Chapter 5

HVDC and FACTS

LEARNING OBJECTIVES

After reading this chapter, you will be able to understand:

- HVDC
- Monopolar link
- Bipolar link
- Homopolar link
- FACTS
- Series connected controllers
- Shunt connected controllers
- Combined shunt and series connected controllers
- Other controllers

High-voltage DC Transmission

The limitations for use of high-voltage AC transmission of bulk power over long distance leads to high-voltage DC transmission (HVDC). The advantages of HVDC transmission are.

1. Power transmitted per conductor is more for DC and DC line is cheaper as it requires two conductors instead of three and hence costs on insulation and towers are less.
2. The line construction is simpler and ground return is possibly by using single conductor in HVDC transmission.
3. There is no charging current in DC transmission system, No dielectric losses.
4. Skin effect is low in DC systems and hence current density is also high.
5. Corona loss and radio interference are low as compared to AC systems.
6. HVDC does not have any stability problem and hence asynchronous operation of transmission link among the connected machines is possible.
7. Line losses are less in HVDC transmission.
8. Voltage regulation problems are less serious in HVDC since the reactance drop does not exist in DC systems.
9. HVDC system is economical for transmitting bulk power over long distances say above 550 km.
10. Low short-circuit current is required on HVDC lines.
11. Grid control of the converters can drastically reduce the fault current in HVDC.
12. Compensation of lines does not require in DC transmission.

However, HVDC transmission system has a few disadvantages as follows.

1. Application of HVDC is restricted to the distance above 500 km due to its high initial cost which is uneconomical for distances below 500 km.
2. Circuit breaking for protection of HVDC is difficult and expensive.
3. Convertor stations require considerable reactive power.
4. Harmonic generation and subsequent filtration are problems in HVDC.
5. Reactive power required by the load is to be supplied locally as no reactive power can be transmitted through HVDC lines.
6. Overload capacity of HVDC converters is low.
7. Maintenance of insulators in HVDC transmission is low.

Principle of HVDC System Operation

A typical HVDC transmission system consists of one rectifier station at the sending end and one inverter station at the receiving end. The two stations are interconnected by a DC transmission line. The rectifier station converts AC to DC while the inverter station converts DC to AC. By varying the firing angle of the thyristor in the convertor, the DC output voltage magnitude is controlled.

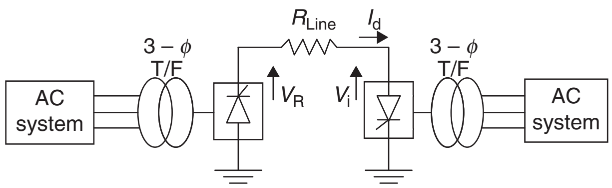


Figure 1 Schematic of a HVDC system

Rectified firing angle is $0° < \alpha < 90°$

Inverter firing angle is $90° < \alpha < 180°$

The current flows from higher voltage to lower voltage by proper setting of the rectifier and inverter. In the DC transmission system the line current (I_d) is given by

$$I_d = \frac{V_R - V_i}{R}$$

where V_R is the DC output voltage at the rectifier and V_i is the DC output voltage at the inverter end.

$$V_R = \left[\left(\frac{3\sqrt{2}}{\pi}\right) V_{AC_r} \cos\alpha - \frac{3X_{cr}}{\pi} I_d\right]$$

$$V_i = \left[\left(\frac{3\sqrt{2}}{\pi} V_{AC_i}\right) \cos\gamma - \frac{3X_{ci}}{\pi} I_d\right]$$

where V_{AC_r} = AC side, line-to-line RMS voltage at rectifier side

V_{AC_i} = AC side, line to line RMS voltage at inverter side

α = Firing angle of rectifier

γ = Extinction angle of inverter

X_{cr} or X_{ci} = Communication reactance at the rectifier and inverter.

