UNIT-1

INTRODUCTION TO FACTS

Need for Transmission Networks Interconnections:

- To make electric energy generation more economical, the generating stations are sited remotely from the load centers, and closer to the source of power.

- For example, the primary concern to hydroelectric power plants is the availability of water and benefits of the sites having higher heads with significant water flows, while thermoelectric power stations are situated near to coal mines and the nuclear power plants are located distantly away from the urban centers for safety.

- Consequently, the transmission lines serve the purpose to pool the generating sites and load centers covering large distances between generation and end-users in order to minimize the total generation capacity and fuel cost.

- To enhance the system reliability, the electric power supply systems are widely interconnected, i.e., interlinking the neighboring power supply utilities, which further extend to inter-regional and international connections.

- Moreover, with the probable unavailability of some generating units, the interconnection lines could force the electric power flows to be redirected through longer routes to provide emergency assistance (e.g., when encountering partial blackouts).

- As such, transmission interconnections enable taking benefit of diversity of loads, availability of sources and fuel price to provide consistent and uninterrupted service to the loads.

Need for Facts Devices

- As power transfers grow, the power system becomes increasingly more complex to operate and the system can become less secure for riding through the major outages.

- It may lead to large power flows with inadequate control, excessive reactive power in various parts of the system, large dynamic swings between different parts of the system and bottlenecks, and thus the full potential of transmission interconnections cannot be utilized.

- The power systems of today, by and large, are mechanically controlled.
- Even though we use of microelectronics, computers and high-speed communications for control and protection of present transmission systems; however, the final power control action is taken by the mechanical switches.

- Also, the mechanical devices is that control cannot be initiated frequently, because they tend to wear out very quickly compared to static devices.

- Increased demands on transmission, absence of long-term planning, and the need to provide open access to generating companies and customers, all together have created tendencies toward less security and reduced quality of supply.

- The FACTS technology is essential to alleviate some but not all of these difficulties by enabling utilities to get the most service from their transmission facilities and enhance grid reliability.

  FACTS: Flexible Alternating-current transmission system is defined by the IEEE as **"AC transmission systems incorporating power electronics based andother static controllers to enhance controllability and increase power transfer capability".**

- The Facts concept originally came into effect in 1980's to solve operation problems due to the restrictions on the construction of new transmission lines, to improve power system stability margins.

- It also facilitates power exchange between different generation companies and large power users, thus considerably utilizing the existing transmission network instead of adding new transmission lines for growing demand of power, as it may be restricted due to economical and environmental problems.

- FACTS Controllers can control the interrelated parameters that govern the operation of transmission systems including series impedance, shunt impedance, current, voltage, phase angle, and the damping of oscillations at various frequencies below the rated frequency.

- These constraints cannot be overcome, while maintaining the required system reliability, by mechanical means without lowering the useable transmission capacity.

- FACTS Controllers can enable a line to carry power closer to its thermal rating.

- Mechanical switching needs to be supplemented by rapid-response power electronics.

- The FACTS technology is not a single high-power Controller, but rather a collection of Controllers, which can be applied individually or in coordination with others to control one or more of the interrelated system parameters.

