ELECTRICAL ENGINEERING

POWER SYSTEMS

Comprehensive Theory
with Solved Examples *and* Practice Questions

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Power Systems

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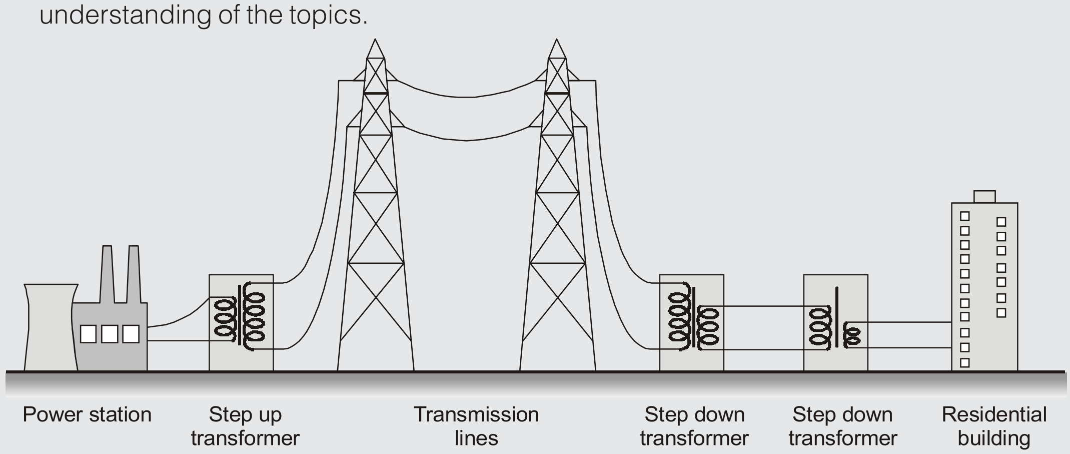
Power Systems

Introduction to Power Systems

An *"Electric power system"* is a network of electrical components used to supply, transmit and use electric power. An example of an electric power system is the network that supplies a region's home and industry with power for sizable regions, this power system is called *"the grid"* and can be broadly divided into the generators that supply the power, the transmission system that carries the power from the generating stations to the load centers and the distribution system that feeds the power to nearby homes and industries. Small power systems are also found in industry, hospitals, homes and commercial buildings. The majority of these systems relay upon *"three-phase AC power"* the standard for large scale power transmission and distribution across the modern world. Specialized power systems that do not rely upon the three-phase AC power are found in aircraft, electric rail systems, automobiles etc.

This course material embodies the principles and objectives of elements of power system. The aim of the course material on power system is to instill confidence and understanding of those concepts of power system that are likely to be encountered in the study and practice of electric power engineering. The presentation is tutorial with emphasis on a thorough understanding of fundamentals and underlying principles. This course material has been prepared in such a way to help the engineering students to understand the basic concept of power system which will help them to excel in the competitive exams like GATE, IES, PSUs and various other competitive examinations. In each chapter, after every topic, wide number of solved examples have been discussed for the better understanding of the topics.



CHAPTER

1

Performance of Transmission Lines, Line Parameters and Corona

1.1 POLY PHASE AC CIRCUITS

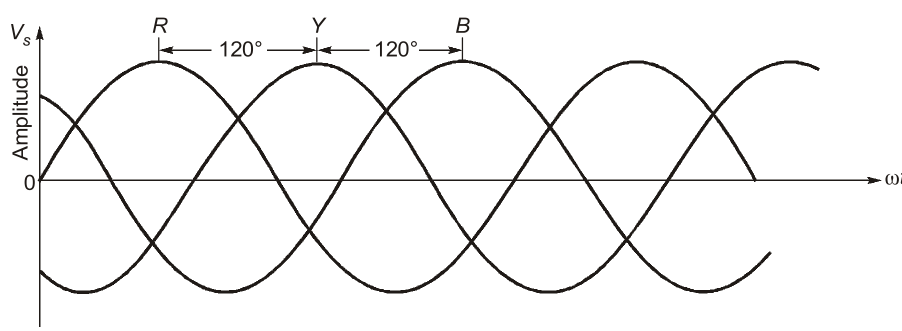
A polyphase system is a means of distributing alternating-current (AC) electrical power where the power transfer is constant during each electrical cycle. Polyphase systems have three or more energized electrical conductors carrying alternating currents with a defined phase between the voltage waves in each conductor.

