Electrical Engineering

Power Systems

Comprehensive Theory

with **Solved Examples** and **Practice Questions**

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Power Systems

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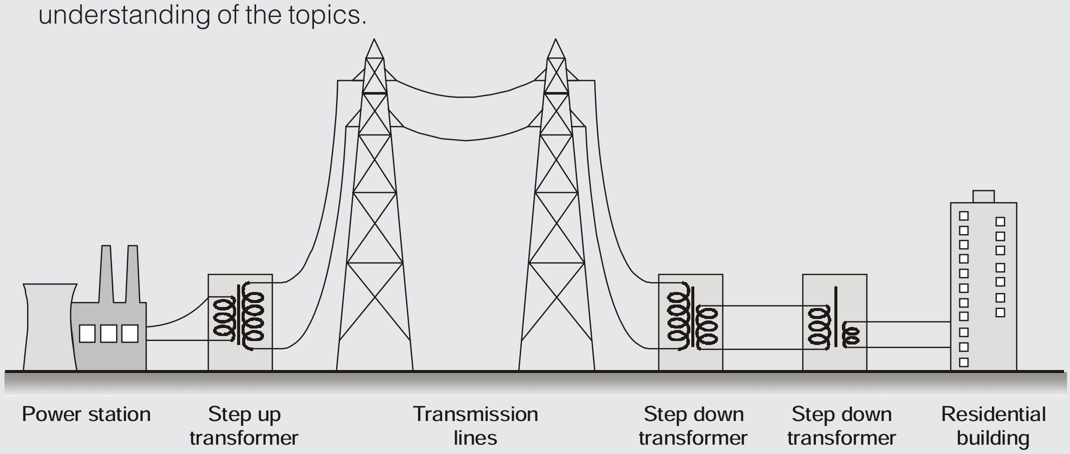
Power Systems

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 in understanding the basic concept of power system which will help them to excel in the competitive exams like GATE, IES, PSUs and other various competitive examinations. In each chapter, after every topic, wide number of solved examples have been discussed for the better understanding of the topics.



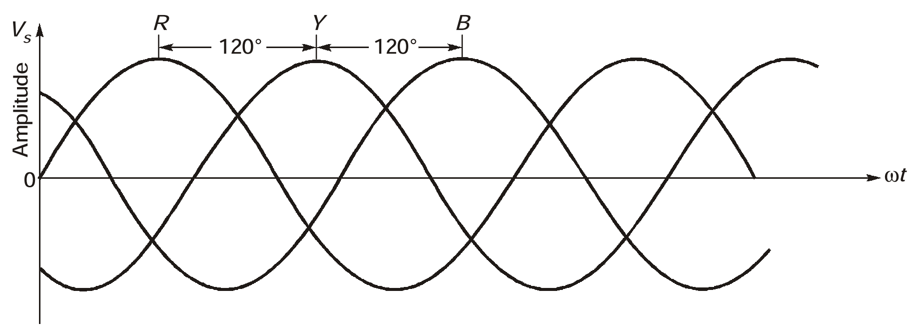
Performance of Transmission Lines, Line Parameters and Corona

1.1 Poly Phase AC Circuits

Poly phase circuits are important because all electric power is generated and distributed three-phase. A three-phase circuit has an ac voltage generator, also called an alternator, that produces three sinusoidal voltages that are identical except for a phase angle difference of 120° electrical. 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.

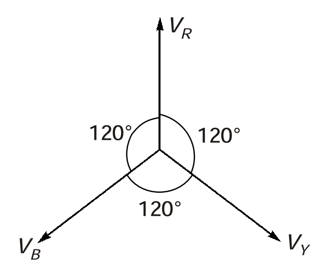
Generally, n phase systems are $\frac{360°}{n}$ apart in space.