Power Flow in AC System

- Consider a simple case of power flow as shown in fig

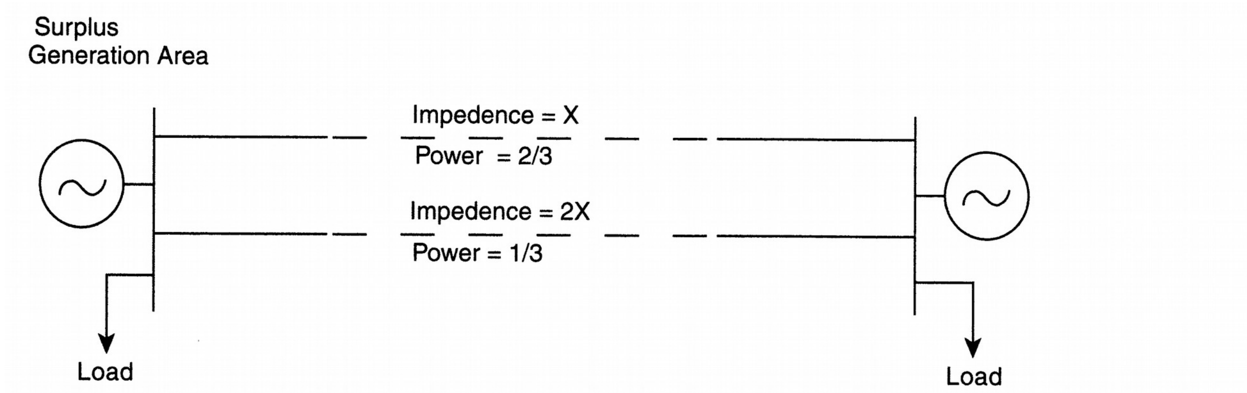
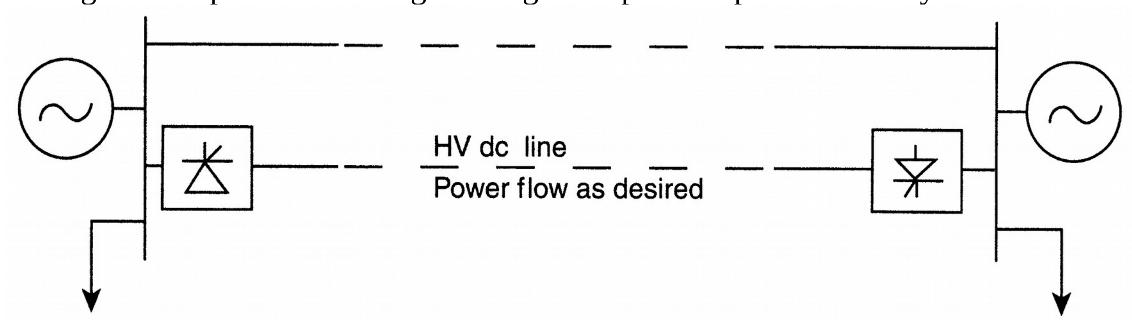


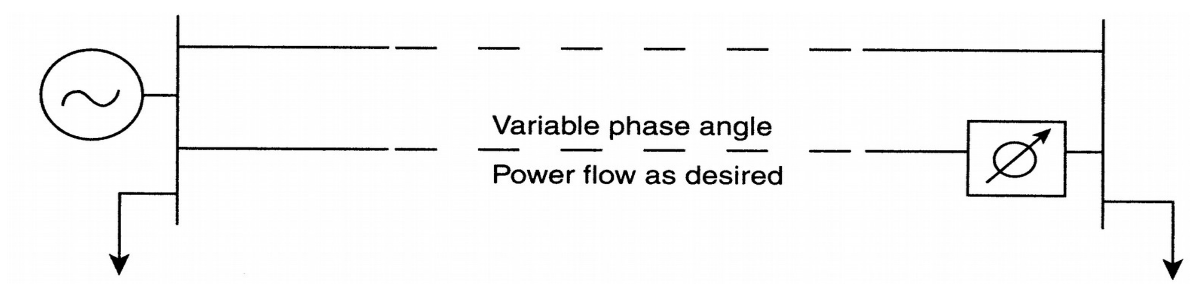
Fig: Power flow with parallel paths

- Power flow is based on the inverse of the various transmission line impedances.
- It is likely that the lower impedance line may become overloaded andthereby limit the loading on both paths even though the higher impedance path is not fully loaded.



fig(b): Power flow with HVDC

- Fig(b) shows two parallel paths but one of these has HVDC transmission.
- With HVDC power flows as ordered by the operator.
- The the HVDC line can be used to its full thermal capacity if adequate converter capacity is provided.
- An HVDC line can also help the parallel ac transmission line to maintain stability.
- HVDC is expensive for general use, and is usually considered when long distances.

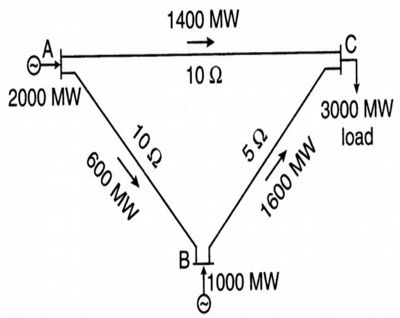


Fig(c): Power flow control with variable impedance.

