A typical two terminal HVDC link has A.C. sub-station, conversion sub-station at each end and the two such sub-stations are linked by the bipolar transmission line.

In bipolar D.C. transmission system has two poles, one positive with respect to earth and the other negative.

The convertors are made up thyristor valves, 12 pulse convertors are used. The convertor is supplied from convertor transformer. The quadruple valve has 4 valves placed vertically to form a limb. These are installed in valve halls.

The convertor transformer is of special design as D.C. voltage on convertor sides causes additional magnetising currents and voltage stresses.

The rating of a typical long-distance HVDC link are :

(*i*) ± 500 kV (*ii*) 1500 MW (*iii*) 900 kM.

The control of HVDC power flow is by tap changing of convertor transformer and gate control of thyristors valves.

The HVDC lines having point-to-point contact do not need HVDC breaker as the line current can be reduced rapidly in the event of fault by blocking thyristor.

With the development of thyristor valves, the HVDC lines have become commercially viable for long distance high power transmission systems, interconnections, sub-marine cables.

Recently multi-terminal HVDC transmission systems having link between 3 or more AC systems have been commissioned in Italy, USA/Canada.

HVDC Back-to-back coupling stations are being preferred for system interconnections. Several Back-to-back HVDC sub-stations have been commissioned and several new contracts have been signed.

HVDC Projects in India :

1	Vindhyachal Back-to-back(WR-NR)	500 MW (1989)
2	Rihand-Delhi	1500 MW ± 500 kV 820 km, Bipolar (1991)
3	Chandrapur, Padghe	1500 MW, ± 500 kV, 850 km Bipolar 1998
4	Chandrapur Back-to back (WR-SR)	1000 MW (1996)
5	National Experimental HVDC (Barsur-Lower Silera)	± 100 MW, 250 kM (1992)
6	Gujwaka-Jaypur Back-to-Back (SR-ER)	1000 MW, (2000)

Note : WR = Western Region NR = Northern Region
SR = Southern Region ER = Eastern Region

48-A

EHV — AC Transmission Systems and Static VAR Sources

Hierarchical levels in Transmission systems—Characteristics of transmission systems—Design aspects : Electrical, mechanical, structural—Power transferability of AC lines and DC lines—Choice of voltage of AC lines and DC lines—Transient stability limit—Control of power flow—Short circuit levels—Voltage control and reactive power compensation—Insulation co-ordination and surge arrester protection—Conductor design, corona, radio interference— Subsynchronous resonance—Static VAr Sources (SVS).

48.1. GENERAL BACKGROUND OF EHV-AC TRANSMISSION

Modern civilization depends heavily on the consumption of electrical energy for industrial, commercial, agricultural, domestic and other purposes. Electrical power is generated in large thermal, hydro, nuclear power stations. The energy transfer from these generating systems to distant distribution networks is *via* transmission systems. The modern electrical power system is in the form of a large interconnected network. The generating stations, transmission and distribution systems are interconnected by means of 3 phase AC system operating synchronously at the common single frequency of 50 Hz (60 Hz in USA). The total network covers a vast geographical area.

The basic function of a transmission system is to transfer (convey) electrical power from one location to another location or from one network to another network. A transmission system includes terminal sub-stations, transmission lines and intermediate sub-stations.

Transmission system are necessary for (1) bulk power transfer from large group of generating stations upto the main transmission network (2) for the main transmission network (3) for system interconnection and (4) for transfer of power from the main transmission network to the distribution sub-stations.

A transmission system is used either for transfer of power from sending-end to the receiving-end or for system interconnection for exchange of power between independently controlled networks.

The network of transmission and distribution lines is formed by three-phase alternating current system. For longer lines and higher power transfer, higher transmission voltages are necessary, ($P \propto V^2$). Higher voltage gives lesser current, lesser $I^2 R$ line losses, higher power transferability.

As a rule, higher the power rating higher is the requirements of transmission voltage. Longer the lines, higher is the required transmission voltage. In the ending-end sub-station, the voltages are stepping up and then transmitted. At the receiving end the voltage may be appropriately stepped down by using power transformers.

Upto 1970's, the choice was exclusively in favour of high voltage AC (upto 220 kV) and extra high voltage AC (above 220 kV, upto 760 kV, AC).

By 1990's Ultra High Voltage AC (1000 kV, 1100 kV, 1200 kV) transmission lines were introduced for bulk power transfer in USSR, USA, Canada etc.

First commercial High Voltage Direct Current transmission system (HVDC) was introduced during 1953. With the successfully development of high power thyristor valves in early 1970's the HVDC transmission systems have become a technically and commercially viable alternative to

EHV/UHV AC transmission particularly for long distance bulk power transmission, cable transmission and system interconnection. For these applications HVDC transmission system have a distinct superiority over EHV-AC and are being increasingly preferred.

Thus, the choice of transmission systems and rated voltages for a transmission line is made from HV AC (upto 220 kV) ; EHV AC (between 400 kV and 760 kV AC); UH-VAC (above 760 kV AC) and HVDC (upto ± 1600 kV DC) depending upon technical and economic considerations.

48.2. VOLTAGE LEVELS FOR TRANSMISSION LINES

The network is formed by several HV, EHV(AC) lines with a few HVDC systems.

The following table give the reference values of voltages used for AC and DC transmission systems.

Table 48.1-A. Reference values of voltages for 3 phase AC lines

Description	*HV-AC*			*EHV-AC*			*UHV-AC*		
Nominal Rated Voltage kV, rms, Phase to Phase	132	220	275	345	400	500	750	1000	1100
Higher operating voltage kV, rms, Phase to Phase	145	245	300	362	420	520	765	1050	1200

Table 48.1-B. Increasing highest transmission voltage in the world

Year	*1965*	*1969*	*1988*	*1990*	*1985*	*2000*
Highest AC Transmission Voltage kV	735	756	1100	1000	1200	1600
Country	Canada	USA	USA	Italy	USSR	USA

Table 48.2. Reference values of Rated Voltages of Bipolar Overhead HVDC Transmission

	I			*II*				*III*
Rated voltage, kV, DC	± 100	± 200	± 300	± 400	± 450	± 500	± 600	± 800
Rated voltage, between poles, kV, DC	200	400	600	800	900	1000	1200	1600

I. Earlier HVDC systems

II. Present HVDC systems

III. Possible future requirement

* Rihand-Delhi HVDC Project, India

± Voltage refers to voltages of poles to earth. One pole is positive with respect to earth and other pole is negative with respect to earth.

48.3. HIERARCHICAL LEVELS OF TRANSMISSION AND DISTRIBUTION

During 1950's small stand-alone AC systems were generally adequate for limited geographical coverage. Such networks were formed by a few radial transmission lines emanating from generating stations.

Modern Transmission systems are interconnected networks and cover a vast geographical area and transmit a large amount of power from various generating stations to various sub-stations and loads. For systematic power transmission and control ; the network is divided into three hierarchical level of transmission and distribution : (Refer Table 48.3).

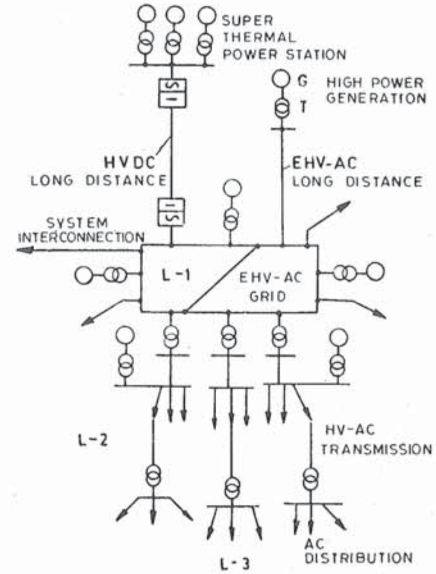
* 400 kV lines introduced in India during 1974 and are now well established for back-bone transmission Network and bulk-power transmission in various regional grids.

