

FACTS: Flexible AC Transmission Systems:

"Power electronic based and other static equipment to enhance controllability and high power transfer capability."
(or)

"power electronic based and other static equipment to control two or more transmission AC systems."

Transmission Interconnections:

Need: ① To reduce the cost of electricity.

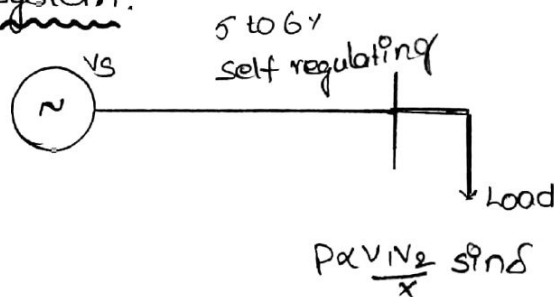
② To maintain Reliability Supply.

③ Transmission Interconnection Enables Advantages of diversity of Loads, Availability of sources with a minimum cost & Supply.

④ For Radial lines more number of Generations should required to save the load. cost of electricity is high.

⑤ Less Transmission capability means the generations are required to transmit the electrical supply to the load regardless whether the system having small or higher plants.

Power flow in AC System:



① The demand of power is increases than generation of voltage at that point should be decreases, frequency also decreases. generation must be electrically balanced with a power demand at that time electricity should be self regulating.

② If the Generation is less than demand voltage and frequency goes down

$$PG = PD + Loss$$

a) power flow in 11th path:

$$P \propto \frac{1}{ZT}$$

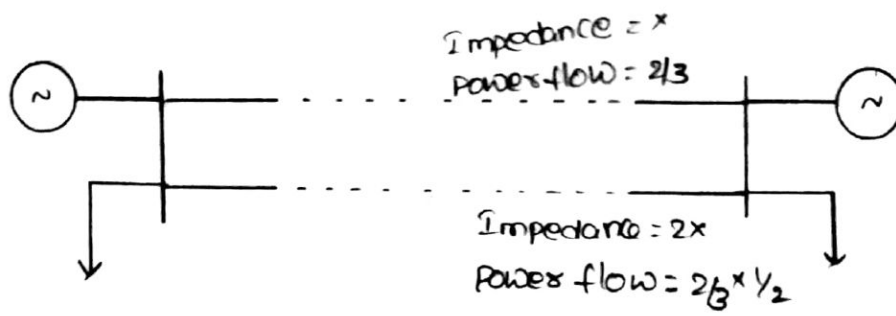


fig (i) power flow in 11th path = $\frac{1}{3}$

The power-flow varies the Inverse of the Impedance.

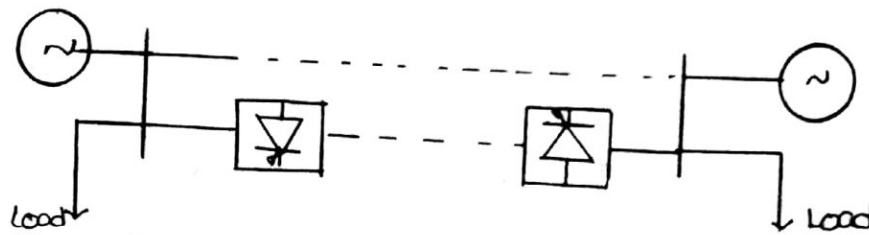


fig (ii) Fast power control of HVDC Link

- ① power is electronically controlled employing power electronic based converters.
- ② HVDC's expensive.
- ③ It is used in longer distances are involved
- ④ With the help of HVDC link bulk amount of power can be transferred.
- ⑤ power can be fast monitoring by employing HVDC Link.