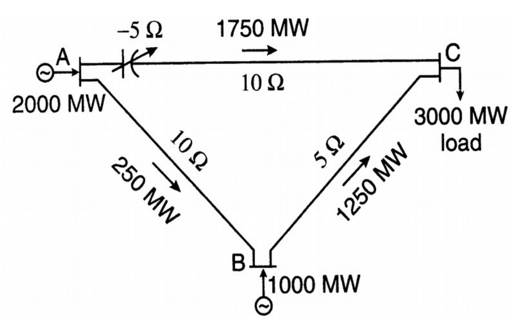
- By means of controlling impedance [Figure 1.1(c)] or phase angle [Figure 1.1(d)], or series injection of appropriate voltage (not shown) a FACTS Controller can control the power flow as required.

Power flow in a Meshed System

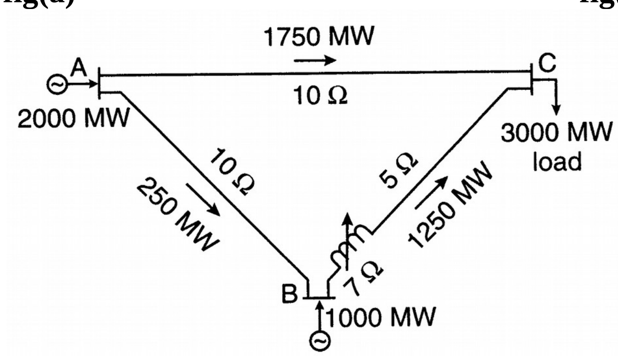
- consider a very simplified case in which generators at two different sites are sending power to a load center through a network consisting of three lines in a meshed connection



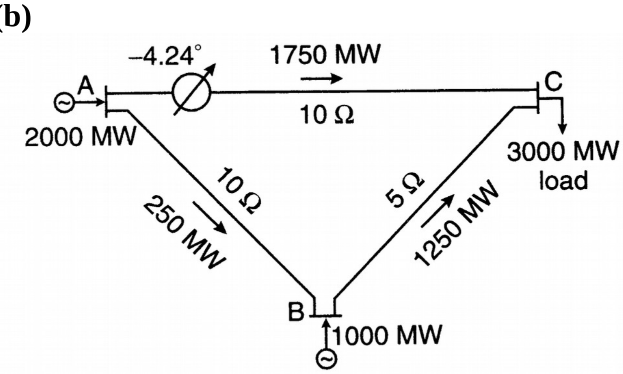
fig(a)



fig(b)



fig(c)



fig(d)

Figure Power flow in a mesh network: (a) system diagram; (b) system diagram with Thyristor-Controlled Series Capacitor in line AC; (c) system diagram with Thyristor-Controlled Series Reactor in line BC; (d) system diagram with Thyristor-Controlled Phase Angle Regulator in line AC.

- The lines AB, BC, and AC have continuous ratings of 1000 MW, 1250 MW, and 2000MW, respectively.

- One of the generators is generating 2000 MW and the other 1000 MW, a total of 3000 MW would be delivered the load center. For the impedances shown, the three lines would carry 600, 1600, and 1400 Mw, respectively. Therefore line BC gets overload.

- Generation would have to be decreased at B, and increased at A. in order to meet the load without overloading line BC.

- If a capacitor whose reactance is -5 ohms at the synchronous frequency is inserted in one line it reduces the line's impedance from 10Ω to -5Ω.

- Power flow through the lines AB, BC, and AC will be 250,1250, and 1750 MW. If the series capacitor is adjustable, then power-flow levels can be adjusted according to the thermal limitations, transmission losses.

- If the capacitor is mechanically switched, the number of operations would be severely limited by wear on the mechanical components because the line loads vary continuously with load conditions, generation schedules, and line outages.

- A series capacitor in a line may lead to subsynchronous resonance (typically at 10-50 Hz for a 60 Hz system).