** Two 750 kV lines under consideration in India (1997).

1. Backbone or Main Transmission Network (EHV - AC)
2. Sub-transmission Network (HV - AC)
3. Distribution Network (MV - AC, LV - AC).

Fig. 48.1 illustrates the concept of hierarchical levels in transmission systems.

The three levels cover the entire geographical area. The distribution network is formed by several distribution sub-stations and distribution lines reaching a wide range of consumers. The distribution sub-stations receive power from local receiving sub-stations. Local receiving sub-stations receive power from sub-transmission lines and sending-end sub-station of these sub-transmission lines receive power from back-bone EHV-AC Network. The EHV-AC Network receives power from large power stations. Back-bone transmission Network is of EHV-AC lines. It is in a ring form (mesh). The long bulk power transmission lines between distant super thermal power stations and this network are either EHV-AC or HVDC.



L—1 : Back-bone EHV-AC network
L—2 : Underlying sub-transmission
L—3 : Distribution

Fig. 48.1. Hierarchical levels in the transmission network.

Table 48.3. Functions of Hierarchical Levels in Transmission and Distribution Network

	Level Title	*Function*	*Remarks*
L-1.	Back-bone EHV-AC network	— To receive power from generating stations and long bulk power EHV-AC/HVDC transmission lines. — To deliver power to sub-transmission system *via* HV transmission lines	— In meshed or Ring Form. — Interconnected with neighbouring network. — Generally EHV-AC lines (400 kV or 760 kV) — Generally double circuit for radial lines.
L-2.	Sub-transmission Network (underlying below the back-bone network)	— To receive power from the back-bone network and some local power stations — To deliver power distribution system *via* HV transmission lines	— Less method — More radial lines — Generally at High voltage AC (220 kV. 132 kV)
L-3.	Distribution Network. (Underlying below the sub-transmission)	— To receive power from the sub-transmission Network and — To deliver power to consumers	— Medium voltage AC and Low voltage AC. Medium voltage : 33 kV, 22 kV, 11 kV, 6.6 kV, 3.3 kV, Low voltage : upto 1000 V

Interconnections between neighbouring independently controlled AC networks are by one of the following :

— Overhead HV/EHV/UHV AC lines, or

— Overhead HVDC lines, or
— Underground/Underwater HVDC cables
— Back-to-back HVDC coupling station.
— Multi-terminal asynchronous HVDC interconnecting system.

Chapter 49 covers power system interconnections.

48.4. TASKS OF TRANSMISSION SYSTEMS

The tasks associated with transmission and distribution systems include :

— Transmission of electric power at specified voltage and frequency.
— Control of power with respect to magnitude and direction. Controlling exchange of energy flow.
— Economic load despatch.
— Ensuring steady state stability and transient stability of the transmission link and associated AC Networks.
— Control of flow of reactive power compensation of reactive power.
— Voltage control at sending-end and receiving-end of transmission lines and voltage control of distribution buses.
— Assistance in frequency control by rapid exchange of power maintaining stability. Network islanding, (Network segregation) and load shedding.
— Security of supply by feeding at various points, providing adequate line-capacity, facility for alternate transmission paths.
— Data transmission *via* power line carrier communication channels (PLCC) for the purpose of telemetry, telecontrol and network automation.
— Minimise transmission losses by selecting shorter transmission paths.
— Adequate protection, minimum faults and minimum fault duration. Pinpointing location of fault, causes and subsequent improvements.

For convenience the transmission lines, sub-stations, distributions circuits and generating stations are identified separately. However, the Network is homogeneous. The function of these parts overlap. Each part has a significant influence on the others.

48.5. FUNCTIONAL REQUIREMENTS OF TRANSMISSION SYSTEMS AND DESIGN ASPECTS

The lines and sub-stations constituting transmission systems are designed to deliver required amount of power continuously, reliably with voltages within specified limits and with environmental factors within specified limits, with lowest overall annual cost over the service period. The system should also have provision of expansion, with minimum changes in existing layouts.

The transmission system designs have four important parts :

— Electrical design
— Mechanical design
— Structural and civil design
— Miscellaneous design

Furthermore, the transmission system design includes :

— Sub-station design
— Transmission line design
— Network planning

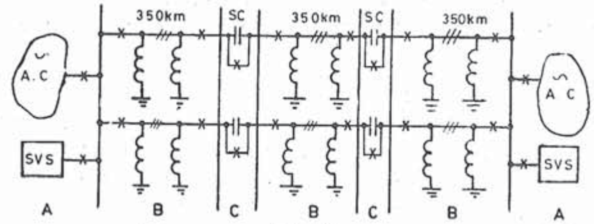
Electrical Design Aspects. The electrical design of AC transmission systems is quite different from that of HVDC transmission systems. The electrical design involves the following aspects :

1. Choice of transmission voltage.
2. Choice of conductor configuration.
3. Voltage control and reactive power compensation.

4. Corona losses and Radio Interference.
5. Transient stability, autoreclosing of circuit-breakers.
6. Abnormal operating conditions and protection systems.
7. Insulation coordination and surge arrester protection.
8. Neutral grounding.
9. Sub-station grounding, tower grounding.
10. Earth electrodes and electrode lines (for HVDC).
11. Harmonics and filters (for HVDC).
12. Overhead shielding wires and lightning protection.
13. Power line communication (PLC).
14. Radio Interference (RI), Telephone Interference (TI).
15. Television Interference (TI).
16. Audible noise (AN).

48.6. CONFIGURATION OF EHV-AC TRANSMISSION SYSTEM AND BIPOLAR HVDC TRANSMISSION SYSTEM

Fig. 48.2 illustrates the configuration of a very long EHV-AC transmission system. Intermediate sub-stations are required at an interval of 300-350 km for installing shunt reactors and series capacitors.

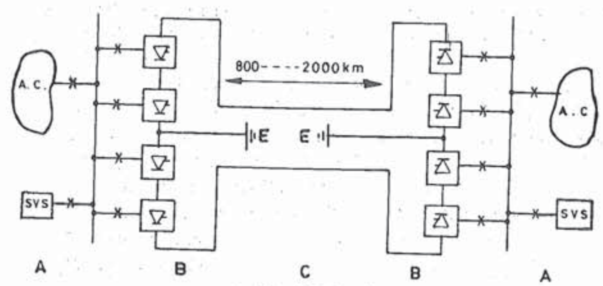


A = Terminal AC systems.
B = Transmission line.
C = Intermediate substation.
SVS = State VAr Source.

Fig. 48.2.

An EHV-AC line always needs a parallel line so that if a fault occurs on one line, the other line continues to provide the transmission path between two ends and system stability is maintained. SVS is necessary at terminal sub-stations for providing controllable shunt compensation.

Fig. 48.3 illustrates the configuration of a bipolar HVDC link. Only two conductors are sufficient. No intermediate sub-station is needed for compensation.



A = Terminal AC systems.
B = Convertor station near A.
C = HVDC bipolar transmission line.

Fig. 48.3. Configuration of a bipolar HVDC link.

48.7. POWER TRANSFERABILITY OF AC LINE

Power transferability of AC lines is governed by the equation :

$$P_{dc} = \frac{|V_1| \cdot |V_2|}{X} \times \sin \delta \quad ...(48.1)$$

where $|V_1|$ = Sending-end voltage, kV
$|V_2|$ = Receiving-end voltage, kV
X = Series inductive reactance, ohm
δ = Power angle, Angle between V_1 and V_2
P_{dc} = Power transfer, MW

In practice angle δ is held around 30° to maintain transient stability. Therefore, power transfer of a single circuit, 3-phase AC line is approximately equal to :

$$P_{dc} = 0.5\ |V_1| \cdot |V_2| \ / X \quad ...(48.2)$$

By introducing a parallel line, the series reactance of the double circuit is reduced to $(X/2)$ resulting in doubling of power transferability. By introducing series capacitor banks is series with a 3-phase AC line, the effective series reactance X is reduced to

$$X = X_L - X_C$$

where X = Equivalent series reactance of the link, ohm
X_L = Series inductive reactance of the line, ohm
X_C = Series capacitive reactance of capacitor banks.