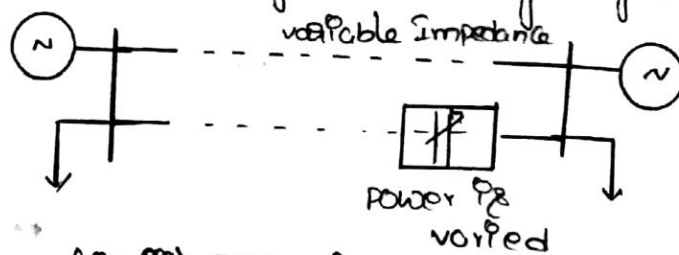


fig (iii) power-flow control by variable impedance

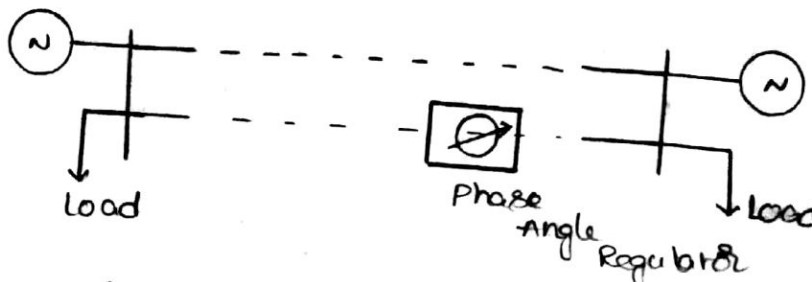


fig (iv) power-flow control by phase angle Regulator

FACTS Controllers are used to control power-flow in an AC system with help of variable impedance by using phase angle regulators.

Advantages of FACTS:

- ① It is having greater loading capabilities
- ② Greater flexibility of operation for new generation.
- ③ NO noise
- ④ Low cost
- ⑤ NO maintenance
- ⑥ It can upgrade lines
- ⑦ It can reduce power-flow i.e., (reactive power flow)
- ⑧ It can reduce the loop-flow
- ⑨ It can decrease the utilization of cost of generation.
- ⑩ Stability can be maintained.

Types of FACTS Controllers: It can be classified into 4 types

- ① Series Controller
- ② Shunt Controller
- ③ Series-Series Controller
- ④ Series-Shunt Controller

① Series Controller:-

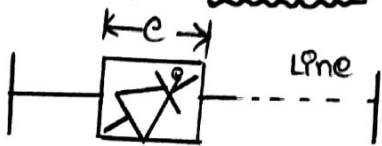


fig (1)

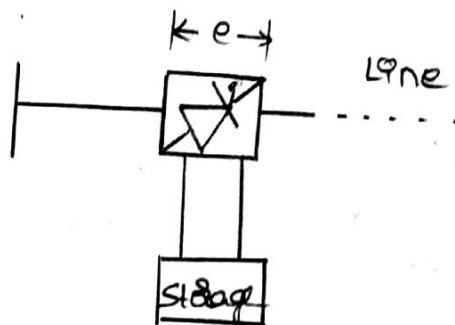


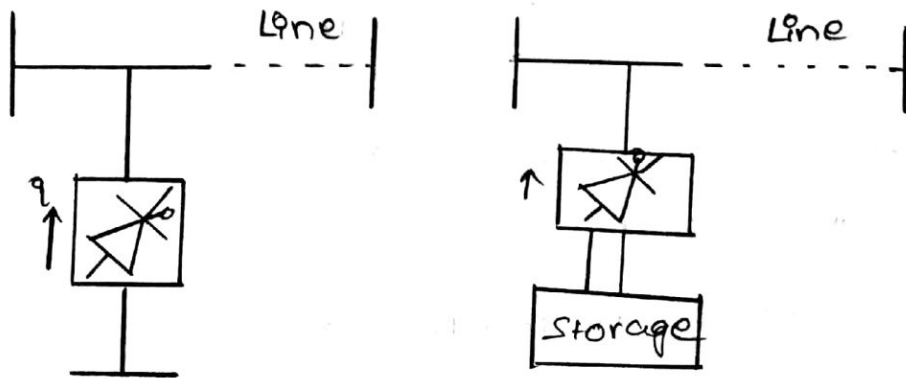
fig (2)