The power transfer is given by

$$P = V_i I_d = \left(\frac{V_R - V_i}{R}\right) V_i \text{ W}$$

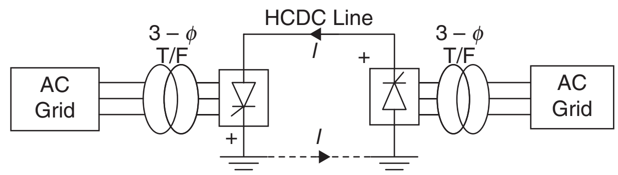
Types of DC Links

HVDC links are classified as

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

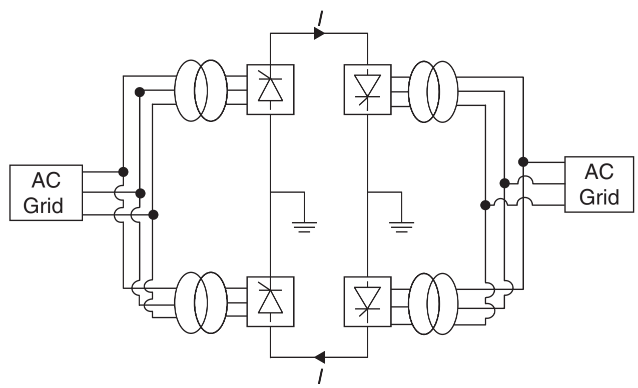
Monopolar Link

This configuration uses only one conductor and ground or sea water is used as return conductor. Negative polarity is used as the transmission conductor due to comparatively lesser ratio interference.



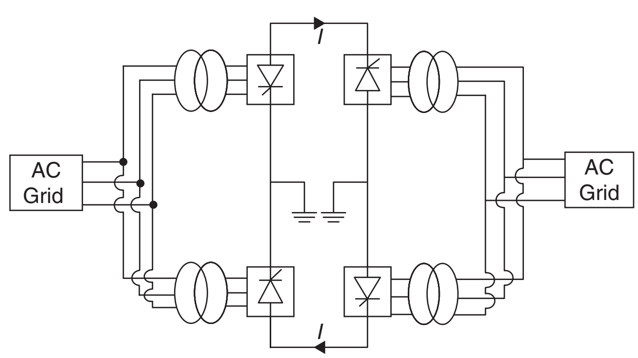
Bipolar Link

This configuration uses two conductors, one positive and another negative. In each terminal, two converters of equal rated voltages are connected in series, neutral points being grounded. Two poles can operate independently when both the terminals are grounded. When the currents in the two conductors are equal, the ground current is zero. In case of fault in one conductor, the other conductor can supply 50% of the rated load along with the ground return.



Homopolar Link

This configuration has two conductors. But having same polarity, ground is used as return path. In case of fault in one conductor, the other conductor can supply 50% of the rated load along with the ground return.



FACTS

Flexible alternating current transmission systems (FACTS) is a technology which provides a methodology for the utilities to effectively utilize their assets, enhance transmission capability by loading lines to their full transmission capability and therefore, minimize the gap between the stability and the thermal limits, and improve grid reliability. The FACTS technology is based on the use of reliable high-speed power electronics, advanced control technology, advanced micro computers, and powerful analytical tools.

Consider a transmission line of reactance X_{pu} (negligible resistance) connecting two buses in a power system. The system voltage magnitudes in per unit and phase angles are indicated in the diagram.

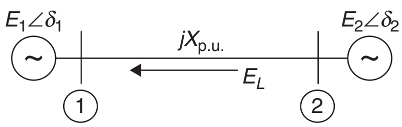


Figure 2 Single-line diagram of AC transmission connecting two buses

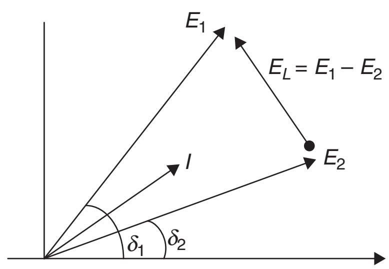


Figure 3 Phasor diagram of the two bus power systems

Line current lags the line voltage drop $E_L = (E_1 - E_2)$ by 90° and is given by

