537*
20.3 Characteristic impedance *541*
20.4 Energy and power of a surge *543*
20.5 Evaluation of surge impedance *544*
20.6 Velocity of travelling waves *545*
20.7 Incident and reflected waves *546*
20.8 Reflection of waves *547*
20.9 Transmission or refraction of waves *548*
20.10 Open-circuited line *549*
20.11 Short-circuited line *551*
20.12 Line terminated in Z_0 *551*

20.13 Series reactive termination *551*
20.14 Parallel reactive termination *554*
20.15 Line terminated in a capacitor *555*
20.16 Junction of two dissimilar lines *556*
20.17 Effect of cable on surge *560*
20.18 Junction of several lines *561*
20.19 Repeated reflections *563*

21 Overvoltage Protection . . . . 574 – 588

21.1 Introduction *574*
21.2 Internal overvoltages *574*
21.3 External overvoltages *575*
21.4 Mechanism of the lightning discharge *575*
21.5 Frequency of lightning flashovers *576*
21.6 Stroke currents *576*
21.7 Direct and induced strokes *577*
21.8 Wave shapes of stroke currents *577*
21.9 Overvoltage protection *577*
21.10 Overhead earth wire *578*
21.11 Rod gap *579*
21.12 Surge diverters *580*
21.13 Expulsion-type surge diverter *580*
21.14 Valve-type surge diverter *581*
21.15 Metal-oxide gapless surge diverters *582*
21.16 Advantages of ZnO diverters *584*
21.17 Location of surge diverters *584*
21.18 Selection of surge diverters *584*
21.19 Lightning performance of lines *585*
21.20 Basic impulse insulation level or basic insulation level (BIL) *585*
21.21 Volt-time characteristic (curve) *585*
21.22 Insulation coordination *586*

22 Corona . . . . 589 – 607

22.1 Introduction *589*
22.2 The phenomenon of corona *589*
22.3 Theory of corona formation *590*
22.4 The calculation of potential gradient *590*
22.5 Factors affecting corona *595*
22.6 Disruptive critical voltage *597*
22.7 Visual critical voltage *599*
22.8 Corona power loss *601*
22.9 Radio and television interference (RI) *604*
22.10 Minimizing corona *604*
22.10.1 Bundled conductors *605*

23 High Voltage Direct Current (HVDC) Transmission . . . . 608 – 626

23.1 Introduction *608*
23.2 Classification of HVDC systems *609*
23.3 AC interconnection *612*
 23.3.1 Limitations of AC interconnection *612*
 23.3.2 Advantages of DC interconnection *613*
23.4 Stability limits *613*
23.5 HVDC cable transmission *613*
23.6 Economic comparison *614*
23.7 Conversion of three-phase AC line to DC line *615*
23.8 Advantages of HVDC transmission *616*
23.9 Economic distances for HVDC transmission *617*
23.10 Components of an HVDC transmission system *618*
23.11 Converter station *618*
23.12 Converter unit *618*
23.13 Converter valves *620*
23.14 Converter transformers *620*
23.15 Filters *621*
 23.15.1 AC filters *621*
 23.15.2 DC filters *621*
 23.15.3 High-frequency filters *621*
23.16 Reactive power source *621*
23.17 Smoothing reactor *621*
23.18 HVDC system pole *622*
23.19 Ground electrodes *622*
23.20 Back-to-back HVDC station (HVDC coupling station) *622*
23.21 Two-terminal HVDC system *623*
23.22 Multiterminal DC (MTDC) system *623*
 23.22.1 Advantages of MTDC systems *623*
 23.22.2 Application of MTDC systems *623*
23.23 DC circuit breakers *624*
23.24 Limitations of HVDC transmission *624*
23.25 Developments in DC technology *625*
23.26 Applications of HVDC transmission *625*
23.27 HVDC systems in India *625*

24 System Neutral Grounding . . . . 627 – 638

24.1 Introduction *627*
24.2 Ungrounded neutral system *627*
24.3 Arcing grounds *629*
24.4 Advantages of neutral grounding *629*
24.5 Methods of neutral grounding *630*
24.6 Solid grounding *630*
24.7 Resistance grounding *631*
24.8 Reactance grounding *632*

24.9 Peterson coil grounding *632*
24.9.1 Construction of Peterson coil *634*
24.9.2 Rating of Peterson coil *634*
24.9.3 Advantages of Peterson coil grounding *634*
24.9.4 Limitations of Peterson coil grounding *634*
24.10 Grounding transformer *634*
24.11 Choice of grounding *636*