- The outage of one line forces other lines to operate at their emergency ratings and carry higher loads, power flow oscillations at low frequency (typically 0.3-3 Hz) may cause generators to lose synchronism.

- If all or a part of the series capacitor is thyristor-controlled, however, it can be varied as often as required. This would allow the transmission system to go from one steady-state condition to another without the risk of damage to a generator shaft and also help reduce the risk of system collapse. In other words, a thyristor-controlled series capacitor can greatly enhance the stability of the network.

- Similar results may be obtained by increasing the impedance of one of the lines in the same meshed configuration by inserting a 7 Ω reactor (inductor) in series withline AB Fig(c).

- The regulator is installed in the third line to reduce the total phase-angle difference along the line from 8.5 degrees to 4.26 degrees. A combination of mechanical and thyristor control of the phase-angle regulator may minimize cost.

What Limits the Loading capability?

Basically there are three kinds of Limitations

1)Thermal 2)Dielectric 3)Stability

Thermal: Thermal capability of an overhead line is a function of the ambient temperature, wind conditions, condition of the conductor, and ground clearance.

- It varies perhaps by a factor of 2 to 1 due to the variable environment and the loading history.
- The nominal rating of a line is generally decided for the worst ambient environment. Some utilities assign winter and summer ratings.
- There are also off-line computer programs that can calculate a line's loading capability based on available ambient environment and recent loading history.
- During planning/design stages, normal loading of the lines is frequently decided on a loss evaluation basis under assumptions which may have changed for a variety of reasons.
- Real time loading capability of transformers is also a function of ambient temperature, aging of the transformer and recent loading history.

Dielectric: For a given nominal voltage rating, it is often possible to increase normal operation by +10Vo voltage (i.e., 500 kV-550 kV) or even higher.

- Care is then needed to ensure that dynamic and transient over voltages are within limits.
- Modern gapless arresters or line insulators with internal gapless arresters, or powerful thyristor-controlled overvoltage suppressors at the substations can enable significant increase in the line and substation voltage capability.
- The FACTS technology could be used to ensure acceptable over-voltage and power flow conditions.

Stability: The stability issues that limit the transmission capability are:

- Transient stability
- Dynamic stability
- Steady-state stability
- Frequency collapse
- Voltage collapse
- Sub synchronous resonance

POWER FLOW AND DYNAMIC STABILITY CONSIDERATIONS OF A TRANSMISSION INTERCONNECTION

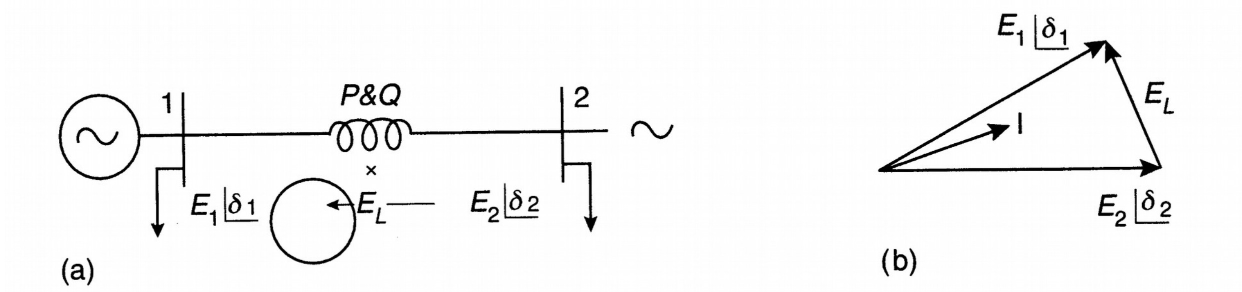
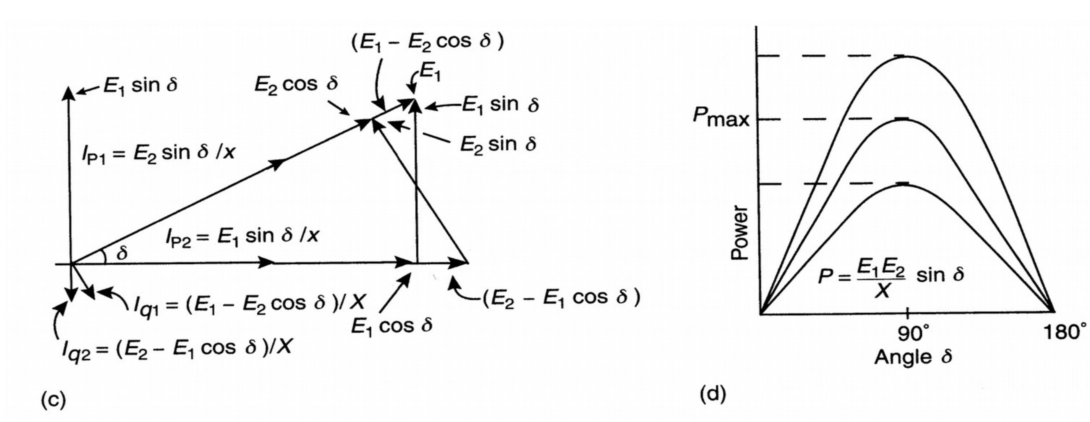