$$I = \frac{E_L}{X} = \frac{E_1 - E_2}{X}$$

Active power flow along the line is given by

$$P = \frac{|E_1||E_2|}{X}\sin\delta$$

where $\delta = \delta_1 - \delta_2$

Reactive power flows Q_1 and Q_2 are expressed as

$$Q_1 = \frac{1}{X}\left(|E_1|^2 - |E_1||E_2|\cos\delta\right)$$

$$Q_2 = \frac{1}{X}\left(|E_2|^2 - |E_1||E_2|\cos\delta\right)$$

From the expression of active and reactive power it can be observed that the active and reactive power on transmission line are depended on line reactance X, voltage magnitudes $|E_1|$ and $|E_2|$, line voltage drop E_L and phase angle difference between the two voltages $\delta = \delta_1 - \delta_2$.

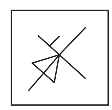
FACTS technology utilizes thyristor-controlled fast-acting controllers to control the following:

1. Line reactance
2. Magnitude of terminal voltages
3. Magnitude of voltage drop (E_L)
4. Phase angle difference

Control action	Parameter affected
(1) Line reactance control	Line current and active power control
(2) Phase angle difference control	Line current and active power control
(3) Voltage injection in series with the line and perpendicular to the current	Real power control through the control of line current
(4) Voltage injection in series with the line and any phase angle with respect to the driving voltage	Accurate control of real and reactive power flow in the line

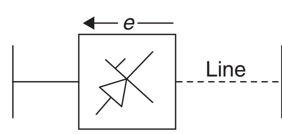
Basic Types of FACTS Controllers

FACTS devices are power electronic based systems and other static equipment that provide control of one or more transmission system parameters. System of FACTS controller is given by