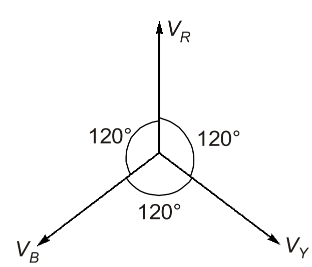
For three-phase voltage, the phase angle is 120° or $\frac{2\pi}{3}$ radians. The electric energy is transmitted over either three or four wires, more often called lines. In them, three of the line currents are identical except for a phase angle difference of 120° electrical.

Generally, n phase systems are $\frac{360°}{n}$ apart in space. (if $n \neq 2$)

For $n = 2$, phase system are 90° apart in space.

1.2 GRAPHICAL REPRESENTATION OF 3-ϕ SYSTEM





Here, phase sequence = RYB

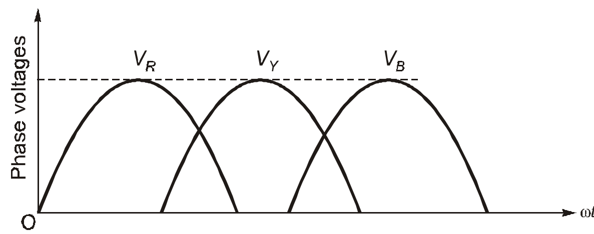
and $V_R = V_m \sin \omega t$ volt $= V\angle 0°$ volt

$V_Y = V_m \sin(\omega t - 120°)$ volt $= V\angle -120°$ volt

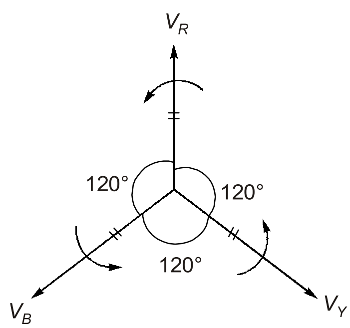
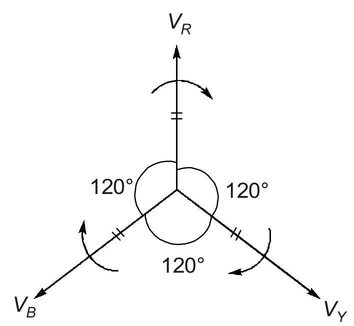
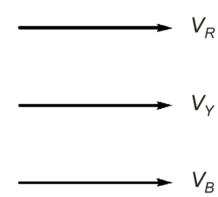
$V_B = V_m \sin(\omega t - 240°)$ volt $= V\angle -240°$ volt $= V\angle +120°$ volt

1.2.1 Phase Sequence

Phase sequence is the order in which voltage waveforms of a polyphase AC source reach their respective peaks. For a three-phase system, there are only two possible phase sequences : RYB and RBY, corresponding to the two possible directions of alternator.



For a 3-ϕ system phase sequence must be defined, RYB is the universally adopted phase sequence.

Positive Phase sequence	Negative Phase sequence	Zero Phase sequence
i.e. *RYB, YBR, BRY* 	i.e. *RBY* 	i.e. no particular order of phase sequence, means zero sequence 

For balanced 3-ϕ system: $I_R + I_Y + I_B = 0$.   For unbalanced 3-ϕ system: $I_R + I_Y + I_B \neq 0$

NOTE

- The phase sequence can be theoretically reversed by reversing the rotation of the rotor but practically it is not possible.
- The phase sequence can be practically reversed by interchanging the any two terminal of the machine.
- The phase sequence of all sources in practical power system will always be same.