However, series capacitor banks are used only in EHV lines when paralleled lines are not economical. Normally, compensation of the order of 50% of X_L is used *i.e.*, $X_C = X_L/2$.

As seen from Eqs. 48.1 and 48.2 ; the power transferability of AC lines is proportional to the square of transmission voltage *i.e.*

$$P_{AC} \propto V^2 \quad ...(48.3)$$

48.8. LINE LOSSES

Current I, through three phases conductors having resistance R ohms each, causes power loss of $3I^2 R$ per circuit.

$$P_{ac} = \sqrt{3}\ VI \cos \phi \quad ...(48.4)$$

$$I = \frac{P_{ac}}{\sqrt{3}\ V \cos \phi} \quad ...(48.5)$$

where I = Current in line conductor, A r.m.s
V = Phase to phase voltage
$\cos \phi$ = Power factor of the line current

$$\text{Line loss } P_L = 3I^2 R \text{ watts} \quad ...(48.6)$$

$$= 3\left[\frac{P_{ac}^2}{3V^2 \cos^2 \phi}\right] R$$

$$P_L = \frac{P_{ac}^2 R}{V^2 \cos^2 \phi} \quad ...(48.7)$$

$$R = \frac{P_L V^2 \cos^2 \phi}{P_{ac}^2} \quad ...(48.8)$$

Line loss decreases with increase of transmission voltage and improvement of power factor, for the same power transfer.

In addition to active power flow P_L, every AC line has reactive power flow Q. Reactive power flow results in additional transmission losses in AC lines.

48.9. CONDUCTOR COST

Volume of an AC conductor = v

$$\text{Resistance } R = \frac{\rho l}{A}$$

where ρ = resistivity,
l = length
A = Cross-section area.

$$v = A \cdot l$$

$$= \frac{\rho l \cdot l}{R} = \frac{\rho\, l^2}{R} \quad ...(48.9)$$

Volume of three line conductors for AC transmission = 3v

$$3\ v = \frac{3\rho\, l^2}{R} \quad ...(48.10)$$

Substituting R from Eq. 48.8 in Eq. 48.9 volume of conductors :

$$3v = \frac{3\rho\, l^2 P_{ac}^2}{V^2 \cos^2 \phi\, P^2} \quad ...(48.11)$$

From Eq. 48.11, we note the following :

The volume of conductor v for AC line is proportional

— directly to square of power transfer P_{ac}.
— inversely to the square of voltage V.
— inversely to the square of loss.

For given loss P_L, the volume of conductor and the cost of conductor reduces in inverse proportion of voltage square.

For a given voltage, $P_L \propto \frac{1}{\sqrt{V}}$ ...(48.12)

For a given voltage V, the transmission loss is inversely proportional to the volume (v) of the conductor.

The choice of higher voltage results in reduced losses and reduced conductor size. However, the cost of line insulation and tower sizes also increase.

Table 48.4 gives the reference values of power per circuit (P_{ac}) percentage loss P_L resistance r per km, reactance X per km of AC lines for various rated voltage.

Refer Fig. 48.2. A high power AC line always needs a double circuit for each transmission path, thus minimum 6 conductors.

Ref. 48.3. An HVDC bipolar HVDC line needs only 2 conductors per path.

Table 48.4. Reference values for AC lines

Rated Voltage kV	r ohm/km	X ohm/km	Length* km	P_{ac} MW	Loss P_L%
400	0.031	0.327	400	640	5.1
750	0.0136	0.272	400	2600	2.7
1000	0.0036	0.231	400	5500	0.85
1200	0.0027	0.231	400	8000	0.64

* For other lenghts l, multiply P_{ac} by $400/l$ because P_{ac} is inversely proportional to the line length l.

48.10. TRANSIENT STABILITY LIMIT OF AC LINE

The power transfer through an AC line has a limit dictated by the transient stability limit (refer Eq. 48.2). During system disturbances such as sudden changes in load, tripping of a line, fault on a busbar the power angle (δ) oscillates widely over a long period. The system tends to fall out of synchronism. The limit of earlier power transfer for given change of load without loss of stability is called transient stability limit. In case of AC lines, the transient stability can be improved by rapid fault clearing, rapid autoreclosing of line circuit breakers, etc. However, with AC transmission, the power angle (δ) swings widely and over longer duration resulting in power swings in AC networks and in the transmission line.

With HVDC transmission, the power flow through the line is dependent on thyristor control of rectifier and invertor. The power flow through the line can be quickly modulated to dampen the power swings in connected AC networks. Moreover HVDC link itself does not have a limit of power flow imposed by transient stability limit related with power angle (δ) and reactance (X). The limit of HVDC link is imposed by convertor rating and stability of convertor control system.

HVDC transmission system can be operated at its rated power transferability which is nearly equal to the thermal limit of convertors.

AC transmission system is operated at only 50% of its thermal limit due to the transient stability consideration.

During a fault on an AC line, the fault power is fed from both the terminal sub-stations. During a fault on a DC line the fault current is limited by the thyristors and does not endanger the stability of connected AC systems.

48.11. CONTROL OF POWER FLOW THROUGH LINE

The magnitude and direction and rate of change of power flow through a transmission line should be controllable, especially for interconnecting lines.

In case of AC lines, the phase angle (δ) gets adjusted naturally in accordance with the load/generation/frequency balance at each end and power flows from surplus end to the deficit end. In some interconnected lines special phase shifting transformers are installed at each end of the transmission line to enable adjustment of angle between V_1 and V_2. However, control of magnitude, direction and rate of change of power flow through AC lines is slow and difficult.

In case of highly meshed lines, parallel lines; phase shifting transformers are necessary for forcing power through AC tie-lines. (Chapter 49).

Control of power flow through a HVDC link is fast, accurate, bidirectional and has a wide range of magnitude limits. The power flow through DC lines is achieved by changing the current I_{dc} by varying the difference ($V_{dc}\,1 - V_{dc}\,2$) *i.e.*

$$P_{dc} = V_{dc} \cdot I_{dc}.$$

$$V_{dc} = \left(\frac{V_{dc} \cdot 1 - V_{dc} \cdot 2}{R}\right)$$

where $V_{dc}\,1$ = Sending end DC voltage

$V_{dc}\,2$ = Receiving end DC voltage R = Line resistance

V_{dc} = Average value of DC voltage

$V_{dc}1$ and $V_{dc} \cdot 2$ are changed by changing delay angle α of the thyristor valves at respective ends. The line resistance (R) being small, a small change ($V_{dc}\,1 - V_{dc}\,2$) bring about a quick significant change in I_{dc} and P_{dc}.

48.12. SHORT CIRCUIT LEVELS

The fault power for a three phase fault is called short-circuit level or fault level at the fault-point.

Addition of new EHV-AC lines and tie lines changes the short-circuit levels of the various sub-stations buses due to reduced equivalent reactance of the network. *With AC interconnected lines,* the fault levels at both ends increases. *With HVDC interconnection* the fault levels at each end remains unchanged, as the current through the line is controlled by firing the thyristor valves.

The short-circuit studies are carried out and equipment ratings are verified while planning transmission networks and designing transmission systems. HVDC interconnections have a distinct advantage that the fault levels at AC station buses remain at previous levels (before interconnections).