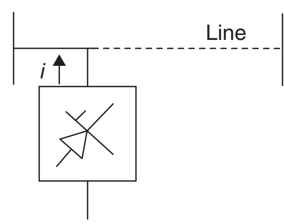


The four basic types of FACTS controllers are given by

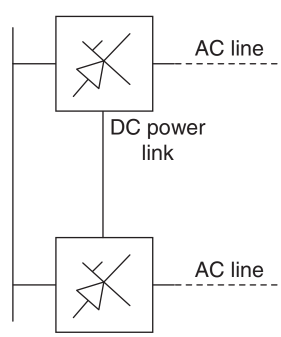
1. Series controllers



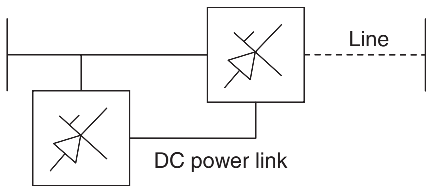
2. Shunt controllers



3. Combined series–series controllers



4. Combined series-shunt controllers



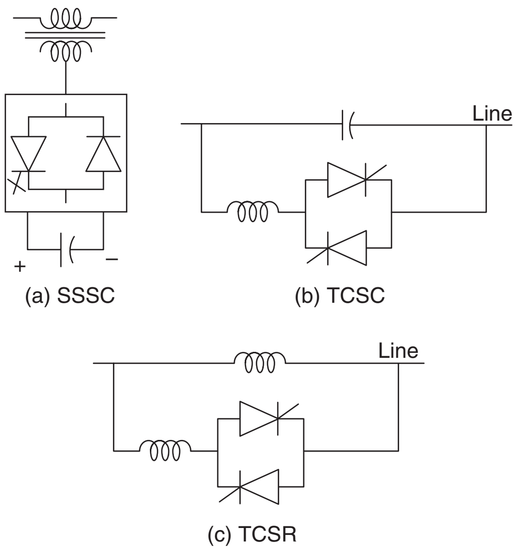


Figure 4 Series-connected FACTS controllers

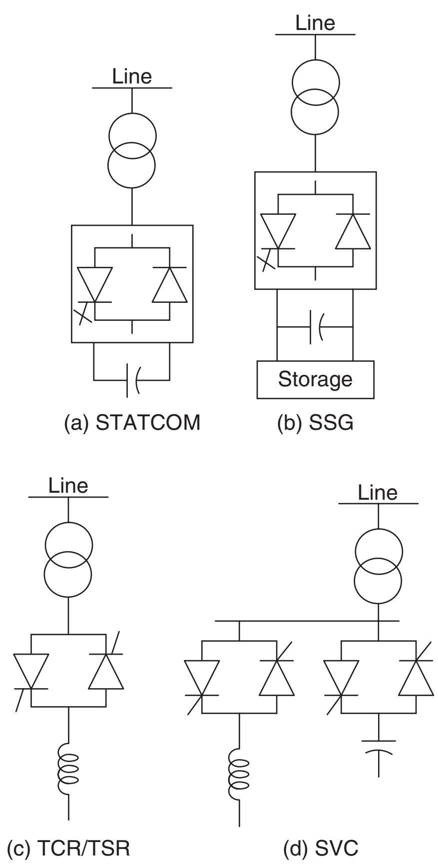


Figure 5 Shunt FACTS controllers

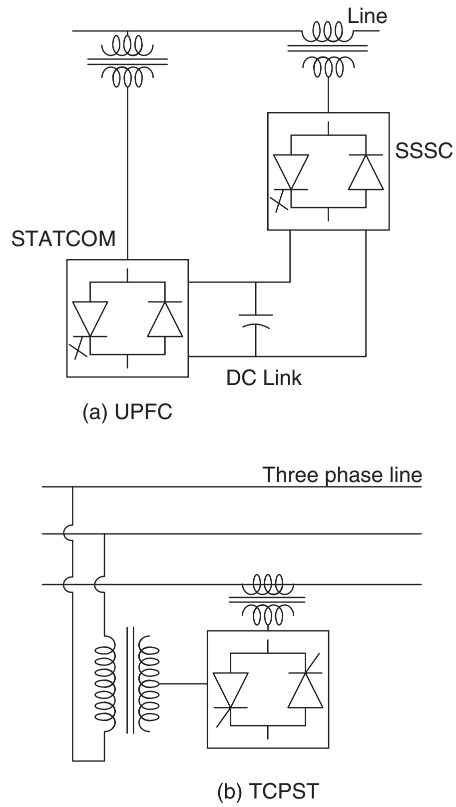


Figure 6 Combined series-shunt controllers

Series-connected Controllers

Static Synchronous Series Compensator (SSSC)

A static synchronous operates as a series compensator whose output voltage is in quadrature with, and controllable independent of, the line current for the purpose of increasing the overall reactive voltage drop across the line and there by controlling the transmitted electrical power.

Inter Power Flow Controller (IPFC)

It is a combination of SSSC's, which are controlled to provide independent reactive compensation for the Adjustment of real power flow in each line.

Thyristor-controlled Services Capacitor (TCSC)

This is a capacitive reactive compensator which consists of a series capacitor bank shunted by a thyristor-controlled reactor in order to provide a smoothly variable series capacitive reactance.

Thyristor-controlled Series Reactor (TCSR)

It consists of a series reactor shunted by a thyristor-controlled reactor in order to provide a smoothly variable series inductive reactance.

Shunt-connected Controllers

Static Synchronous Compensator (STATCOM)

It is a shunt-connected static VAR compensator whose capacitive or inductive output current can be controlled independent of the AC system voltage.

Static Synchronous Generator (SSG)

It produces a set of adjustable multiphase output voltages, which may be coupled to an AC power system for the purpose of exchanging independently controllable real and reactive power.

Static VAR Compensator (SVC)

Its output is adjusted to exchange capacitive or inductive current so as to maintain or control specific parameters of the electrical power system.

Thyristor-controlled Reactor (TCR)

Its effective reactance is varied in a continuous manner by partial conduction control of the thyristor value.

Combined Shunt- and Series-connected Controllers

Unified Power Flow Controller (UPFC)

It is a combination of STATCOM and SSSC to provide real and reactive series line compensation. The UPFC may also provide independently controllable shunt reactive compensation.