- ① Series Controller is a variable impedance (or) voltage source of same frequency.
- ② In a Series Controller the line voltage injected in series with a line then we can control the current

$$V = I Z$$

- ③ The variable Impedance is multiplied by current flows through it. Then we applied line voltage.
- ④ The Line voltage is in phase quadrature with the line current. It consumes (or) supplies reactive power finally smooth handling of Real power.
- ⑤ In series controller we can control current, VAR compensation, Dynamic stability, low power oscillation damping.

② Shunt Controller:



① It is a variable Impedance

② The Reactive ~~power~~ ^{current} injected shunt part of the element & (or) at the point of interconnection

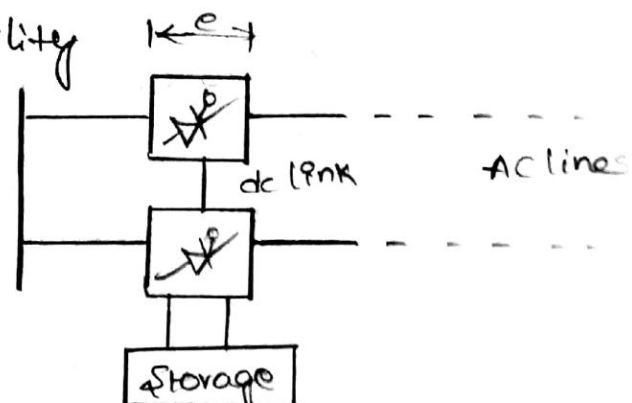
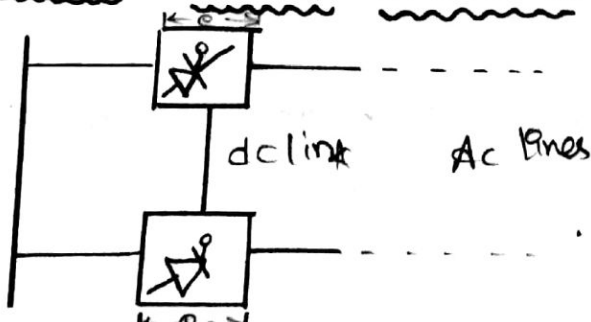
$$I = V/Z$$

③ The variable Impedance is shunted with a line voltage then we applied current flows through it.

④ The Reactive current is in phase quadrature the line voltage. It consumes or supplies reactive power, finally smooth handling of Real power.

⑤ The shunt controller controls voltage, VAR compensation, low power oscillation damping, Transition stability