With interconnection between two AC networks by AC tie line, the fault levels of both networks get nearly added resulting in higher fault levels at terminal sub-stations. This may call for replacement of sub-station equipment of higher short-circuit capability. Such a replacement is not envisaged with HVDC interconnections.

Limiting Short-circuit Levels in today's AC system

Rated Voltage kV, r.m.s.	220	400	760	1000
Short-circuit level, kA r.m.s.	40	40	63.5	63.5

48.13. VOLTAGE CONTROL OF AC LINES AND COMPENSATION OF REACTIVE POWER (Ref. Sec. 45.20)

The voltages at sending end bus and receiving end bus of AC line should be held within specified limits under conditions of varying power flow and reactive power flow. The algebraic difference ($V_1 - V_2$) between sending-end AC voltage and receiving end-end AC voltage is related with flow of reactive power (Q).

During low loads, the receiving end voltage increases above sending-end voltage due to predomination of shunt capacitance of the transmission line (Ferranti Effect). During heavy loads or low power factor loads, the receiving voltage drops below sending end voltage. In case of long AC lines, the natural voltage variation is much beyond permissible limits. However, the voltages are maintained within specified limits by following means :

— Use of on-load tap changers with power transformers.

— Use of shunt reactors connected between line and earth at each end of the transmission line section to compensate the shunt capacitance of the transmission line.

— Use of shunt capacitor banks in receiving-end sub-stations to compensate lagging power factor load currents.

— Use of static VAr Sources (SVS) Sec. 48.B.

In case of very long lines of above 500 km, intermediate switching sub-stations are necessary to install the shunt reactors for compensation. For very long lines intermediate compensation would be required at certain intervals of line length (250 to 300 km).

In the case of DC lines, the effects of shunt reactance and series reactance are absent. The voltage drop $I_{dc} R_{dc}$ is small, uniform along the line and is directly proportional to the line load. Hence voltage control of HVDC line is easier. Intermediate compensating station is not required even for longest HVDC lines.

48.14. INSULATION CO-ORDINATION AND SURGE ARRESTER PROTECTION

Transmission lines and sub-stations are subjected to over voltages due to lightning, switching, faults, resonance and other causes. The surge *arrestors* are provided at strategic locations to protect the line insulation and sub-station equipment insulation from transient and temporary overvoltages.

The basic insulation level of an apparatus refers to the rated values of power frequency withstand voltage, lightning impulse withstand voltage and switching impulse withstand voltage.

The insulation level of an apparatus should be co-ordinated with the protective characteristics of surge arresters.

Insulation levels of EHV systems is determined from considerations of *switching surges.* Switching over-voltages are causes by switching of lines with no load/low inductive current/short-circuits etc. The overvoltages called dynamic over-voltages are caused by line dropping. Ferranti effect, overspeeding of generators, increase in emf due to leading power factor currents, etc. The insulation characteristic of various equipment is defined in terms of rated voltage, standard switching impulse, standard lightning impulse. These are co-related with protective characteristic of surge arresters.

The insulation levels of various sub-stations apparatus and the transmission line should be co-ordinated with various surge arresters such that the overvoltages are discharged to earth without causing damage to the equipment insulation.

The general method of insulation co-ordination in HVDC transmission systems is basically same as for an AC system. The insulation of each equipment is correlated with the protective characteristics and current/energy stresses of surge arresters.

The overvoltage in AC system are classified as switching surges, lightning surges and temporary overvoltages.

Switching overvoltages in AC system occur with high amplitude and only for first half cycle.

The temporary overvoltages last for a few cycles to several hundred cycles.

The overvoltages in HVDC system are caused by

— Pole faults
— Switching operation on DC side
— Loss of pulses in convertor control
— Short circuits near convertor terminals
— Transformation of overvoltage from AC side
— Switching of AC filter banks

Zinc oxide surge arresters (ZnO Arresters) are connected in DC yard, Valve hall, AC yard. Filter circuits, etc. HVDC system needs a large number of surge arresters. These are co-ordinated with surge arresters in AC yard.

The rated voltage switching impulse withstand characteristics, lightning impulse withstand characteristics, test voltages, test procedures, connection surge arresters, etc. form a part of insulation co-ordination studies. In case of HVDC system design, these studies are carried out with the help of

— HVDC simulator
— Digital computer simulation
— Transient network Analyser (TNA)

48.15. LINE INSULATION, CLEARANCE AND CREEPAGE DISTANCES

The clearance refers to the insulating distance along a stretched string. The creepage (leakage) distance refers to the shortest distance along the insulation surface.

The principles of insulation design for AC lines are same as those of DC lines. However the stresses due to alternating electric field are quite different than those with unidirectional fields. Hence the requirements of clearances and creepage for AC are quite different than those for DC.

The clearances, contours of conducting parts, design of grading rings etc., are determined on the basis of required impulse withstand levels. Lightning impulses wave (1.2/50 μs) and switching impulse wave (250/2500 μs) impose different kind of voltage stresses. The polarity of the impulse wave (+/−) also has a different influence.

The creepage distance (leakage distance) is the distance between live metal part and earthed metal part along the surface of an insulator. The atmospheric dust, carbon particles, chemicals, salt, etc. get deposited on the surface of insulator along the lines of electric field. The insulator fail due to tracking. DC insulators need more creepage distance (mm/kV) than AC insulators, because of unidirectional electric field in DC. The requirements of creepage distance of HVDC insulators is almost twice the corresponding valves of EHV-AC insulators.

Table 48.5. Leakage Distance (Creepage Distance)

Type of Atmosphere	*HVDC⁺ mm/kV⁺*	*EHV-AC *mm/kV**
1. Very heavily polluted industrial area	70	30
2. Sea shore, industrial area	50	25
3. Moderately polluted area	40	22
4. Agricultural, forest area	30	16
5. Indoor insulators	26	15

⁺Rated phase-to-ground voltage of DC pole.
*Rated rms voltage of AC line, phase-to-phase.

48.16. RIGHT-OF-WAY (ROW)

Transmission line requires right-of-way for the line through urban, rural, jungle and other areas en-route. The cost of purchase of land, clearing and keeping right-of-way clean, free from trees is considered while selecting the line route.

In some cases, big cities, industrial localities it is becoming impossible to acquire right-of-way for EHV-AC lines.

48.17. CORONA

The design of conductors for EHV-AC transmission lines and HVDC transmission line should be such that the corona losses and radio interferences are within specified/permissible limits. *Corona is a visible, audible, partial electrical discharge at the surface of conductors at high voltage.* The corona discharge occurs in the air surrounding a charged conductor when the voltage stress at the conductor surface reaches the critical value. Corona generally occurs in foul weather.

Corona commences at voltage (V_c) called critical voltage at which the maximum voltage gradient at the surface E_{max} attain critical valve (E_c) · (E_c = 30 kV/cm at n.t.p., *i.e.* 760 mm Hg and 25°C).

The critical value of voltage stress depends upon pressure, temperature, humidity, pollution level in air and condition of conductor surface.

The conductor diameter should be made so large by using bundle-conductors or hollow conductors that the corona losses and radio interference are within limit.

Critical corona voltages are different for positive voltage and negative voltage, the negative voltage being more severe.

Corona cause losses, losses, radio interference and television interference.

In DC corona, the charges releases from one conductor must be carried to the ground or the other conductor because of the opposite polarity. Therefore the corona performance is characterised by the line voltage rather than the surface gradient.

The corona behaviour of a monopolar HVDC line is different from that of bipolar line due to the difference in release of the charge from the vicinity of the conductor surface.

Corona losses depend upon the roughness, cleanliness of conductor surfaces, and also weather condition. It is difficult to predict the corona loss in exact mathematical form. Corona losses vary through the year depending upon weather condition. Table 48.6 gives reference values of average annual corona loss for AC and DC lines.