Thyristor-controlled Phase-Shifting Transformer (TCPST)

It is adjusted by thyristor switches to provide a rapidly variable phase angle

Interphase Power Controller (IPC)

The active and reactive power can be set independently by adjusting the phase shifts and/or the branch impedances, using mechanical or electrical switches.

Other Controllers

Thyristor-controlled Voltage Limiter (TCVL)

A thyristor-switched metal-oxide varistor (MOV) used to limit the voltage across its terminals during transient conditions.

Thyristor-controlled Voltage Regulator (TCVR)

Thyristor-controlled transformer is one which can provide variable in-phase voltage with continuous control.

- When the inverter fundamental output voltage is higher than the system line voltage, the STATCOM works as a capacitor, however when the inverter voltage is lower than the system line voltage, the STATCOM acts as an inductor.

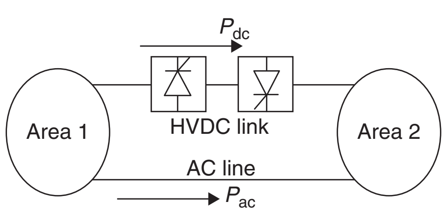
Advantages of STATCOM are as follows:

1. Steady-state load ability of lines is improved.
2. The voltage rise due to capacitance switching is substantially reduced both in magnitude and duration.
3. Voltage variation due to customer's loading is reduced.
   - In SVC devices, the current injected into the system depends upon the system voltage.
   - TCSC provides dynamic control of the series compensated lines, which would increase the transfer capability.
   - A thyristor control phase angle regulator (TCPAR) is equivalent to a mechanically phase shifting transformer but, unlike a UPFC, it does not provide a controlled reactive power generation.
   - STATCOM mainly provides dynamic reactive power to the system but it does not directly controls the flow of real power on a transmission line.

Exercises

Practice Problems I

1. In a two area power system both the areas are interconnected by an AC line and a HVDC link as shown in figure. Which one of the following statement is true in steady state.



(A) The total power flow between the regions (P_{AC} + P_{DC}) can be changed by controlling the HVDC converters alone.
(B) Both regions need not have the same frequency.
(C) The directions of power flow in the HVDC link (P_{DC}) can be reversed.
(D) The power sharing between the AC line and the HVDC link can be changed by controlling the HVDC converters alone.

2. Which one of the following is an advantage of HVDC transmission over EHV-AC?
(A) System stability can be improved
(B) VAR compensation is not required
(C) Harmonic problem is avoided
(D) HVDC terminal equipment inexpensive

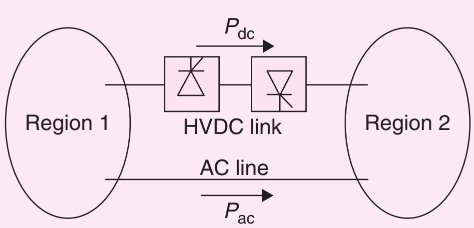
3. Main application of HVDC transmission is
(A) Bulk power transmission over long distances.
(B) Interconnecting two systems with the same nominal frequency.
(C) Minimizing harmonics at the converter station.
(D) Eliminating reactive power requirement in the operation.

Previous Years' Questions

1. HVDC transmission is mainly used for **[2005]**
(A) Bulk power transmission over very long distances
(B) Inter-connecting two systems with the same nominal frequency
(C) Eliminating reactive power requirement in the operation
(D) Minimizing harmonics at the converter stations

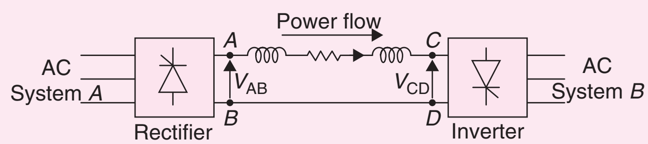
2. An HVDC link consists of rectifier, inverter transmission line and other equipments. Which one of the following is true for this link? **[2006]**
(A) The transmission line produces/supplies reactive power
(B) The rectifier consumes reactive power and the inverter supplies reactive power from/to the respective connected AC systems
(C) Rectifier supplies reactive power and the inverted consumes reactive power to/from the respective connected AC systems
(D) Both the converters (rectifier and inverter) consume reactive power from the respective connected AC systems

3. Two regional systems, each having several synchronous generators and loads are interconnected by an AC line and a HVDC link as shown in the figure. Which of the following statements is true in the steady state?