1.2 Graphical Representation of 3-ϕ System



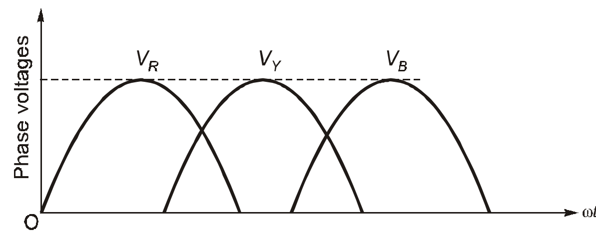
Here, phase sequence = RYB

and
$$V_R = V_m \sin\omega t \text{ volt} = V\angle 0° \text{ volt}$$
$$V_Y = V_m \sin(\omega t - 120°) \text{ volt} = V\angle -120° \text{ volt}$$
$$V_B = V_m \sin(\omega t - 240°) \text{ volt} = V\angle -240° \text{ volt}$$
$$= V\angle +120° \text{ volt}$$

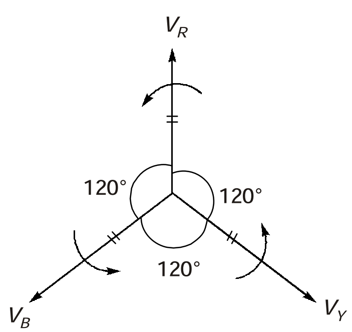
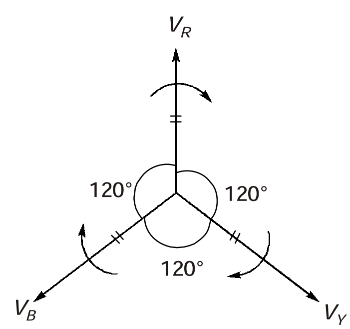
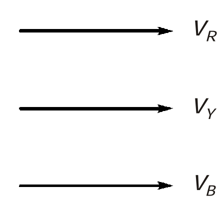


1.2.1 Phase Sequence

It is the order by which the phase voltages attains their peak value. The phase sequence may be positive, negative or zero (No particular sequence).



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

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 

Balanced and Unbalanced 3-ϕ System

For balanced 3-ϕ system: $I_R + I_Y + I_B = 0$

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

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.

(*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 machine.

Example - 1.1 What is the current flowing through the neutral in a balanced 3-phase star system?

Solution:

Current flowing through the neutral is always zero as long as the system is working under balanced condition.

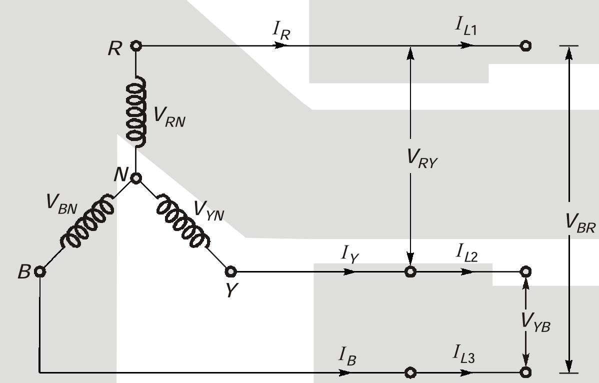
Under balanced condition: $I_R + I_Y + I_B = I_N = 0$ A

1.3 Type of 3-ϕ Connections

1. Star (Y) connection
2. Delta (Δ) connection

1.3.1 Star (Y) Connection

Figure shows a balanced three phase star connected system having phase sequence *RYB* (Positive phase sequence).