In case of AC voltage, the peak value of voltage wave is $\sqrt{2}$ times the rms value. In case of DC there is no such great factor.

Corona losses of AC lines increase more rapidly with increase in rated voltage than the corresponding increase in DC line voltage.

With AC voltage, the ions going away from the conductor surface due to like polarity of charge during a half cycle get attracted towards the conductor during the next half cycle of AC wave.

With DC voltage, the ions with the same polarity as that of the conductor get a time to go away from the conductor. Therefore the corona phenomenon acts differently with AC and DC lines.

Table 48.6. Reference values of corona Losses of AC and DC lines

Weather Condition	*Corona loss kW/km*	
	± 400 kV DC	*500 kV AC*
Average loss in fair weather	1.35	1.33
Minimum losses in fair weather	0.62	0.12
Maximum loss worst weather condition	8.00	18.00
Annual mean loss kW/km	2.5	5.5
Line Particulars		
Conductor numbers	2	3
Conductor diameter, mm	46	36
Spacing between conductors, m	10.5	11
Average height	21	18.06

Corona inception voltage gradient is an important parameter for conductor design. For AC lines, standard bundled conductors are generally used. The corona inception voltage gradient should have about 25% margin above the surface voltage gradient at maximum operating voltage, based on fair weather conditions. If this margin is 0%, under foul weather severe radio interference is likely to occur along the line route and the width of the corridor should be increased.

Corona losses under foul weather conditions should be limited to about 5 kW/km. If more, the power available at receiving end would be reduced due to high corona losses.

48.18. TOWERS (SUPPORTS)

Galvanised steel structures are most common for transmission lines above 132 kV. Towers must be strong enough to support the line conductors and shield wires.

Self-supporting steel towers are commonly used for 132 kV and above.

Upto 220 kV, the towers are designed for supporting double circuit three-phase lines, with three conductors on each side and one overhead shielding wire on top.

For 400 kV and 765 kV, the self-supporting tower for single circuit three-phase line is used.

During development testing of 765 kV AC lines in USA and Canada, it was learnt that switching surge withstand level of EHV-AC towers is influenced by tower width (in direction of line). Losser width gives higher withstand level. Entirely new design configurations like chainnete, flexible, semi-flexible towers have been developed.

48.19. BUNDLE CONDUCTORS (MULTIPLE CONDUCTOR)

The voltage gradient at the surface of a conductor is inversely proportional to its radius.

The surface voltage gradient, hence the corona, corona losses, radio interference are reduced by increasing the radius of conductors, by using bundled conductor.

For EHV-AC lines bundled conductors are used. Only in a few cases, expanded ACSR conductors of 2.5 to 4 inch diameter are used.

Bundle conductors or multiple conductors consist of two or more (individually standard) conductors per phase, supported on one or more insulator string (per insulator span). A bundle conductor is said to have N sub-conductors per phase. These sub-conductors are distributed uniformly on a circle of radius R with a spacing B between adjacent sub-conductors.

Let N = Number of sub-conductors in a bundle
R = Bundle radius
B = Sub-conductor spacing
r_{eq} = Geometrical mean radius of a bundle

Normally, $N = 2, 3, 4, 6, 8, 12, 18$
$R = B/2 \sin (\pi/N)$
$B = B/2 \sin (\pi/N)$
$r_{eq} = (N_r R^{N-1})$

In India, for a 400 kV AC line a bundle conductor with two sub-conductors are used. For this bundle conductor

$N = 2 \qquad r_{eq} = 0.51$ metre $\qquad B = 46$ cm

For a 1000 kV line in Italy, a bundle conductor with six subconductors is used.

In case of AC lines, the equivalent radius of a bundle conductor is larger than the single conductor. Therefore, as compared with the single conductor.

— Inductive reactance is lesser — Capacitive reactance is higher

— LC product is the same.

In case of HVDC line conductors. The corona is dependent on the conductor voltage rather than the surface voltage gradient. The crest factor $\sqrt{2}$ is not applicable. For ± 500 kV HVDC lines in India, twin-bundle conductor is used.

To reduce corona losses and in the bundle conductors or hollow conductors are used. *The choice of configuration and cross-section of AC conductors with reference to corona considerations is generally above the economic cross-section based on thermal considerations or transient stability considerations.*

In other words, the design of AC conductors based on corona limitations gives a cross-section much larger than that with respect to economical power transfer limit (imposed by stability limit).

However with DC conductors, the conductor design based on corona can be optimised by suitable choice of transmission voltage as the question of the stability limit does not arise.

Conductor Material

Aluminium Conductor Steel Reinforced (ACSR) conductors are used universally for overhead transmission lines. The steel reinforcement gives high tensile strength. Aluminium gives higher conductivity with lower weight. Table 48.7 gives data about ACSR bundle conductors for AC transmission lines.

Table 48.7

Normal Voltage kV	*Highest Voltage kV*	*Phase Spacing m*	*Sub-conductor Diameter mm*	*No. of sub-conductors per phase*
230	245	6	25	1
345	365	8.3		2
500	550	11		3
765	800	15.3		4
1100	1200	20		8

Overhead Shielding Wire. The line conductors are protected from direct lightning strokes by overhead shielding wires. One or two overhead shielding conductors are attached on the topmost point on tower. The angle of protection with reference to vertical plane is 30° to 45°. The over-head shielding wire is usually of galvanised steel standed wire. Earthing is provided at each tower *via* flexible earthing conductor between the overhead shielding wire and tower-earth mat.

48.20. SWITCHING PHENOMENA ASSOCIATED WITH EHV-AC LINE SWITCHING

The circuit-breakers to be used for switching of EHV-AC lines should be capable of performing following duties :

1. Short-line fault duty (Sec. 3.16)
2. Switching unloaded lines (Sec. 3.14.2)
3. Phase opposition switching (Sec. 3.17)

Switching Overvoltages occurring during opening and closing transmission line breakers should be held within specified limits. The permissible *Switching overvoltage factors K* should be held within the following specified values by using pre-closing resistors with circuit-breakers and other means (Sec. 18.7).

Rated voltage, kV	245	525	750	1000
Permissible switching overvoltage factor K	3	2.5	2	1.7

48.21. AUDIBLE NOISE (AN)

Audible noise is generated by EHV-AC and HVDC transmission lines and sub-stations due to the following causes :

— Corona
— Humming of transformers
— Cooling systems and mechanical and electrical auxiliaries.

The design of transmission lines and sub-stations is governed by the limits of AN. The limits of audible noise are specified by some national standard specifications and the specifications of major utilities in terms of dB at a particular distance from the line sub-station, transformer.

EHV-AC and HVDC line generate audible noise, generally when the corona is present on the conductor during bad weather. The audible noise is in the frequency range from very low frequency to 15 kHz.

The design of lines and sub-stations is the basis of limit of audible noise. The reference values of the limits of audible noise are used on complaints from people working in the vicinity. These limits are given below :

No complaints	:	Below 52.5 dB
A few complaints	:	52.5 59 dB
Many complaints	:	Above 59 dB.

The width of *right-of-way* (ROW) for the line corridor has a reference to the decision about audible noise. *Line geometry is based upon 50 dB at the edge of ROW.*

The AN caused by a transmission line is a function of the following :

(*a*) Voltage gradient on surface of conductor.
(*b*) Number of sub-conductors in a bundle.
(*c*) Diameter of conductor.
(*d*) Atmospheric condition
(*e*) Lateral distance between the line and the point of measurement of noise.

The audible noise is caused by vibrations produced in the air due to change in the air pressure.

48.22. BIOLOGICAL EFFECT OF ELECTRIC FIELD AND LIMITING VALUE OF ELECTRIC FIELD STRENGTH.

The biological effect of electric field of EHV lines and EHV sub-stations has been studied extensively during 1970s.