1.2.2 Advantages of 3-ϕ System

The advantages of a 3-phase system over a single phase system are as under:

(*i*) The amount of conductor material needed to transfer same amount of power is lesser for three phase system thus it is more economical.

(*ii*) Domestic power and industrial/commercial power can be provided from the same source.

(*iii*) Voltage regulation of three phase is better.

(*iv*) The torque produced by a three phase motor is more. Also having better power factor.

(*v*) As three phase motors are self-starting while single phase motor are not, three phase system is certainly advantageous and versatile.

(*vi*) For a given size of the frame, three phase generator provides more output.

(*vii*) With the help of 3-ϕ system, interconnection is possible either in star or in delta.

(*viii*) A rotating magnetic field can be produced with the help of a balanced 3-phase winding (in space) when supplied with a balanced three phase current (in time).

(*ix*) Three phase machines produce less vibration compared to a single phase machines.

(*x*) For a while in use a three-phase system, converting systems like rectifiers the DC voltage waveform becomes smoother with the increase in the number of phases of the system.

Vibration

The overhead line experiences vibrations in the vertical plane and there are two types of such vibration in additional to normal swinging in wind, called **aeoline vibrations** or **resonant vibrations** or **high frequency oscillation and galloping** or **low frequency vibrations.**

- Aeoline vibration are high frequency (5 -100 Hz) and low amplitude (20 mm to 50 mm) vibration. They are caused by vortex phenomenon of light winds (5-20 km/hr). The line conductor vibrates in number of loops. The length of loop depends on tension (T) and weight of conductor (W) per meter length,

  i.e., $\frac{1}{2f}\sqrt{\frac{T}{W}}$.

  Loop length varies from 1 to 10 meters.
- Low frequency vibration (about 1 Hz) occur during sleet storms with a strong wind.

  The amplitude is very large about 6 m or more.

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Important Expressions

1. Percentage efficiency of a transmission line is given by

$$\%\eta = \frac{P_R}{P_S}\times 100 = \frac{(P_S - P_{Loss})}{P_S}\times 100 = \frac{P_R}{(P_R + P_{Loss})}\times 100$$

2. Percentage voltage regulation is given by

$$\%\text{ V.R.} = \left(\frac{|V_S| - |V_R|}{|V_R|}\right)\times 100 = \frac{|V_{XL}|}{|V_R|}\times 100 = \left(\frac{|V_{R,NL}| - |V_{R,FL}|}{|V_{R,FL}|}\right)\times 100$$

3. If % V_R and V_X are know then, percentage voltage regulation can also be written as

$$\%R = (\%\ V_R \cos\phi_R) \pm (\%\ V_X \sin\phi_R)$$

where,sign is +ve for lagging p.f. load and sign is –ve for leading p.f. load

4. Zero regulation in a line occurs at leading p.f. load when $(\phi_R + \theta) = 90°$

or, $$\phi_R = \tan^{-1}\left(\frac{R}{X_L}\right)$$

5. Maximum regulation occurs at leading p.f. load when $\phi_R = \theta$ or $\tan\phi_R = \left(\frac{R}{X_L}\right)$

6. Negative regulation occurs at leading p.f. load, i.e., $\tan\phi_R$ (leading) > $\frac{R}{X_L}$

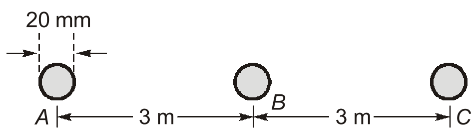
7. **Transmission matrix:**

   (*i*) Short transmission line: $\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & Z \\ 0 & 1 \end{bmatrix}$

OBJECTIVE BRAIN TEASERS

Q.1 A 3-ϕ transmission line has corona loss of 48 kW at 96 kV and 90 kW at 112 kV. The disruptive voltage between lines is _____.