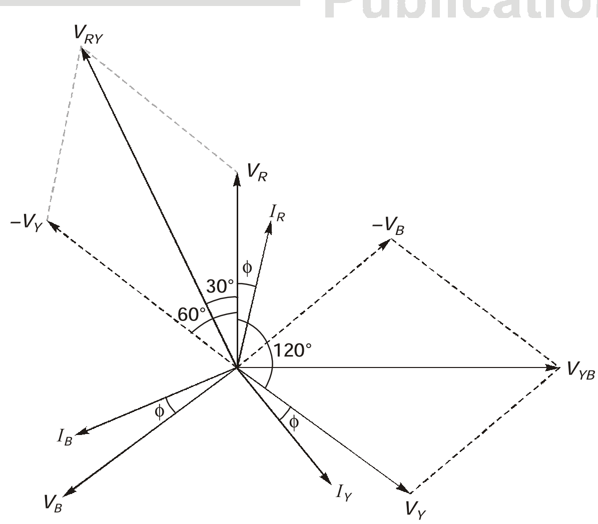
Here,

⇒ $|V_{RN}| = |V_{YN}| = |V_{BN}| = V_{Ph}$ are phase voltages (Voltage between a line and neutral)

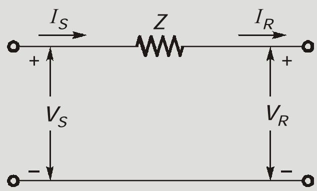
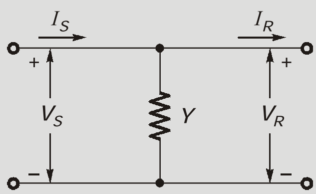
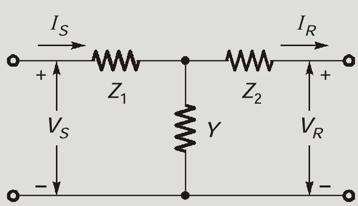
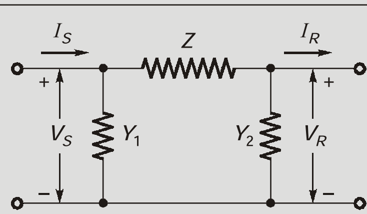
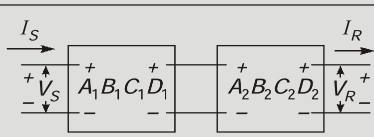
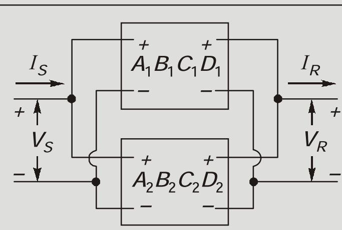
⇒ $|V_{RY}| = |V_{YB}| = |V_{BR}| = V_L$ are line voltages (i.e. voltage between two phases)

⇒ $V_{RN} = (V_R - V_N)$

It's phasor diagram is shown below:



The table given below summaries the *ABCD* constants for various networks.

 Series impedance	$A = 1$ $B = Z$ $C = 0$ $D = 1$
 Shunt admittance	$A = 1$ $B = 0$ $C = Y$ $D = 1$
 Unsymmetrical-T	$A = 1 + YZ_1$ $B = Z_1 + Z_2 + YZ_1Z_2$ $C = Y$ $D = 1 + YZ_2$
 Unsymmetrical π	$A = 1 + Y_2Z$ $B = Z$ $C = Y_1 + Y_2 + ZY_1Y_2$ $D = 1 + Y_1Z$
 Networks in cascade	$A = A_1A_2 + B_1C_2$ $B = A_1B_2 + B_1D_2$ $C = A_2C_1 + C_2D_1$ $D = B_2C_1 + D_1D_2$
 Network in Parallel	$A = (A_1B_2 + A_2B_1)/(B_1 + B_2)$ $B = B_1B_2/(B_1 + B_2)$ $C = C_1 + C_2 + (A_1 - A_2)(D_2 - D_1)/(B_1 + B_2)$ $D = (B_2D_1 + B_1D_2)/(B_1 + B_2)$

CHAPTER 5

Fault Analysis

5.1 Introduction

Whenever there is insulation failure of equipment in a power system or flashover of the lines initiated by a lightning stroke or accidental faulty operation of the system, a heavy symmetrical short circuit current flows in the system. The system must be protected against flow of that heavy short circuit currents by disconnecting the faulty part of the system by means of circuit breakers operated by protective relays. The main objective of fault analysis is to determine the fault level or the fault MVA at the fault location. This fault MVA is the breaking capacity of the circuit breaker that has to be kept at the point of fault location.