EHV and UHV lines are designed such that maximum electrostatic field gradient is below 9 kV/m at mid-span under the line near ground level.

Safe line is ground clearance of 20 m at mid-span is recommended for 400 kV lines and 24 m for 1100 kV lines. This permits movement of vehicles safely.

48.23. RADIO INTERFERENCE AND TELEVISION INTERFERENCE

Operation of EHV-AC and HVDC transmission lines and transmission sub-stations can cause Radio Interference (RI). The lines and sub-stations should be so designed that the RI and TI shall be less than 40 dB and 1 m V/m at 1 MHz at the edge of ROW. (Refer Table 48.7).

Radio interference and television interference is caused by electromagnetic waves in the frequency range of broad cast frequencies

RI : 0.5 MHz — 1.6 MHz
TI : 54 MHz — 216 MHz

The line is designed such that the radio noise within the width of the line corridor should be below permissible limits (say 40 dB at 1 MHz).

Radio interference is more important factor in line design and in deciding right of way (ROW).

The main causes for RI are the following :

Table 48.8

		EH-AC	*HVDC*
1.	Corona	*	
2.	Partial discharges on insulators	*	
3.	Sparks across gaps	*	
4.	Pulses due to triggering of thyristors		*

The RI can be eliminated and/or minimised by appropriate design of line conductor and hardware.

The main source of RI in case of AC lines is corona discharge on the surface of conductors surface corona on insulators and sparking at conductor insulator hardware of lines and sub stations. For AC lines bundling of conductors reduces surface voltage stress corona and radio interference.

Corona rings are provided for conductor insulator assembly to reduce surface stress.

Table 48.9. RI limits in various countries

Countries	*Distance from outermost phase*	*R limit*	*Frequency*
USSR	100 m	40 dB	500 kHz
Switzerland	20 m	200 μ V/m	500 kHz
Poland	20 m	760 μ V/m	500 kHz

In case of DC line the space charge surrounds the conductor eliminating the advantage of bundling of conductors. Radio interference is normally not a decisive factor to choose a bundle conductor.

In case of HVDC transmission systems, the triggering of thyristors give high frequency harmonics in the range of 0.1 MHz to 10 MHz. The radio interference is reduced by

— Selection of a valley as the site for a sub-station.
— Screening of valve hall for electromagnetic radiation
— Installing ground wires on switchyard
— Limiting the height and the length of the conductors in the switchyard.
— Proper selection of insulators and hardware to prevent partial discharges.

48.24. RAPID-AUTO RECLOSING AND DELAYED AUTO-RECLOSING OF CIRCUIT BREAKERS

EHV-AC lines are provided with static distance protection incorporating *auto-reclosing* feature. (Sec. 44.20, 44.21).

Rapid-Auto Reclosing (Breaker reclosed within 20 cycles) — are used for transmission lines which are not strongly interconnected. The rapid autoreclosing helps in reclosing without synchronous check.

Delay auto-reclosing (5 to 60 sec.) is used for strongly interconnected system. Synchronous check is necessary before reclosing.

48.25. SURGE IMPEDANCE LOADING OF AC TRANSMISSION LINES

Surge impedance loading is defined as (SIL) the load at the receiving end which is equivalent to $\sqrt{(L/C)}$. The concept of surge impedance loading gives an approx. loading of transmission line. We can say, the loading of transmission line is 1 p.u. SIL or 1.5 p.u. SIL.

$$\text{Surge Impedance} = \sqrt{(L/C)},$$

where L = Inductance per km Henry

C = Capacitance per phase per km, Farads

1 p.u. SIL is called natural load (P_n).

When the line carries natural load $P = P_n$, the voltage along the entire length of line is the same.

When the line carries load above 1 P_n, the voltage at the middle of the line is higher.

Typical values of surge impedance of transmission lines are given in the table.

Rated voltage kV	132	230	400	765	1100
Natural load P_n, MW	40	125	500	1700	5000

Considering the voltage along the line (Fig. 45.15) short lines can be loaded to more than 1 P_n.

Medium lines can be loaded upto 1 P_n.

Long lines can be loaded to less than 1 P_n.

48.26. SUB-SYNCHRONOUS RESONANCE IN SERIES COMPENSATED AC LINES

Series capacitors are installed in series with long lines for providing compensation of reactive power and giving higher power transferability. (Sec. 45.14F).

Series compensated lines having capacitance C have a tendency to produce *series resonance at frequencies lower than power frequency. This is called sub-synchronous resonance.*

The sub-synchronous resonance currents produce mechanical resonance is turbogenerator shafts. The mechanical resonance causes following in the generator shafts :

— induction generator effect — torsional torques — transient torques

These problems have resulted in damage to rotor shafts of turbine generators. Sub-synchronous resonance causes failure of series capacitors.

Sub-synchronous resonance is, therefore analysed in the design of series compensated lines.

Let f_n = Normal (Synchronous) frequency

f_r = Sub-synchronous resonance frequency of series compensated line

$2\pi f_n L$ = Series inductive reactance of EHV line at normal frequency

$1/(2\pi f_n C)$ = Series capacitive reactance of series compensation at normal frequency.

$X_C/X_L = K$ = Degree of compensation

X = Equivalent reactance of compensated line

$$X = X_L - X_C = X_L\,(1 - K)$$

Let sub-synchronous resonance occur at frequency f_r. Then

$$2\pi f_r L = 1/(2\pi f_r C)$$

$$f_r^2 = \left(\frac{1}{2\pi L} \cdot \frac{1}{2\,\pi\,C}\right)$$

Dividing both sides by f_r^2

$$\left(\frac{f_r}{f_n}\right)^2 = \frac{1}{2\pi f_n L} \cdot \frac{1}{2\pi f_n C} = \frac{X_C}{X_L} = K$$

$$f_r = f_n \sqrt{K}$$

Thus sub-synchronous resonance occurs at frequency f_r, equal to normal frequency multiplied by square-root of degree of compensation.

Table 48.9 gives the resonance frequency f_r, for various degree of compensation for a 50 Hz series compensation.

Table 48.10

Degree of Compensation $K = \frac{X_C}{X_L}$	0.1	0.2	0.3	0.1	0.5	0.6
Sub-synchronous Resonance Frequency for 50 Hz system	15.8	22.4	27.4	31.6	35.36	38.7

A single series compensated line with 40 to 60% compensation can resonate at frequencies between 30 and 35 Hz for normal 50 Hz system.

The condition of sub-synchronous resonance can occur during the faults on the power system, during switching operations and changing system configurations.

Solution to Sub-synchronous Resonance Problem and Series Compensated lines.

Several methods are employed to overcome the problem. These include :

1. *Use of filters* for eliminating/damping the harmonics. The various filters include Static blocking filters, bypass damping filters, dynamic filters.
2. Bypassing the series capacitor bank under resonance condition.
3. Tripping of generator units under conditions of sub-synchronous resonance.

Section 48-B

48.27. STATIC VAR SYSTEM (SVS)

The static VAr systems (SVS), static VAr control (SVC) Utilize shunt reactors and shunt capacitor combination with high voltage high power thyristor control for achieving fast, accurate source of controlled reactive power (Q, kVAr). Ref. Sec. (45.20)

48.28. APPLICATIONS

SVS has several applications including the following :

1. **Normal voltage Regulation of transmission Systems.** Better stepless, fast accurate *voltage control* of sub-station buses over a wide range of loads by supplying reactive power.

2. **Dynamic Compensation of fluctuating reactive loads.** With arc furnaces, rolling mills etc. SVS are used for *rapid change* (a few cycles) *in reactive power compensation* in accordance with varying load. This reduces lamp flicker and voltage dips. The first application of SVS to reduce lamp flicker was introduced in 1973. Now SVS is commonly used in industrial distribution systems.