Q.2 The capacitance and charging current per unit length of the line for the following arrangement of conductors of diameter 20 mm shown in figure below will be respectively given by (Line voltage = 220 kV).



(a) 9.3737 μF, 1.261 mA
(b) 3.2323 pF, 1.261 mA
(c) 9.37.37 pF, 0.374 mA
(d) 3.2323 mF, 0.374 mA

Q.3 In context of corona which statement is not true?
(a) corona is voltage effect
(b) corona takes place on short transmission lines
(c) corona is accompanied with power loss
(d) corona attenuates lightning surges

Q.4 When an alternating current flows through a conductor
(a) entire current passes through the core of the conductor.
(b) portion of conductor near the surface carries more current in comparison to the core.
(c) current remains uniformly distributed over the whole cross-section of the conductor.
(d) portion of conductor near the surface carries less current in comparison to the core.

Q.5 For equilateral spacing of conductors of an untransposed 3-phase line, we have
(a) balanced receiving-end voltage and no communication interference.
(b) unbalance receiving-end voltage and no communication interference.
(c) balance receiving-end voltage and communication interference.
(d) unbalanced receiving-end voltage and communication interference.

Q.6 The regulation of a line at full load 0.8 pf lagging is 12%. The regulation at full load 0.8 pf leading can be
(a) 24% (b) 18%
(c) 12% (d) 4%

Q.7 Power dispatch through a line can be increased by
(a) installing series capacitors
(b) installing shunt capacitors
(c) installing series reactors
(d) installing shunt reactors

Q.8 The surge impedance of a 500 miles long line 400 Ω. For a 250 miles length it will be
(a) 400 Ω (b) 500 Ω
(c) 200 Ω (d) None of these

Q.9 The dielectric strength of air is
(a) proportional to barometric pressure
(b) proportional to absolute temperature
(c) inversely proportional to barometric pressure
(d) none of the above

Direction for Questions (10 to 13):

Each of the following question consists of two statements, one labelled the **'Assertion (A)'** and the other labelled the **'Reason (R)'**. Examine the two statements carefully and decide if the Assertion (A) and Reason (R) are individually true and if so whether the Reason (R) is correct explanation of the Assertion (A). Select your answers to these questions using the codes given below:

Codes:
(a) Both A and R are true and R is the correct explanation of A.
(b) Both A and R are true but R is not a correct explanation of A.
(c) A is true but R is false.
(d) A is false but R is true.

Q.10 Assertion (A) : EHV transmission lines make use of bundled conductors.
Reason (R) : Bundled conductors reduce the line inductance per phase and increase the capacitance.

Q.11 Assertion (A): Transposition of conductors in a transmission line is necessary.
Reason (R): Corona losses are reduced by transposition of conductors.

HINTS & EXPLANATIONS

1. (52.65)

Power loss due to corona

$$P_c = \frac{244}{\delta}(f+25)\sqrt{\frac{r}{d}}(V_{ph}-V_{d0})^2 \times 10^{-5}$$

kW/km/phase

Taking δ, r, d and f as constant

$$P_c \propto (V_{ph} - V_{d0})^2$$

$$48 \propto \left(\frac{96}{\sqrt{3}} - V_{d0}\right)^2 \quad ...(1)$$

and
$$90 \propto \left(\frac{112}{\sqrt{3}} - V_{d0}\right)^2 \quad ...(2)$$

From equation (1) and (2) we get,

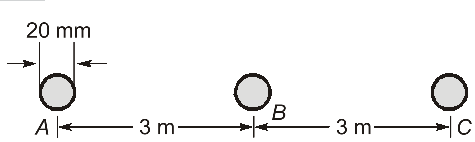
$$\frac{90}{48} = \frac{\left(\frac{112}{\sqrt{3}} - V_{d0}\right)^2}{\left(\frac{96}{\sqrt{3}} - V_{d0}\right)^2}$$

$$V_{d0} = 30.4 \text{ kV}$$

∴ Disruptive voltage between lines

$$= \sqrt{3} \times V_{d0} = 52.65 \text{ kV}$$

2. (c)