25 Tariffs **639**
25.1 Introduction *639*
25.2 Types of tariffs *640*
25.2.1 Flat demand rate tariff *640*
25.2.2 Straight-line meter rate tariff *640*
25.2.3 Block meter rate tariff *641*
25.2.4 Two-part tariff *641*
25.2.5 Power factor tariff *641*
25.2.6 Seasonal rate tariff *642*
25.2.7 Peak-load tariff *642*
25.2.8 Three-part tariff *642*

26 Power Factor Improvement **648**
26.1 Introduction *648*
26.2 Disadvantages of a low power factor *648*
26.3 Causes of low power factor *649*
26.4 Power factor improvement *650*
26.5 Power factor correction by static capacitors *650*
26.6 Capacitor rating calculations *651*
26.7 Power factor correction in three-phase systems *654*
26.8 Advantages and limitations of static capacitors *657*
26.9 Location of capacitors *658*
26.10 Power factor correction by synchronous motors *658*
26.11 Economics of power factor improvement *661*
26.11.1 Most economical power factor when kW demand is constant *662*
26.11.2 Most economical power factor when kVA demand is constant *663*
26.12 Economics of supply of increased power demand *664*

27 Voltage Stability **671**
27.1 Introduction *671*
27.2 Classification of voltage stability *671*
27.2.1 Large-distance voltage stability *672*
27.2.2 Small-distance voltage stability *672*
27.3 Rotor-angle stability and voltage stability *672*
27.4 Voltage stability limit *672*

27.5 Voltage stability analysis 674
27.5.1 P-V curves 674
27.5.2 V-Q curves 675
27.6 Methods of improving voltage stability 675
27.6.1 Reactive power compensation 675
27.6.2 Load shedding during contingencies 676
27.6.3 Use of LTC (load tap changing transformers) 677

28 Flexible AC Transmission Systems (FACTS) . . . . 678 – 683

28.1 Introduction 678
28.2 Basic types of FACTS controllers 679
28.2.1 Series controllers 680
28.2.2 Shunt controllers 680
28.2.3 Combined series-series controllers 680
28.2.4 Combined series-shunt controllers 680
28.3 STATCOM 680
28.4 Static synchronous generator (SSG) 680
28.5 Static synchronous series compensator (SSSC) 681
28.6 Interline power flow controller (IPFC) 681
28.7 Unified power flow controller (UPFC) 682
28.8 Thyristor-controlled phase shifting transformer (TCPST) 682
28.9 Interphase power controller (IPC) 682
28.10 Thyristor-controlled voltage limiter (TCVL) 683

***Appendix* 685**
***Index* . . . . 687 – 694**

Example 1.5 The load-duration curve for a system is shown in Fig. 1.2. Determine the load factor.

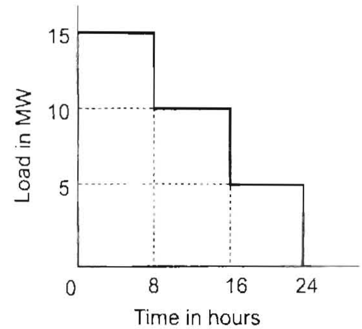

Fig. 1.2.

Solution

From the load-duration curve, the actual energy consumed $= 15 \times 8 + 10 \times 8 + 5 \times 8 = 240$ MWh

$$\text{Average load} = \frac{240}{24} = 10 \text{ MW}$$

Maximum demand = 15 MW

$$\text{Load factor} = \frac{\text{average load}}{\text{maximum demand}} = \frac{10}{15} = 0.666$$

Example 1.6 The yearly load duration curve of a power plant is a straight line. The maximum load is 500 MW and the minimum load is 400 MW. The capacity of the plant is 750 MW. Find (a) plant capacity factor, (b) load factor, (c) utilization factor, (d) reserve capacity.

Solution

$$\text{Average annual load} = \frac{500 + 400}{2} = 450 \text{ MW}$$

$$\text{Capacity factor} = \frac{\text{average annual load}}{\text{capacity of the plant}} = \frac{450}{750} = 0.6$$

$$\text{Load factor} = \frac{\text{average load}}{\text{maximum demand}} = \frac{450}{500} = 0.9$$

$$\text{Utilization factor} = \frac{\text{maximum demand}}{\text{capacity of the plant}} = \frac{500}{750} = 0.667$$

Reserve capacity = plant capacity − maximum demand = 750 − 500 = 250 MW

Example 1.7 A power system had the daily load curve given by the following table :

Time	Load in MW
12.00 night to 2 a.m.	20
2 a.m. to 8 a.m.	10
8 a.m. to 12.30 noon	50
12.30 noon to 1.00 p.m.	40
1.00 p.m. to 6 p.m.	50
6 p.m. to 12 night	70

Plot the following curves :

(a) Chronological load curve

(b) Load-duration curve