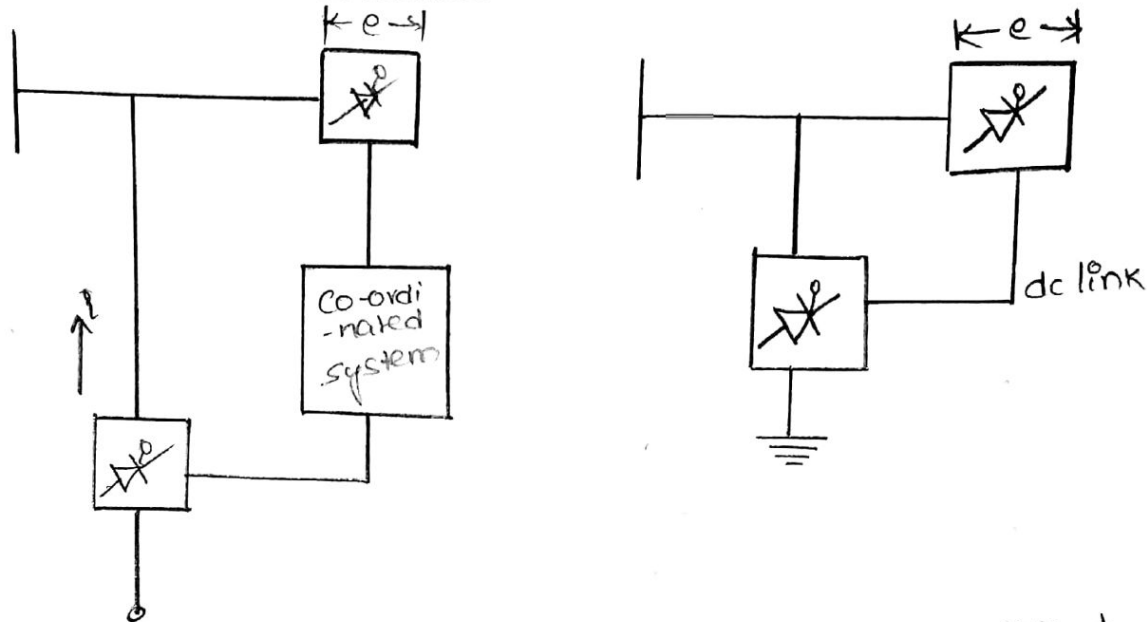
③ Series - Series Controller :-



③ Series - Series Controller are used in multistage transmission system

③ In a series-series controller we can provide independently controlling of Real power by compensating reactive power.

④ Series - Shunt Controller:



① In a series-shunt controller for reactive ^{current} ~~power~~ element injected in a shunt controller with a shunt connected part of the system. In a series controller the line voltage is injected in a series part of the terminals.

② In a shunt, series controller both are unified controllers

③ With the help of both controllers we can control real and reactive powers

④ "Unified" means dc terminals of all converters are connected together.

Relative Importance different types of controllers:

① Series controller impacts on driving voltage, VAR compensation, low power oscillation damping

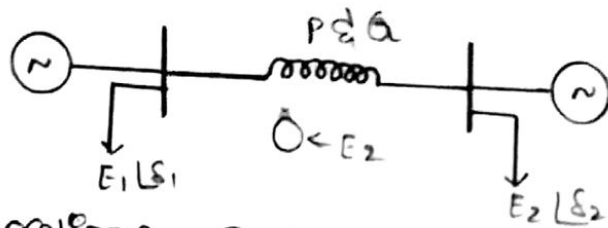
② Series controller are most powerful than shunt controller because of MVA size of series controller is less compared to the shunt controller.

③ Shunt controller is a current control device.

④ Shunt Controller is a good way Controller line voltages injecting reactive currents.

⑤ The Alternative arrangement of above figure shows that reactive power control to the dc link.

Power flow and Dynamic Stability Considerations of a Transmission Interconnection:-