There are two types of fault occurring in the power system, namely ***"symmetrical fault"*** and ***"unsymmetrical fault"***. The majority of fault occuring in power system are faults involving one line to ground occasionally two lines to ground which are termed as ***"unsymmetrical faults"***. The faults involving all the three phase to ground or all the three phase short-circuited belongs to ***"symmetrical fault".*** The symmetrical faults generally leads to most severe fault current which need to be interrupted. Though the operating conditions at the time of fault are important, the loads can be neglected during fault, as voltage dip very low so that currents drawn by loads can be neglected in comparison to fault current. The most common and dangerous fault, that occur in a power system, is the ***short-circuit*** or ***shunt faults*** which involves power conductor or conductors-to-ground or short-circuit between conductors and causes a heavy current, called the ***"short-circuit current"***. Short circuit calculation are very important since they provide data, which is necessarily required for designing the protective scheme for the power system."

Type of Faults in a Power System

There are basically two types of faults occurring in a power system namely:

1. **Symmetrical faults:**
   These constitutes the fault involving:
   (*i*) All the three phase to earth (3-phase fault, **3% chances of occurrence**).
   (*ii*) All the three short-circuited.

2. **Unsymmetrical faults:**
   This types of fault constitutes the fault involving:
   (*i*) Single phase to ground **(85% chances)** – SLG (Single Line to Ground fault)
   (*ii*) Phase to phase **(5% chances)** – LL (Line to Line fault)
   (*iii*) Two phases to ground **(7% chances)** – LLG (Line-Line to Ground fault)

NOTE

- Although the unsymmetrical faults are more prevalent, the symmetrical fault usually give the more severe duty on the circuit breaker.
- The calculation of symmetrical short-circuit current or symmetrical short-circuit KVA at a certain point in power system is, therefore, very important for the purpose of determination of circuit breaker ratings.
- The different kinds of faults in order of decreasing severity are:
  Three phase fault **(3-ϕ fault)** > Double line to ground **(LLG)** fault > Line to line **(LL)** fault > Single line to ground **(LG)** fault.

5.2 Per Unit System

- In power system, it is usual to express voltage, current, voltamperes and impedance of an any electrical circuit in per unit or percentage.
- The per unit (pu) value of any quantity is defined as ***"the ratio of the quantity (in some unit) to it's base value (in same unit)".***

i.e. p.u. value of a quantity $= \left[\dfrac{\text{the actual value in any unit}}{\text{the base or reference value in the same unit}}\right]$

Selection of Base Values for pu System

1. Single-Phase System:

Let,

Base Mega volt-amperes $= (MVA)_b$

or, Base kilovolt-ampere $= (kVA)_b$

Base kilovolts $= (kV)_b$

Now, Base current, $I_b = \dfrac{(MVA)_b}{(kV)_b} \times 1000 = \dfrac{(kVA)_b}{(kV)_b}$ Amperes

$\therefore$ Base impedance, $Z_b = \dfrac{(kV)_b^2}{(MVA)_b} = \dfrac{(kV)_b^2}{(KVA)_b} \times 1000$ ohms

Hence, per unit impedance;

$$Z(\text{pu}) = \frac{(MVA)_b}{(kV)_b^2} \times Z \text{ (ohms)} \quad \text{or} \quad Z_{1-\phi}(\text{pu}) = \frac{(kVA)_b \times Z(\text{ohms})}{(kV)_b^2 \times 1000} \qquad ...(1)$$