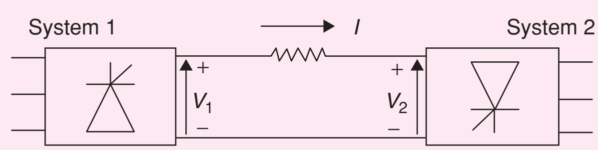
(A) Both regions need not have the same frequency **[2007]**
(B) The total power flow between the regions (P_{AC} + P_{DC}) can be changed by controlling the HVDC converters alone
(C) The power sharing between the AC line and the HVDC link can be changed by controlling the HVDC converters alone.
(D) The direction of power flow in the HVDC link (P_{DC}) cannot be reversed.

4. Power is transferred from system A to system B by an HVDC link as shown in the figure. If the voltages V_{AB} and V_{CD} are as indicated in the figure, and $I > 0$, then **[2010]**



(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) $V_{AB} > 0$, $V_{CD} < 0$

5. Consider a HVDC link which uses thyristor based line-commutated converters as shown in the figure. For a power flow of 750 MW from system 1 to System 2, the voltages at the two ends, and the current, are given by: V_1 = 500 kV, V_2 = 485 kV and I = 1.5 kA. If the direction of power flow is to be reversed (that is, from System 2 to System 1) without changing the electrical connections, then which one of the following combinations is feasible? **[2015]**



(A) V_1 = –500 kV, V_2 = –485 kV and I = 1.5 kA
(B) V_1 = –485 kV, V_2 = –500 kV and I = 1.5 kA
(C) V_1 = 500 kV, V_2 = 485 kV and I = –1.5 kA
(D) V_1 = –500 kV, V_2 = –485 kV and I = –1.5 kA

Answer Keys

Exercises

Practice Problems I

1. D **2.** A **3.** A

Previous Years' Questions

1. A **2.** B **3.** C **4.** C **5.** B

Test
Power Systems

Time: 60 min.

Directions for questions 1 to 25: Select the correct alternative from the given choices.

1. A Non conventional source of energy is
(A) Water
(B) Radio active substances
(C) Fossil fuels
(D) Geothermal, ocean tides and waves

2. The function of steel wire in an ACSR conductor is
(A) Reducing conductivity
(B) Compensating skin effect
(C) Providing additional mechanical strength
(D) Purely of economical consideration

3. The string efficiency of insulators can be increased by
(A) Changing the orientation of strings
(B) Increasing the number of strings
(C) Correct grading of insulators of various capacitances
(D) Reducing the number of strings

4. In a DC transmission line
(A) It is necessary for the sending end and receiving end to be operated in synchronism
(B) There are no effects due to inductive and capacitive reactances
(C) Power transfer capability is limited by stability considerations
(D) The effects of inductive and capacitive reactance are greater

5. RRRV depends upon the
(A) Inductance of the system only
(B) Capacitance of the system only
(C) Inductance and capacitance of the system
(D) Type of circuit breaker

6. The largest size of thermal generating unit in India
(A) 265 MW (B) 310 MW
(C) 660 MW (D) 500 MW

7. Base Impedance of a power system is given as
(A) $(\text{Base KV})^2/\text{Base MVA}$
(B) $\text{Base KV}/(\text{Base MVA})^2$
(C) Base KV/Base MVA
(D) $(\text{Base KV})^2/(\text{Base MVA})^2$

8. The values of current and voltage for an unloaded synchronous generator which has a fault occurring at the terminals is given as I_{a0}, I_{a1} and I_{a2} as $j1.37$ p.u., $j2.05$ p.u. and $j0.68$ p.u. respectively $V_{a0} = V_{a1} = V_{a2} = j1.\ 37$ p.u. The fault that has occurred is
(A) L–G fault (B) L–L–G fault
(C) L–L fault (D) None of the above