Fig: Ac power flow control of a transmission line:
(a) simple two-machine system (b) current flow perpendicular to the driving voltage

- E1 and E2 are the magnitudes of the bus voltages with an angle δ between the two. The line is assumed to have inductive impedance X, and the line resistance and capacitance are ignored.
  $I = \frac{E_L}{X}$ and lags E_L by 90^0.
- E_L is the driving voltage drop in the line.
- The current flow on the line can be controlled by controlling E_L or X or δ.
- The rating of series FACTS controllers would be a fraction of the throughput rating of a line.
- If the angle between the two bus voltages is small the current flow largely represents the active power.
- Increasing or decreasing the inductive impedance of a line will greatly affect the active power flow
- Therefore impedance control can be the most cost-effective means of controlling power flow.



Active component of the current flow at E1 is:

$I_{p1} = (E_2 \sin\delta)/X$

Reactive component of the current flow at ,E1 is:

$I_{q1}= (E_1 - E_2\cos \delta)/X$

Thus, active power at the E1 end:

$P_1 = E_1 (E_2 \sin \delta)/X$

Reactive power at the E_1 end:

$Q_1= E_1 (E_1 - E_2\cos \delta)/X$

Similarly, active component of the current flow at E_2 is:

$Ip2= (E_1 \sin \delta)/X$

Reactive component of the current flow at E2 rs:

$I_{q2}= (E_2-E_1 \cos \delta)/X$

Thus, active power at the E2 end:

$P_2=E_2 (E_1 \sin \delta)/X$

Reactive power at the E2 end:

$Q_2= E_1(E_2 - E_1 \cos \delta)/X$

Naturally P1 and P2 a;re the same:

$P = E_1 (E_2 \sin \delta)/X$

- By varying the value of 'X' P, Q_1 and Q_2 will vary.
- When δ increases from 0^0 to 90^0 active power increases. Further increase of δ from 90^0 to 180^0 power then falls.
- Therefore without the high speed control of any one of parameters E_1, E_2, E_1-E_2, X and δ, the transmission line can be utilized only to a level well below that corresponding to 90^0.
- This is necessary, in order to maintain an adequate margin needed for transient and dynamic stability.
- For a given power flow, varying of X will correspondingly vary the angle between the two ends.
- Power/current flow can also be controlled by regulating the magnitude of voltage phasor. El or voltage phasor E2
- With change in the magnitude of E_1, the magnitude of the driving voltage phasor $E_1 – E_2$ does not change by much, but its phase angle does. This means regulation of E_1, or E_2 has much more influence over the reactive power flow.