3. **Control of Over voltages in transmission systems arising due to load rejection.** When a large load is switched off due to any reason (frequency control/fault), the receiving bus voltage rises rapidly (few seconds) SVS provides rapid change in reactive power compensation (few cycles) and regulates the voltage.

4. Compensation of reactive power to HVDC sub-station AC buses for Reactive power required is about 60% of active power P, for stable operation of convertors.

5. Damping of sub-synchronous Resonance Frequency Oscillations in power systems.

6. Improving transient stability of power system by rapid voltage control. By controlling V_S and V_R and load angle δ. SVS helps in improving stability (indirectly).

Configuration of SVS. In conventional shunt compensation schemes shunt reactors in switched in during low loads and shunt capacitors are switched in during heavy loads or low lagging power factor loads (Sec. 45.14 C, D).

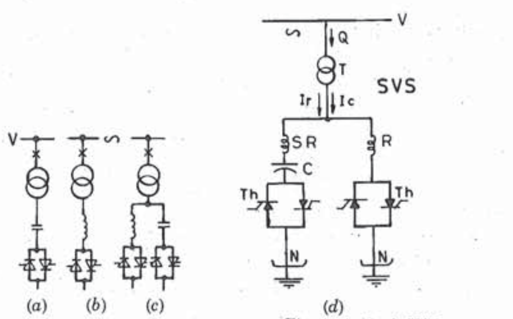
In SVS, the compensation is controlled by any of the following :

— Thyristor switched capacitors (TSC).

— Thyristor controlled reactors (TCR).

— Thyristor switched capacitors combined with thyristor controlled reactors (TSC/TCR).

Thyristor controlled capacitors (TSC). Fig. 48.4 (*a*) illustrates principle of thyristor switched capacitor. The principle of thyristor switch illustrated in Fig. 38.11, Sec. 38.7.6 is employed in switching of required number of capacitor units. The thyristors are used as power switching device. The capacitor banks are connected in shunt with the sub-station bus *via* the thyristor switches. During heavy loads the thyristor switch is switched on. Here, the thyristors are used as switching devices and the scheme is called *Thyristor Switched Capacitor (TSC)*.



(*a*) Thyristor Switched Capacitors (TSC)
(*b*) Thyristor Controlled Reactor (TCR)
(c) Combined TSC/TCR. Total SVS
R = *Reactor*,
C = Capacitor,
S.R. = Smoothing Reactors
T = Transformer.

Fig. 48.4. Static VAR sources.

Thyristor Controlled Reactor (TCR). Fig. 48.4(*b*) illustrates the TCR. In this scheme the duration of the current flowing through reactor during every cycle is controlled by controlling phase angle of thyristor gate pulses.

For every half cycle, the thyristor is given a triggering pulse by the control circuit. The TCR scheme is used for EHV lines are providing lagging, kVr during low loads or load throw-off.

Combined TSC/TCR (Fig. 48.4 *c*) **SVS.** In case of EHV-transmission systems, the compensation requirements demand shunt capacitors during high loads and shunt reactors during low loads. Depending upon the desired control range of reactive power compensation required, thyristor-controlled compensation (Static VAR Source-SVS) is built up using a suitable combination of Thyristor Switched Capacitors (TSC) and Thyristor Controlled Reactor (TCR), SVS (Fig. 48.4 *d*) is used for voltage control of transmission system buses.

The *Power Transformer* (T) interface is used for stepping down bus-voltage (from 420 kV or 245 kV to practical voltage levels such as 36 kV) for economic design of SVS.

Thyristors (Th) connected in series with Reactor R phase controlled (control of phase angle of triggering pulses) to allow continuous adjustment of inductive current (Lagging Q) Refer Fig. 48.5.

As per convention Q absorbed by inductive loads is considered positive (Sec. 45.15). Hence by increasing the current conduction through reactor R, the operating point A is shifted towards right from C to D. The capacitor C are either by switching discrete capacitor groups or fixed depending upon the system requirements.

Automatic Voltage Regulator (AVR) for SVS is programmed to regulate transmission bus voltage with pre-selected tolerances and time delays.

As the transmission voltage varies with load, the AVr preforms the function of controlling current flowing through the reactor R during each half cycle *via* the thyristor (Th). Smoothing Reactor (SR) provides a smoothing effect for current flowing through capacitor branches.

Filters. Harmonic filters are necessary with each SVS to eliminate harmonics from AC bus voltage.

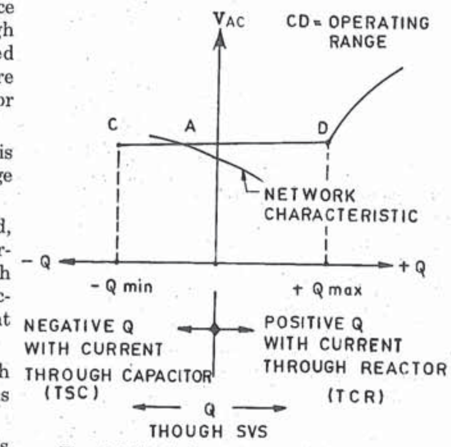


Fig. 48.5. Static characteristic of a SVS system.
(Point A moves along CD with variation of Q of SVS)

Speed. An important advantage of SVS is its speed. SVS controls the voltage by varying reactive current drawn by the combination of capacitors are reactors. SVS can respond to system voltage variation automatically within a few cycles. As a result lamp flicker due to load variations is reduced in case of distribution systems.

Also it provides dynamic voltage control to sub-stations buses and improves system stability.

Steady Characteristic of SVS. Fig. 48.5 illustrates the Voltage V/Reactive power Q steady State characteristic of sub-station bus as affected by the reactive power compensation Q by SVS.

The operating range is represented by segment CD. Operating point A moves towards left (negative Q) with increasing current in capacitors C. Operating point A moves towards right (positive Q) by increasing current through reactor R.

Operating point A is decided by intersection of network characteristic (dashed) with line CD.

Control System for SVS. The amount of sophistication required for control system of SVS depends on application.

The basic requirements of the control include :

(*i*) Voltage control (*ii*) VAr flow control

Refer Fig. 48.16. The busbar voltage (V) and current flowing into compensator (I) are both sensed by means of VT and CT. Both these values are fed to the automatic voltage regulator (AVR)

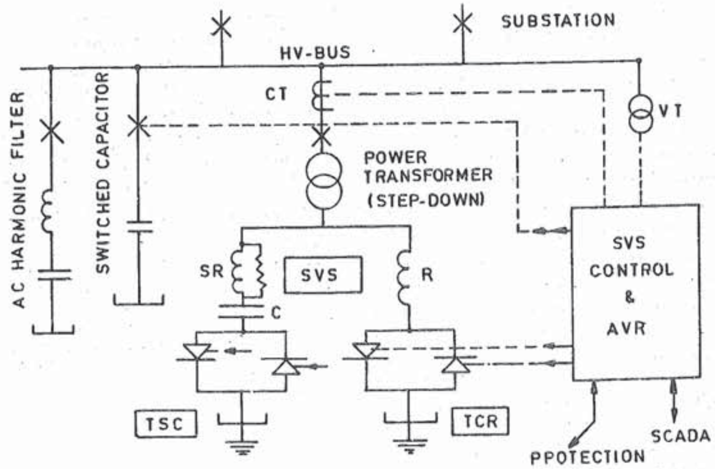


Fig. 48.6. SVS system – Schematic diagram of an SVS system and centre.

and automatic VAr compensator. The Automatic Voltage Regulator and Automatic VAr compensator performs the following tasks :

— Sends command to switched capacitor banks for voltage control.

— Controls phase angle of triggering of thyristor in SVS.