9. An overhead transmission line having surge impedance 'Z_1' is terminated to an underground cable of surge impedance 'Z_2'. The reflection coefficient for the travelling wave at the junction of the line and cable is

(A) $\dfrac{Z_2}{Z_1 + Z_2}$ (B) $\dfrac{-Z_2}{Z_1 + Z_2}$

(C) $\dfrac{Z_2 - Z_1}{Z_1 + Z_2}$ (D) $\dfrac{Z_1 - Z_2}{Z_1 + Z_2}$

10. The insulation resistance of a cable of length 20 km is 1 MW, its resistance for 100 km length will be
(A) 0.2 MW (B) 1 MW
(C) 5 MW (D) None of the above

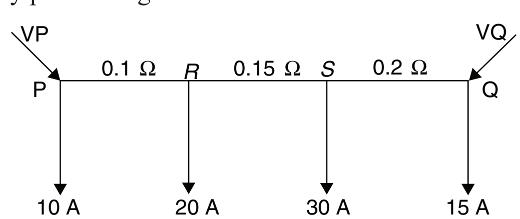
11. If a generator of 250 MVA has an inertia constant of 20 MJ/MVA, its inertia constant on 500 MVA base is
(A) 5 MJ/MVA (B) 10 MJ/MVA
(C) 15 MJ/MVA (D) 20 MJ/MVA

12. A power station is to supply three regions of loads whose Peak values are 40 MW, 25 MW and 50 MW. The diversity factor and annual load factor is given as 2.2 and 0.25 respectively. The maximum demand on the station and average load respectively will be
(A) 52.27, 13.07
(B) 45.08, 15.08
(C) 72.28, 16.08
(D) 60.04, 10.02

13. A transmission line conductor having a diameter of 18.2 mm, weights 0.80 kg/m. The span is 270 m. The wind pressure is 35 kg/m^2 of projected area with ice coating of 12 mm. The ultimate strength of the conductor is 6500 kg. If the factor of safety is 2 and ice weights 890 kg/m^3; the value of maximum sag will be
(A) 6.95 m (B) 5.36 m
(C) 4.82 m (D) 5.20 m

14. A 2 km of a three phase metal sheathed belted cable gave a measured capacitance of 1.2 μF between one conductor and the other two conductors joined together with the earth sheath and 1.5 μF measured between all the three conductors joined and sheath. The value of charging current when the cable is connected at 11 KV, 50 Hz supply is
(A) 1.42 A/ph (B) 3.09 A/ph
(C) 1.59 A/ph (D) 0.68 A/ph

15. In the DC distribution system shown below, the two ends of the feeder are fed by voltage source such that $V_p - V_q = 3$ V. The value of the voltage V_p for a minimum voltage of 220 V at any point along the feeder.



(A) 220 V (B) 228.58 V
(C) 225.89 V (D) 222.89 V

16. The velocity of wave propagation of a lossless overhead EHV line operating at 50 Hz is 3×10^5 Km/s. If the total reactance and susceptance are given by 0.035 p.u. and 1.3 p.u. respectively, approximate length of the line is
(A) 158 Km
(B) 140 Km
(C) 180 Km
(D) 175 Km

17. A power system network consists of three elements 0–1, 1–2, and 2–0, of per unit impedances 0.2, 0.4 and 0.4 respectively. Its bus impedance matrix is given by ______.