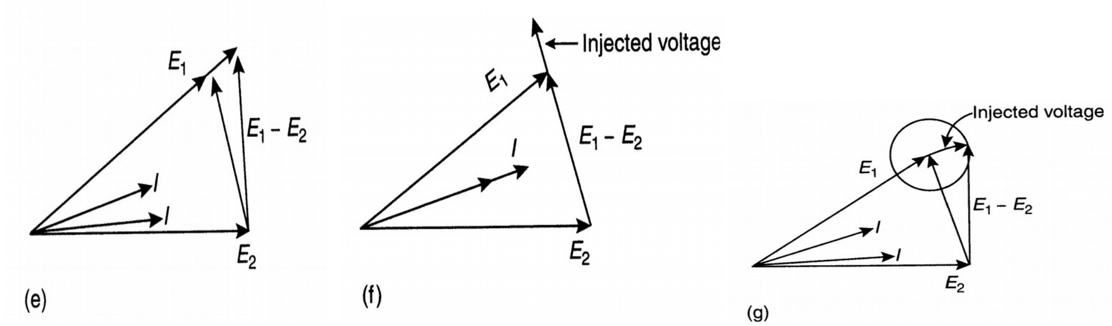


FIG: (e) regulating voltage magnitude mostly changes reactive power (f) injecting voltage perpendicular to the line currentmostly changes active power (g) injecting voltage phasor in series with the line.

- Figure (f) that when the injected voltage is in phase quadrature with the current (which is approximately in phase with the driving voltage) it directly influences the magnitude of the current flow, and with small angle influences substantially the active power flow.

- The voltage injected in series can be a phasor with variable magnitude and phase relationship with the line voltage [Figure (g)]. It is seen that varying the amplitude and phase angle of the voltage injected in series, both the active and reactive current flow can be influenced.

Importance of controllable Parameters

- Control of the line impedance X can provide a powerful means of current control.
- When the angle is not large, control of X or the angle substantially provides the control of active power.
- Control of angle which in turn controls the driving voltage, provides a powerful means of controlling the current flow and hence active power flow when the angle is not large.
- Injecting a voltage in series with the line, and perpendicular to the current flow, can increase or decrease the magnitude of current flow and hence the active power when the angle is not large.
- Injecting voltage in series with the line and with any phase angle with respect to the driving voltage can control the magnitude and the phase of the line current. This means that injecting a voltage phasor with variable phase angle can provide a powerful means of precisely controlling the active and reactive power flow. This requires injection of both active and reactive power in series.
- Because the per unit line impedance is usually a small fraction of the line voltage, the MVA rating of a series Controller will often be a small fraction of the throughput line MVA.
- When the angle is not large, controlling the magnitude of one or the other Line voltages (e.g., with a thyristor-controlled voltage regulator) can be a very cost-effective means for the control of reactive power flow through the interconnection.
- Combination of the line impedance control with a series Controller and voltage.

BASIC TYPES OF FACTS CONTROLLERS

In general, FACTS Controllers can be divided into four categories:
1)Series Controllers
2)Shunt Controllers
3)Combined series-series Controllers
4)Combined series-shunt Controllers

Series Controllers: [Figure (b)] The series Controller could be a variable impedance, such as capacitor, reactor, etc., or a power electronics based variable source of main frequency, sub synchronous and harmonic frequencies (or a combination) to serve the desired need. In principle, all series Controllers inject voltage in series with the line. Even a variable impedance multiplied by the current flow through it, represents an injected series voltage in the line. As long as the voltage is in phase quadrature with the line current, the series Controller only supplies or consumes variable reactive power. Any other phase relationship will involve handling of real power as well.

Shunt Controllers: [Figure (c)] As in the case of series Controllers, the shunt Controllers may be variable impedance, variable source, or a combination of these. In principle, all shunt Controllers inject current into the system at the point of connection. Even a variable shunt impedance connected to the line voltage causes a variable current flow and hence represents injection of current into the line. As long as the injected current is in phase quadrature with the line voltage, the shunt Controller only supplies or consumes variable reactive power. Any other phase relationship will involve handling of real power as well.

Combined series-series Controllers: [Figure (d)] This could be a combination of separate series controllers, which are controlled in a coordinated manner, in a multiline transmission system. Or it could be a unified Controller, Figure (d), in which series Controllers provide independent series reactive compensation for each line but also transfer real power among the lines via the power link. The real power transfer capability of the unified series-series Controller, referred to as Interline Power Flow Controller, makes it possible to balance both the real and reactive power flow in the lines and thereby maximize the utilization of the transmission system. Note that the term "unified" here means that the dc terminals of all Controller converters are all connected together for real power transfer.