2. Three-Phase System:

Let, the base Mega volt-amperes $= (MVA)_b$

and line-to-line base kilovolts $= (kV)_b$

For star connected circuit, we have,

Base current, $I_b = \dfrac{(MVA)_b \times 1000}{\sqrt{3} \times (kV)_b} A$

Base impedance, $Z_b = \dfrac{(kV)_b \times 100}{\sqrt{3} \times I_b}$ ohms $= \dfrac{(kV)_b^2}{(MVA)_b} = \dfrac{(KV)_b^2 \times 1000}{(kVA)_b}$ ohms

$$\therefore \text{ p.u. impedance is, } Z_{3-\phi}(\text{pu}) = \frac{(MVA)_b \times 1000}{(kV)_b^2} = \frac{(kVA)_b \times Z(\text{ohms})}{(kV)_b^2 \times 1000} \qquad ...(2)$$

CHAPTER 10

Recent Trends in Power Systems

10.1 High Voltage DC Transmission (HVDC)

In recent trends DC transmission has staged a comback in the form of HVDC transmission to supplement the HVAC transmission system. DC transmission is an effective means to improve system performance. It is used to complement AC systems rather than to displace these. In India, the first HVDC 810 km long distance OH line is Rihand - Delhi (±500 kV, 1500 MW) for bulk power transmission from Rihand/Singrauli complex to Delhi. The highest transmission voltage reached is ±800 kV. HVDC is also used to interconnect systems of different frequency.

Principle of Operation of HVDC System

DC transmission requires a converter at each end of the line. The sending end converter acts as a rectifier converting AC to DC and the receiving end converter acts as an inverter converting DC to AC. The rectifier at the sending end is fed from an AC source through a transformer (step up) and the inverter feeds AC load through a transformer (Step down). The basic principle of HVDC system operation is explained by Figure 10.1 as shown below.

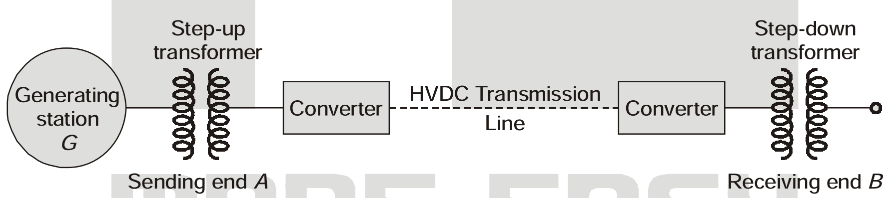


***Figure*-10.1 :** *Line diagram of HVDC transmission system*

The power dispatched from the generating station P_S less the power received at the receiving end P_R i.e. $(P_S - P_R)$ represents the power losses due to conversion and transmission. The *dc* output voltage magnitude is controlled by varying the firing angle of the thyristor valves in the converter. In rectifier the firing angle is between 0° and 90° while in inverter it is between 90° and 180°. As the *dc* output voltage is a function of cosine of the firing angle hence the converter voltage becomes negative when firing angle α exceeds 90°. This makes the converter to operate as an inverter.

In practical HVDC converter stations three-phase bridge converters are employed at both ends. Reversible operations of converters as well as bidirectional power flow in HVDC link is possible simply by the control of firing angle.

Power Control in HVDC System

In AC transmission systems the power transfer is governed by phase difference (magnitude as well as phase) of the voltages at the two ends while in DC systems the power transferred from one station to another station is governed only by the magnitudes of terminal *dc* voltages at the two ends. Due to these reasons, the controllability of HVDC power is fast and stable. Here, the current flows from higher voltage to lower voltage which are set by adjustment of firing /extinction angle of two converters namely rectifier and inverter.