Radius, $r = \frac{20}{2} = 10 \text{ mm} = 0.01 \text{ m}$

spacing between conductors are

$d_1 = AB = 3$ m; $d_2 = BC = 3$ m; $d_3 = CA = 6$ m

Capacitance per phase per m length is

$$C_N = \frac{2\pi\varepsilon_0}{\log_e \frac{\sqrt[3]{d_1 d_2 d_3}}{r}}$$

$$= \frac{2\pi \times 8.854 \times 10^{-12}}{\log_e \frac{\sqrt[3]{3 \times 3 \times 6}}{0.01}} = 9.3737 \times 10^{-12} \text{ F}$$

$$= 9.3737 \text{ pF}$$

Charging current per phase, $I_C = 2\pi f C_N V_{ph}$

$$= 2\pi \times 50 \times 9.3737 \times 10^{-12} \times \frac{220 \times 10^3}{\sqrt{3}}$$

$$= 0.374 \text{ mA}$$

3. (b)

- Corona on an overhead line occurs due to high electric field intensity at the surface of the conductor (resulting in ionization of air particles). For occurrence of corona, the potential gradient of the conductor must be greater than the dielectric strength of air. Hence it is a voltage effect phenomenon.
- Corona results into power loss called “corona loss”.
- Corona acts as safety valve for the conductor surface and decreases the impact of lightning surges on the surface of the conductor. Hence, it attenuates lightning surges.
- Corona does not occur in short transmission lines (because of low voltage). Hence, option (b) is not true.

4. (b)

When an AC current flows through a conductor, the inductive reactance of the inner strands increases while that for the outer strand decreases so that outer strand conducts more correct than the inner strand. Due to this reason, portion of conductor near the surface carries more current in comparison to the core (or inner strand). This phenomenon is called skin effect.

5. (c)

Since conductors having equilateral spacing will have symmetrical spacing therefore, the receiving end voltage will be balanced. Also, as the conductors are not transposed therefore, it will result into communication interference with the neighbouring communication lines.

CONVENTIONAL BRAIN TEASERS

Q.1 A 3-phase, 50 Hz transmission line at 11 kV delivers a load of 1000 kW at 0.8 p.f. (lagging) over 10 kms. Calculate the line current, receiving end voltage and efficiency of transmission. Resistance and reactance of each line conductor may be assumed to be 0.5 Ω/km and 0.56 Ω/km respectively.

1. (Sol)

Here, receiving end voltage is not given.

Sending end voltage (per phase) is,

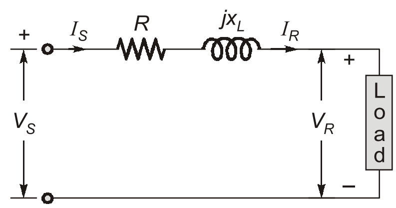
$$V_S = \frac{11\times 10^3}{\sqrt{3}} = 6351 \text{ volts or } 6350.8\text{ V}$$

We know that,

$$V_S - V_R = I_R R\cos\phi_R \pm I_R X_L \sin\phi_R$$

For lagging p.f.,

$$V_S - V_R = I_R R\cos\phi_R + I_R X_L \sin\phi_R$$



Given, $R = 0.5\ \Omega/\text{km}$

$X_L = 0.56\ \Omega/\text{km}$ (Per phase)

Length of line = 10 km

So, $R = 5\ \Omega/\text{phase}$; $X_L = 5.6\ \Omega/\text{phase}$

Also,

$$I_R = I_S = \frac{1000\times 10^3}{3\times V_R\cos\phi_R} = \frac{10^5}{3\times V_R\times 0.8} = \frac{416.67\times 10^3}{V_R}$$