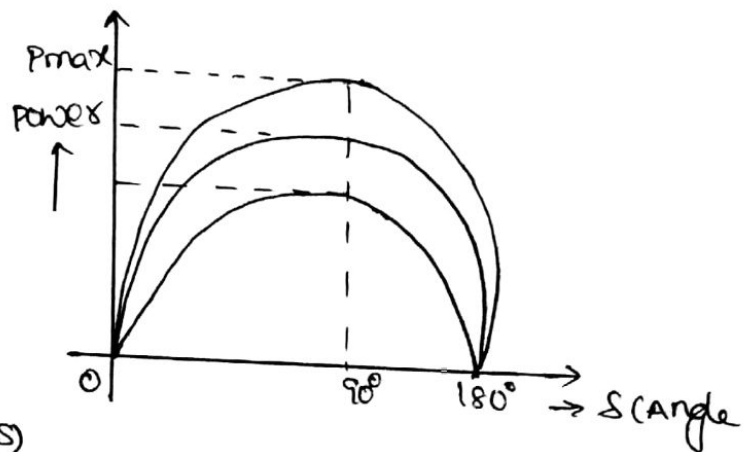
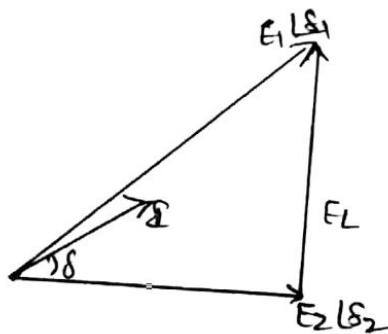
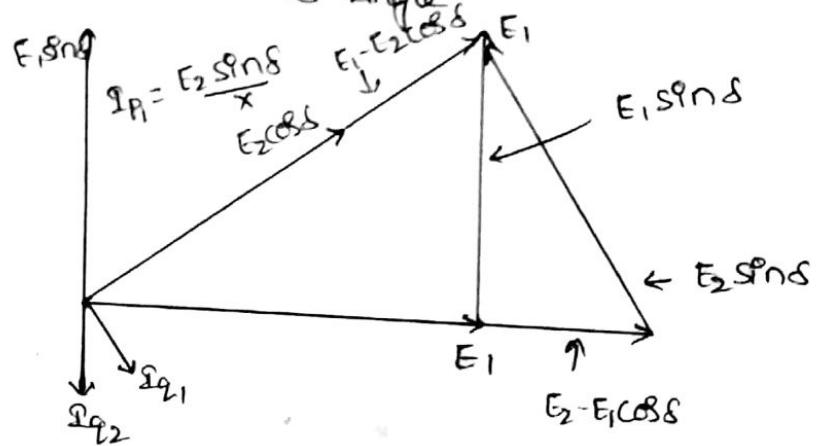


Locations ① & ② should be any Transmission Substation connected by a Transmission Line E_1, E_2 are the magnitude of the bus voltages and δ is the Angle

$$P = \frac{E_1 E_2}{X_{12}} \sin \delta$$

I_L lags E_L by 90°

$$I = \frac{E_L}{X}$$



for E_1 :- (1ex voltages)

Active Current at E_1 i.e., $I_{P1} = \frac{E_2 \sin \delta}{X}$

Reactive Current at E_1 i.e., $I_{Q1} = \frac{E_1 - E_2 \cos \delta}{X}$

Active power at E_1 i.e., $P_1 = E_1 \left(\frac{E_2 \sin \delta}{X} \right)$

Active power of E_1 i.e., $Q_1 = E_1 \left(\frac{E_1 - E_2 \cos \delta}{x} \right)$

$$Q_1 = \frac{E_1^2}{x} - \frac{E_1 E_2 \cos \delta}{x}$$

for E_2 :-

Active current at E_2 i.e., $I_{P2} = \frac{E_1 \sin \delta}{x}$

Reactive current at E_2 i.e., $I_{Q2} = \frac{E_2 - E_1 \cos \delta}{x}$

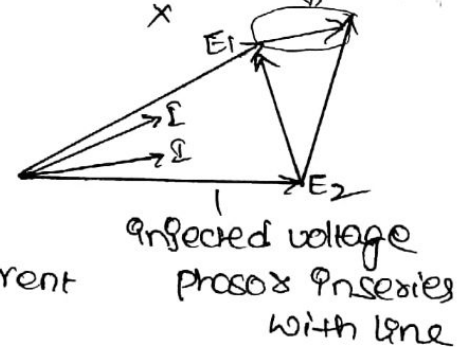
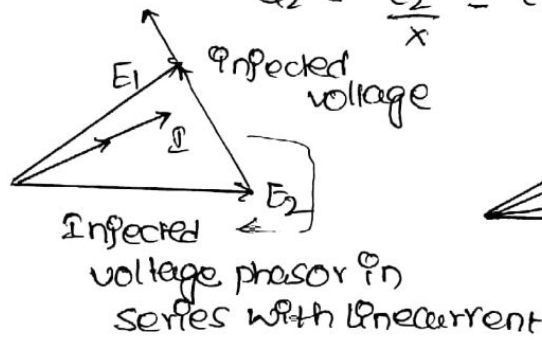
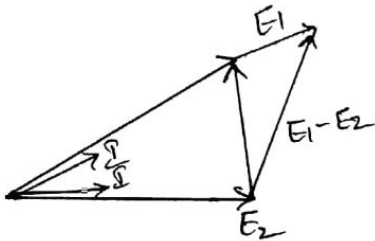
Active power at E_2 i.e., $P_2 = E_2 \left(\frac{E_1 \sin \delta}{x} \right)$