Combined series-shunt Controllers: [Figures (e) and (f)] This could be a combination of separate shunt and series Controllers, which are controlled in a coordinated manner [Figure (e)], or a Unified Power FIow Contoller with series and shunt elements [Figure (f)]. In principle, combined shunt and series Controllers inject current into the system with the shunt part of the Controller and voltage in series in the line with the series part of the Controller. However, when the shunt and series Controllers are unified, there can be a real power exchange between the series and shunt Controllers via the power link.

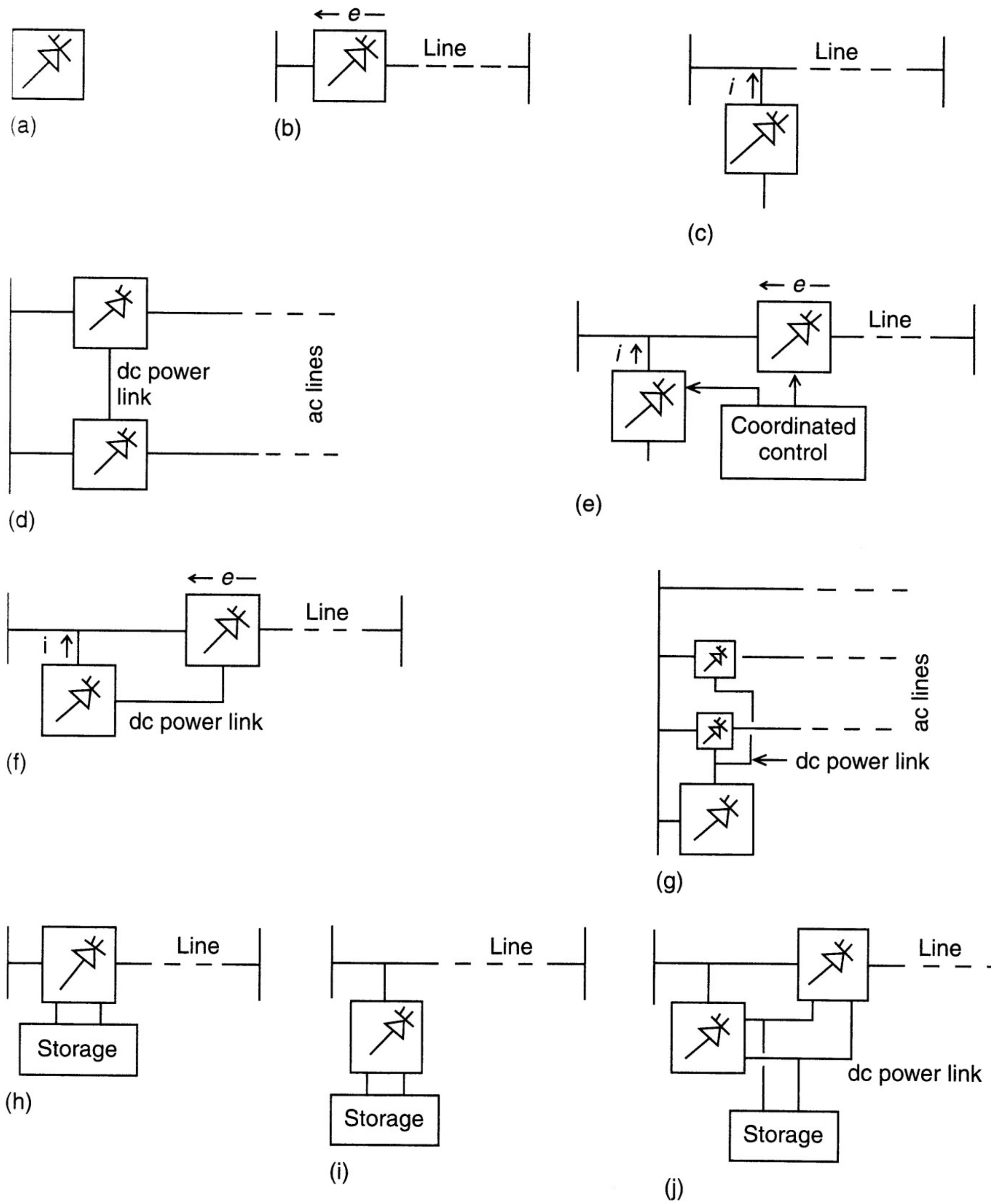


Fig: Basic types of FACTS controllers: (a) general symbol for FACTS controller(b) series Controller (c) shunt Controller (d) unified series-series Controller (e) coordinated series and shunt Controller; (f) unified series-shunt Controller (g) unified Controller for multiple lines (h)series Controller with storage(i) shunt Controller with storage(j)unified series-shunt Controller with storage.

HIGH-POWER DEVICE CHARACTERISTICS AND REQUIREMENTS

Voltage and Current Rating:

- Device cells for high power are usually single crystal silicon wafers, 75-125 mm in diameter, and pushing toward 150 mm in diameter.
- silicon crystal has a very high voltage breakdown strength of 20 kV/cm and a resistivity somewhere in between metals and insulators.
- Doping with impurities can alter its conduction characteristics.
- Lower doping means higher voltage capability, but also higher forward voltage drop and lower current capability. To some extent the current and voltage capabilities are interchangeable.
- A larger diameter naturally means higher current capability.
- A 125 mm device may have a current-carrying capability of 3000-4000 amperes and a voltage-withstand capability in the range of 6000-10,000 volts.
- The useable device voltage will be about half the blocking voltage capability.
- Devices are connected in series for high-voltage valves.
- Ensuring equal sharing of voltage during turn-on, turn-off, and dynamic voltage changes becomes a major exercise for a valve designer in considering trade-off among various means to do so and deciding on the best mix.
- The short-circuit current duty determines the required current capacity.
- The device selection must therefore consider all possible fault and protection scenarios to decide on the current and also voltage margins and redundancy.
- The thyristor family of devices can carry a large overload current for short periods and a very large single-cycle fault current without failures. The thyristor and diode family of devices fail in a short circuit with low-voltage drop, so the circuit may continue to operate if the remaining devices in the circuit can perform the needed function.