Now,

$$6351 - V_R = \frac{416.67\times 10^3}{V_R}[5\times 0.8 + 5.6\times 0.6]$$

or,

$$6351 = V_R + \frac{3066.69\times 10^3}{V_R}$$

or,

$$V_R^2 - 6351V_R + 3066.67\times 10^3 = 0$$

Solving we get, $V_R = 5824.5\text{ V or } 526.5\text{ V}$

But, V_R can't be 526.5 volt. So, $V_R = 5824.5$ volts

∴ Line current,

$$I_S = I_R = \frac{416.67\times 10^3}{5824.5} = 71.5\text{ A or } 71.537\text{ A}$$

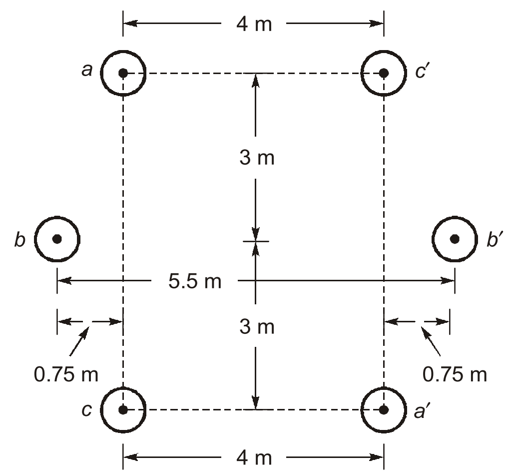
Receiving end voltage, Line voltage

$$V_{RS} = \frac{\sqrt{3}\times 5824.5}{1000} = 10.09\text{ kV} \quad \text{(line value)}$$

Also, efficiency of transmission is,

$$\%\eta = \left(\frac{\text{Output power}}{\text{Output power + losses}}\right)\times 100 = \frac{1000\times 10^3}{1000\times 10^3 + [3\times(71.5)^2\times 5]}\times 100 = 92.87\%$$

Q.2 A 3-phase double circuit line is arranged as shown below.



The conductors are transposed. The radius of each conductor is 0.75 cm. Phase sequence is *ABC*. Find the inductance per phase per km.

2. (Sol)

Radius of each conductor is : $r = 0.75$ cm

∴ Self GMD for each conductor is

$$= 0.7788r = 0.7788 \times 0.75 \text{ cm} = 0.5841 \text{ cm}$$

Now,
$$d_{bc} = d_{ab} = \sqrt{3^2 + 0.75^2} = 3.092 \text{ m}$$
$$d_{ab'} = \sqrt{4.75^2 + 3^2} = 5.618 \text{ m;}$$
$$d_{aa'} = \sqrt{4^2 + 6^2} = 7.211 \text{m}$$

∴ Mutual GMD,
$$D_{m_1} = (3.092 \times 6 \times 4 \times 5.618)^{1/4} = 4.518 \text{ m} = D_{m_3}$$
$$D_{m_2} = (3.092 \times 3.092 \times 5.618 \times 5.618)^{1/4} = 4.168 \text{ m}$$

Hence, equivalent mutual GMD is,

$$D_m = (D_{m_1} D_{m_2} D_{m_3})^{1/3} = (4.518 \times 4.168 \times 4.518)^{1/3} = 4.398 \text{ m}$$

Also, self GMD of each phases are

$$D_{s_1} = (0.00584 \times 7.211)^{1/2} = 0.2052 \text{ m} = D_{s_3}$$

and
$$D_{s_2} = (0.00584 \times 5.5)^{1/2} = 0.179 \text{ m}$$

So, equivalent self GMD is

$$D_s = (D_{s_1} D_{s_2} D_{s_3})^{1/3} = (0.2052 \times 0.179 \times 0.2052)^{1/3} = 0.196 \text{ m}$$

∴ Inductance,
$$L = 2 \times 10^{-4} \, ln\left(\frac{D_m}{D_s}\right) \text{ H/km/phase}$$
$$= 2 \times 10^{-4} \, ln\left(\frac{4.398}{0.196}\right) \text{ H/km/phase} = 0.622 \text{ mH/km/phase}$$