(A) $\begin{array}{c} \\ 1 \\ 2 \end{array}\begin{array}{c} \begin{array}{cc} 1 & 2 \end{array} \\ \begin{bmatrix} 7.5 & -2.5 \\ -2.5 & 5.0 \end{bmatrix} \end{array}$ (B) $\begin{array}{c} \\ 1 \\ 2 \end{array}\begin{array}{c} \begin{array}{cc} 1 & 2 \end{array} \\ \begin{bmatrix} 0.16 & 0.08 \\ 0.08 & 0.24 \end{bmatrix} \end{array}$

(C) $\begin{array}{c} \\ 1 \\ 2 \end{array}\begin{array}{c} \begin{array}{cc} 1 & 2 \end{array} \\ \begin{bmatrix} 0.16 & -0.18 \\ -0.08 & 0.24 \end{bmatrix} \end{array}$ (D) $\begin{array}{c} \\ 1 \\ 2 \end{array}\begin{array}{c} \begin{array}{cc} 1 & 2 \end{array} \\ \begin{bmatrix} 0.6 & 0.4 \\ 0.4 & 0.8 \end{bmatrix} \end{array}$

18. The incremental fuel cost of a power plant consisting of three generating units are
$IC_1 = 20 + 0.3P_1$
$IC_2 = 30 + 0.4P_2$
$IC_3 = 30$
where P_i is the power in MW generated by unit i, for i = 1, 2, and 3. Assume that all three units are operating all the time. Minimum and maximum load on each unit are 50 MW and 300 MW respectively. If the plant supplies a total power demand of 700 MW power generated by each unit is
(A) P_1 = 157.14 MW P_2 = 242.86 MW P_3 = 300 MW
(B) P_1 = 242.86 MW P_2 = 157.14 MW P_3 = 300 MW
(C) P_1 = 300 MW P_2 = 300 MW P_3 = 100 MW
(D) P_1 = 233.3 MW P_2 = 233.3 MW P_3 = 233.4 MW

19. The leakage reactance referred to lv side for a 3 kVA 11/0.4 KV single phase transformer is given as 0.90 Ω. Then the leakage reactance in per unit is
(A) 0.001 p.u. (B) 0.017 p.u.
(C) 0.584 p.u. (D) 1.23 p.u.

20. The maximum allowable tension in an overhead line having a span of 150 m is given as 1200 kg. If the line conductor weights 0.5 kg per meter, then the maximum sag will be
(A) 1.17 (B) 3.5
(C) 0.15 (D) 4.8

21. For a step up transformer the line to ground voltage on phases a, b and c are given as 80 KV, 33 KV and 42 KV respectively. The voltage relations are given like phase a lags that of phase b by 150° and leads that of phase c by 80°. Then the positive and negative components of phase voltage are
(A) (13.51 – 6.2 1i), (46.91 + 14.49j)
(B) (13.51 + 15.78j), (46.91 – 14.49j)
(C) (13.51 – 15.78j), (15.63 + 14.49j)
(D) (13.51 + 5.26j), (15.63 – 14.49j)

22. The losses and other mechanical load for a synchronous motor which improves the p.f. from 0.5 to 0.7 lagging is given as (150 + 100) kW. If the load is given as 1200 kW, then the value of the input to the synchronous motor in kVA
(A) 649 (B) 550
(C) 700 (D) 585

23. For a DC three wire system the same supply and load voltages are given to neutral and balanced conditions. If this system is converted into a 3-phase four wire AC system which of the following expression is correct
(A) $P_2 = P_1$ (B) $P_2 = 1.5\ P_1$
(C) $P_1 = -P_2$ (D) $P_1 = 1.5\ P_2$

Statement for Linked Answer Questions 24 and 25:
The maximum demand at a power station is 60 MW, at a load factor of 0.7 and plant capacity factor of 0.6.

24. The annual energy generated in kWh is
(A) 367.920×10^6 (B) 183.96×10^6
(C) 735.84×10^6 (D) 147.17×10^6

25. The reserve capacity of the plant is
(A) 5 MW (B) 10 MW
(C) 15 MW (D) 20 MW

Answer Keys

1. D	**2.** C	**3.** C	**4.** B	**5.** C	**6.** C	**7.** A	**8.** B	**9.** C	**10.** A
11. B	**12.** A	**13.** A	**14.** B	**15.** B	**16.** A	**17.** D	**18.** B	**19.** B	**20.** A
21. A	**22.** A	**23.** B	**24.** A	**25.** B					