- As dictated by the market needs of converters, most of the devices made with turn-off capability, are made with no reverse blocking capability. They are therefore referred to as asymmetric turn-off devices, often just turn-off devices. As it turns out the voltage-sourced converters also require a reverse diode in parallel with each main device.

LOSSES AND SPEED OF SWITCHING

Apart from the voltage withstand and current-carrying capabilities, there are many characteristics that are important to the devices. The most important among these are:

- Forward-voltage drop and consequent losses during full conducting state.
- Speed of switching. Transition from a fully conducting to a fully nonconducting state (turn-off) with corresponding high dv/dt just after turn-off, and from a fully nonconducting to a fully conducting state (turn-on) with corresponding high di/dt during the turn-off are very important parameters. They dictate the size, cost, and losses of snubber circuits needed to soften high dv/dt and, di/dt, ease of series connection of devices, and the useable device current and voltage rating.
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circuits needed to soften high dv/dt and, di/dt, ease of series connection of devices, and the useable device current and voltage rating.

- The gate-driver power and the energy requirement are a very important part of the losses and total equipment cost. with large and long current pulse requirements, for turn-on and turn-off, not only can these losses be important in relation to the total losses, the cost of the driver circuit and power supply can be higher than the device itself. The size of all components that accompany a power device increases the stray inductance and capacitance, which in turn impacts the stresses on the devices, switching time and snubber losses.

PARAMETER TRADE OFF OF DEVICES

The cost of devices is related to production yield of good devices, which are then graded into various ratings. This therefore calls for good quality control all the way from the starting material to the finished product and including the quality of the electric power supply in the production plant. All power devices for high-power Controllers are individually tested, as is the practice with HVDC converters, and their record kept for future replacement service.

Apart from the trade-off between voltage and current capability, other tradeoff parameters include:

- power requirements for the gate
- di/dt capability
- dv/dt capability
- turn-on time and turn-off time
- turn-on and turn-off capability
- uniformity of characteristics
- quality of starting silicon wafers
- class of clean environment for manufacturing of devices, etc.