$$P_2 = \frac{E_1 E_2 \sin \delta}{x}$$

Reactive power at E_2 i.e., $Q_2 = E_2 \left(\frac{E_2 - E_1 \cos \delta}{x} \right)$

$$Q_2 = \frac{E_2^2}{x} - \frac{E_1 E_2 \cos \delta}{x}$$

Regulating voltage magnitude change reactive power



- ① δ is the angle difference b/w two phasors of E_1 & E_2 influence on Active power flow.
- ② Increasing or decreasing reactance 'x' we can get decreasing voltage and current flow will large.
- ③ The current magnitudes are same there is a voltage injection method is used to control current and power flow.
- ④ By using voltage injection method we can get stable operation.

Relative Importance of Controllable parameters:-

$$I = \frac{E_L}{X}$$

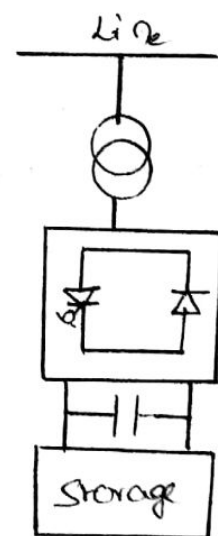
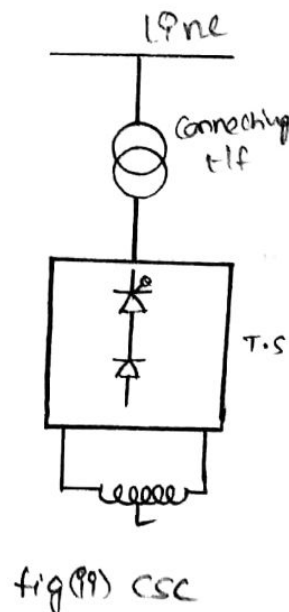
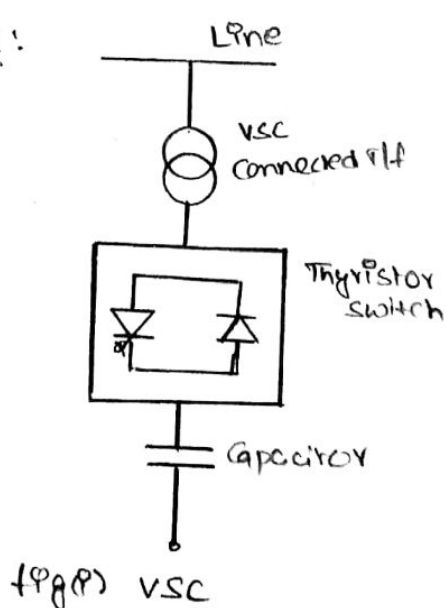
- ① The current can be controlled by controlling Line Impedance (or) Reactance.
- ② Active power should be controlled by controlling Line Reactance Angle is not large.
- ③ Driving voltage, current flow and active power flow should be controlled by controlling Impedance angle should be minimum.
- ④ To controlling the magnitudes of current flows by injecting a line voltage in series with the line when we can control current flows.
- ⑤ By injecting a voltage in phase with the phase angle regulator we can control both active & reactive power flows.
- ⑥ By controlling magnitudes of one or more line voltages we can control reactive power flows.