SVS control is integrated with sub-station protection and SCADA system.

Harmonic Filters. Operation of thyristor causes generation of harmonic frequencies on AC bus side. The harmonic tuned filters appropriate frequencies (*e.g.* 11th, 13th, 23rd) are connected in shunt with the AC bus. The requirements of filter is matched with the prevailing system condition. (Refer Fig. 48.7).

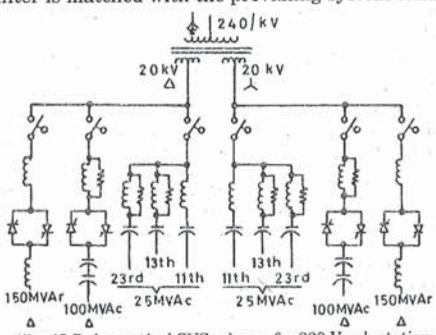


Fig. 48.7. A practical SVS scheme for 220 V sub-station.

An Example of SVs Scheme. (*Courtesy* : Westinghouse, USA).

Fig. 48.7 gives a single line diagram of SVS scheme for 245 kV sub-station bus at Langdon (USA).

The ± 250 MVAr rated, SVA system was installed to regulate 245 kV bus voltage and to improve stability limit of transmission.

The 12-pulse thyristor switched capacitor (TSC), thyristor controlled reactor (TCR) type system, selected for fast response, low average operating losses and very low harmonic content. SVS can provide ± 302.5 MVAr output continuously at 1.1 PU line voltage and upto 496 MVAr absorption on overload at 1.17 PU line voltage for 10 minutes.

The SVC control is of recent design utilizing advanced analogue and microprocessor techniques to provide optimum performance for all system conditions. The control techniques used had been tested prior to final equipment design with the model of the TNA (Transient Network Analyser).

Thyristor valves

Two types of thyristor valves are used in the SVC at Langdon, six of each type to control the current in the main reactors and in the capacitor banks respectively. The single-phase thyristor valve, rated nominally at 20 kV, are constructed of individual, self-contained, bi-directional thyristor switch modules connected in series.

Each module contains one reverse parallel pair of thyristors between liquid called copper heat sinks with their associated firing circuits and snubber components. These modules are supported on a "deck" structure accommodating upto 12 interconnected modules, the associated piping for the coolant and the conductor bus elements.

The TCR valves for the control of reactor currents contain two decks of 12 thyristor modules each per phase (24 in series). The TSC valves for switching capacitor current contains four decks of 10 thyristor modules each per phase (40 in series).

Gating control signals are transmitted to the valves from the SVC control via fibre optic cables. Fibre optics are used also for the transmission of the thyristor failure indication to the remote thyristor status scanner at the SVC control.

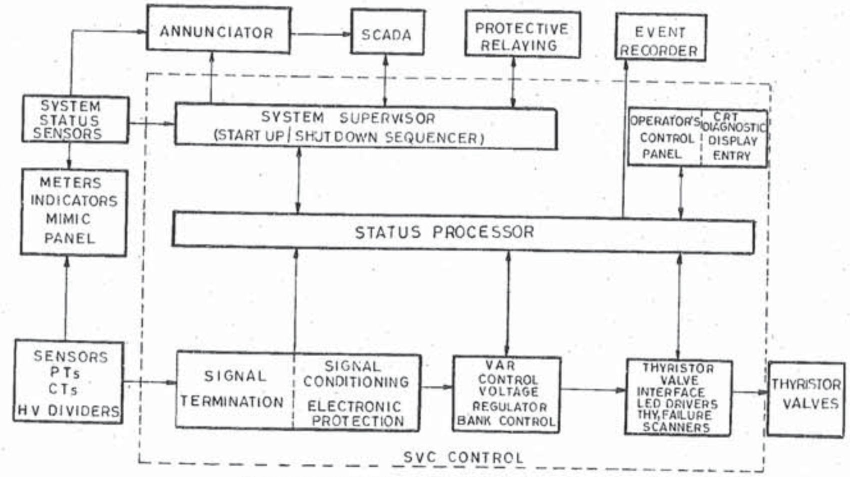


Fig. 48.8. Control system for SVS system shown in Fig.

The gate firing circuits of each thyristor are powered from energy derived locally at each thyristor module. The firing circuit is able to provide continuous gate drive to the thyristor. Overvoltage protection for the thyrsitors at the module level is provided by the individual emergency triggering circuit. The emergency triggering circuit normally operates at a "high" voltage level that is switched to a "low" level if repeated operations are called for without normal gate fire pulses (*e.g.* signal or gate firing circuit failure).

Controls. The major functional blocks in the control of SVS are illustrated in Fig. 48.8. The SVS control receives signals from CTs , VTs, HV voltage dividers. The control is arranged for :

(*i*) line voltage control (*ii*) VAr control

This is achieved by controlling phase angle of thyristor valves of thyristor switched capacitors (TSC) and thyristor controlled Reactor (TCR). In addition to the above usual controls of SVC, the SVS control has interface with the following :

(*i*) SCADA system (*ii*) Protective relaying

(*iii*) System status processor

The total control system incorporates a status processor and cathode ray tube (CRT) display/data entry terminal in the control system.

The primary functions of the status processor are the monitoring of the control circuits in operation for any alarm or trip conditions and the execution of control commands and adjustments of operating parameters by the operator.

The status processor also includes diagnostic software routines accessible by maintenance personnel *via* the CRT terminal on the SVC control panel aid trouble shooting and system checkout. A detailed status history is also maintained by the status processor which can be displayed on the CRT terminal.

This capability has provided to the extremely useful and a flexible tool in diagnosing control and thyristor valve related problems.

49

Interconnected Power Systems

49.1. INTRODUCTION

During the early years small local generating stations supplied power to respective local loads. Each generating station needed enough installed capacity to feed the local peak loads. Gradually, the merits of interconnected AC power systems were recognised.

The interconnection of individually controlled AC networks gives several advantages such as :

— Lesser spinning reserves

— Lesser installed capacity

— Better use of energy reserves

— Economic generation

— Minimise operational costs, maximise efficiency

— Better service to consumers.

Modern power system (Network) is formed by interconnecting several individually controlled AC networks. Each individually controlled AC network has its own generating stations, transmission and distribution systems, loads and a load control centre. The regional load control centre controls the generation and in its geographical region to maintain the system frequency within targeted limits (50.5 – 49.5 Hz). The exchange of power (Import/Export) between neighbouring AC networks is dictated by the National Load Control Centre. Thus the entire AC network is an interconnected network called National Grid. Even neighbouring National Grids are interconnected to form a Super Grids. (*e.g.* USA Canada; European Grid ; UK-France). Interconnections between India-Pakistan, India-Shri Lanka, India-Nepal etc. are in initial planning stage (1997).

The main task of an interconnecting transmission system is to transfer adequate power from one AC system to the other AC system during normal conditions and also during emergency condition and maintain system security. Traditionally AC lines have been used for interconnection. However, HVDC links give asynchronous interconnection and have a distinct superiority over AC links for the application of system interconnection. HVDC system interconnection may have a transmission line/cable or it may be in the form of a back-to-back convertor station without a transmission line. HVDC links are also used for interconnection between AC systems having different frequencies *e.g.* 50 Hz to 60 Hz. The choice of voltage of EHV-AC or HVDC Inter-connection link is decided by the economic studies related with power transfer and distance.

Present HVDC interconnections are with two terminals. Recently multi-terminal HVDC systems have been executed (1987). With multi-terminal HVDC systems, several AC systems can be interconnected. Back-to-back HVDC stations are preferred for interconnecting adjucent AC systems to provide Asynchronous tie.

Inter-connection has significant influence on load-frequency control, short-circuit levels, power system security and stability, power system protection and control, energy management, financial accounting etc.