Let V_s be the voltage at the sending end and V_R be the voltage at the receiving end then, the line current will be

$$I_{dc} = \left(\frac{V_S - V_R}{R}\right) \qquad (R = \text{resistance of the entire transmission link.})$$

The sending end voltage is given by

$$V_s = \left[\left(\frac{3\sqrt{2}}{\pi}V_{ac_s}\right)\cos\alpha - \frac{3X_{cs}}{\pi}I_{dc}\right] \qquad ...(1)$$

and the receiving end voltage is given by

$$V_R = \left[\left(\frac{3\sqrt{2}}{\pi}V_{ac_R}\right)\cos\beta - \frac{3X_{C_R}}{\pi}I_{dc}\right] \qquad ...(2)$$

Where,
α = firing angle of rectifier
β = extinction angle of inverter.
V_{ac_S} = *ac* side line-to-line *rms* voltage at sending end
V_{ac_R} = *ac* side line-to-line *rms* voltage at receiving end
X_{C_S} = commutation reactance at the sending end and
X_{C_R} = commutation reactance at the receiving end

Hence, the power transmitted is given by

$$P = V_S \cdot I_{dc} = \left[\frac{V_S - V_R}{R}\right].V_S \text{ watts} \qquad ...(iii)$$

⇒ Here, tap-changers on the ac side take care of voltage variations on *ac* side and *dc* power is controlled by controlling the sending - end and receiving-end voltages V_S and V_R which is possible by control of firing and extinction angles α and β respectively.

Type of HVDC Link or Transmission Modes

The *DC* links can be divided into the following three types:

1. Monopolar Link

- A monopolar link has only one energized conductor normally of negative polarity and uses ground or sea water as the return path. Earth has a much lower resistance to DC as compared to AC. The negative polarity is preferred on overhead lines due to lesser radio interference and corona loss. Figure 10.2 shows a monopolar HVDC link.

Example - 10.6 The power transmission capability of bipolar lines is approximately

(a) half that of 3-phase single circuit line.
(b) same as that of 3-phase single circuit line.
(c) Twice that of 3-phase single circuit line
(d) Thrice that of 3-phase single circuit line.

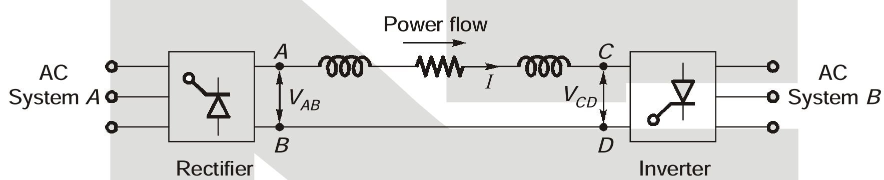
***Solution:* (b)**

Example - 10.7 In the case of HVDC system, there is

(a) charging current but no skin effect
(b) no charging current but skin effect
(c) neither charging current nor skin effect
(d) both charging current and skin effect

***Solution:* (c)**

Example - 10.8 Power is transferred from system A to system b by an HVDC link as shown in figure. If the voltages V_{AB} and V_{CD} are as indicated in the figure, and $I > 0$ then,



(a) $V_{AB} < 0$, $V_{CD} < 0$, $V_{AB} > V_{CD}$
(b) $V_{AB} > 0$, $V_{CD} > 0$, $V_{AB} < V_{CD}$
(c) $V_{AB} > 0$, $V_{CD} > 0$, $V_{AB} > V_{CD}$
(d) $V_{AB} > 0$, $V_{CD} < 0$

***Solution:* (c)**

Since current $I > 0$ as indicated in figure, therefore a positive current will always flow from higher potential to lower potential i.e. $V_{AB} > 0$, $V_{CD} > 0$, $V_{AD} > V_{CD}$

Example - 10.9 Voltage regulation is better in case of HVDC transmission system because of

(a) presence of charging current
(b) presence of series capacitors
(c) absence of inductance in system
(d) none of these

***Solution:* (c)**

In HVDC system since frequency $f = 0$ therefore, the inductive reactance $X_L = 2\pi fL = 0$ and hence, HVDC systems has no problem of voltage regulation.

Example - 10.10 Why is HVDC transmission system superior to that of EHV-AC transmission system?