Definitions of FACTS Controllers:

1. Shunt Controllers:

- i. STATCOM - Static Synchronous Compensator
- ii. SSG - Static Synchronous Generator
- iii. BESS - Battery Energy Storage System
- iv. SVC - Static VAR Compensator
- v. TCR - Thyristor Control reactor
- vi. TSR - Thyristor switched reactor or Inductor
- vii. TSC - Thyristor switched Capacitor.

P) STATCOM:



STATCOM:- "A Shunt Connected static synchronous generator operated as a static VAR compensator whose effective capacitive ^{inductive output} ~~by~~ the system AC voltage"
 can be controlled independent of

2. SSG: Static Synchronous Generator:

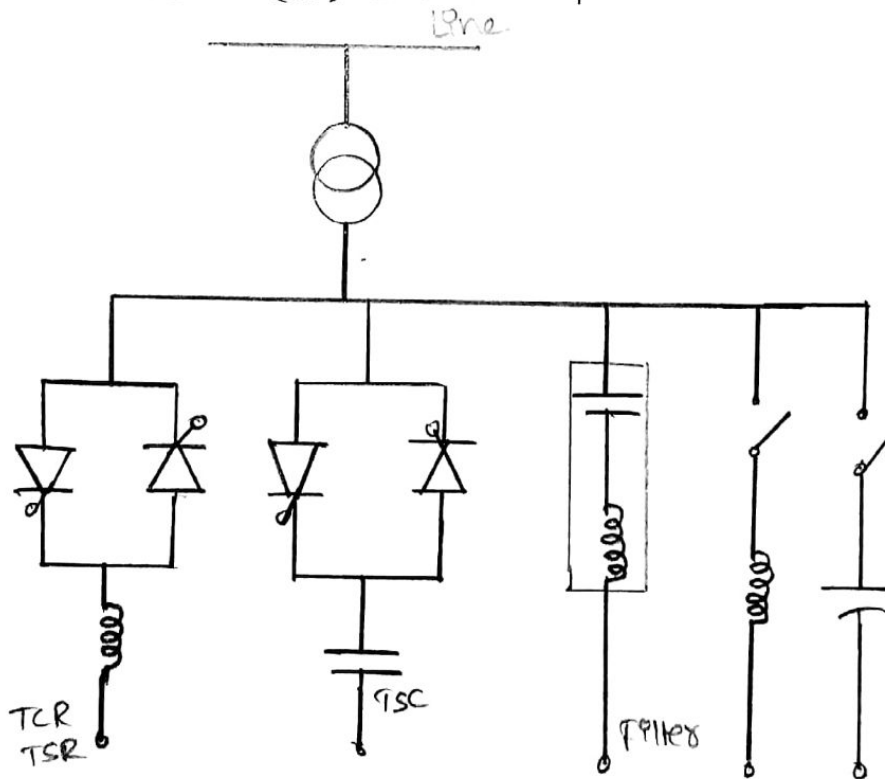
A static self commutated power converter supplied from an appropriate energy source to operate to produce a multistage output voltages which is coupled to a power system for exchanging real and reactive powers.

③ BESS: Battery Energy Storage system:

A shunt connected voltage source converter capable of rapidly adjusting the amount of energy which supplied to an AC system.

④ SVC: Static VAR Compensator:-

It is a static VAR Generator or Observer whose output is adjusted to exchange capacitive and inductive currents so as to maintain (or) control specific parameters of power system.



⑤ TCR: Thyristor Control Reactor: It is a shunt connected thyristor controlled inductor whose effective reactance is varied in continuous manner by partial conduction of thyristor valves.

⑧ TSR: Thyristor Switched Reactor:

It is a shunt connected thyristor controlled reactor whose effective reactance is varied in stepwise manner by ~~zero~~ conduction of four thyristor valves.