Solution:

Refer to the previous articles for advantages of HVDC transmission system over EHV-AC transmission system for detail explanation of the problem.

Example - 10.11 What are the types of HVDC transmission system applications?

Solution:

There are three types of HVDC transmission systems namely:

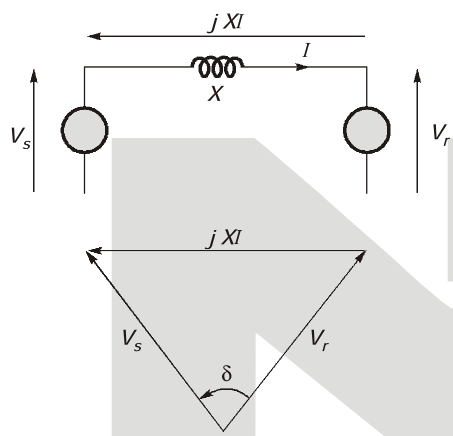
1. Monopolar link
2. Bipolar link
3. Homopolar link

These have been already explained in details in previous articles.

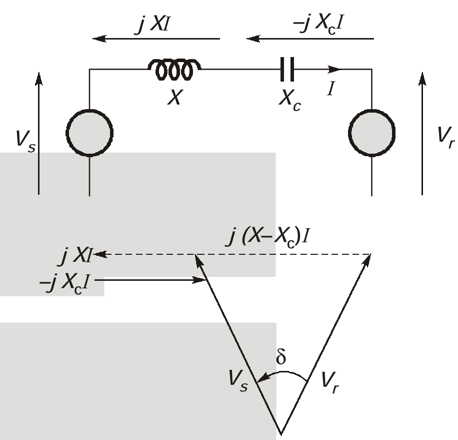
10.2 FACTS

Series Compensation

In series compensation, the FACTS is connected in series with the power system. It works as a controllable voltage source. Series Inductance exists in all AC transmission lines. In long lines, when a large current flows, this causes a large voltage drop. To compensate, series capacitors are connected, decreasing the effect of the inductance. Also by connecting series capacitors in series with line, the inductive reactance between the receiving end and the sending end will be reduced due to which power factor of the system can be improved. But the effect on power factor is very little when compared to shunt capacitor.



Transmission on a no-loss line



Series Compensation

Shunt Compensation

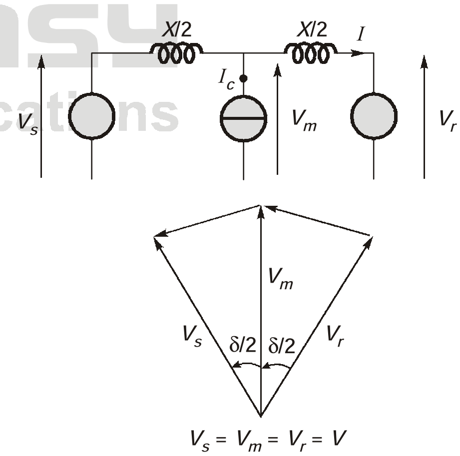
In shunt compensation, power system is connected in shunt (parallel) with the FACTS. It works as a controllable current source. Shunt compensation is of two types.

Shunt capacitive compensation

This method is used to improve the power factor. Whenever an inductive load is connected to the transmission line, power factor lags because of lagging load current. To compensate, a shunt capacitor is connected which draws current leading the source voltage. The net results is improvement in power factor.

Shunt inductive compensation

This method is used either when charging the transmission line, or, when there is very low load at the receiving end. Due to very low, or no load – very low current flows through the transmission line. Shunt capacitance in the transmission line causes voltage amplification (Ferranti effect). The receiving end voltage may become double the sending end voltage (generally in case of very long transmission lines).



Shunt Compensation

To compensate, shunt inductors are connected across the transmission line. The power transfer capability is thereby increase depending upon the power equation.