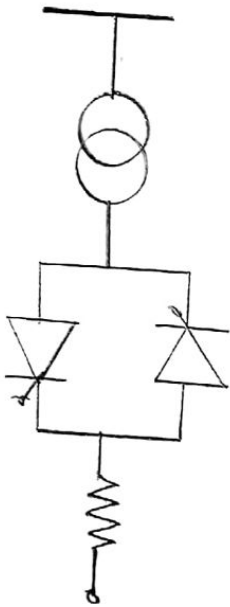
⑨ TSC: Thyristor Switched Capacitor:

It is a shunt connected thyristor switched capacitor whose effective reactance is varied in a stepwise manner by ~~portion~~ ^{full or zero} conduction of four thyristor valves.

⑩ SVS - Static VAR System:

Two different static and mechanically VAR compensators whose outputs are co-ordinated.

⑪ TCBR - Thyristor Control Braking Resistor:



A shunt connected thyristor switched resistor which is to aid stabilisation of power system or minimize generating units under disturbance.

Series Controllers:

① SSSC - Static Synchronous series Compensator

② IPFC - Inter line power flow Controller

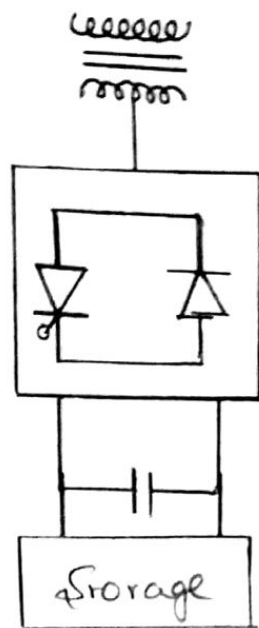
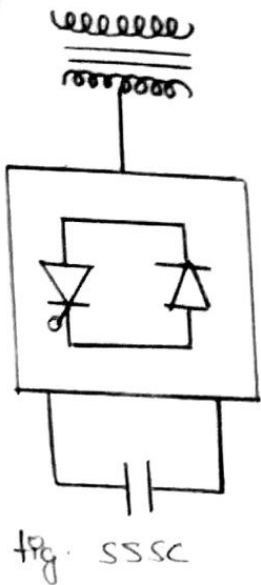
③ TCSC - Thyristor Controlled series Capacitor

④ TSSC - Thyristor Switched series Capacitor

⑤ TCSR - Thyristor controlled series Reactor

⑥ TSSR - Thyristor Switched series Reactor

SSC : Static Synchronous Series Compensator :



A static synchronous generator operated as without an external electrical energy source, as a series compensator the output voltage in phase quadrature with line currents. The purpose of increasing or decreasing the overall reactive voltage drops across line their by controlling transmitted

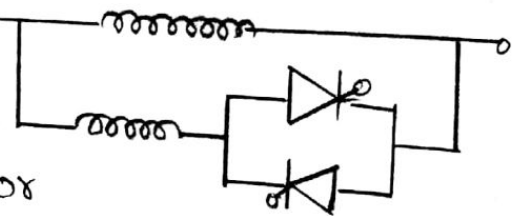
② IPFC : Interline power flow controller :

It is a recently introduced controller it does not have any IEEE definition. IPFC is a combination of two or more static synchronous series compensators which are coupled via a common dc link to facilitate bidirectional flow of real power & power between AC terminals of SSSCs.

1) we are going to compensate reactive power independently in each line by adjusting real power.

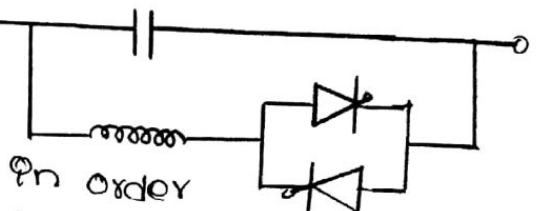
③ TCSP : Thyristor Controlled Series Capacitor Reactor :-

A inductor reactance compensator which consisting of a series inductive bank. By a thyristor controlled reactor in order to provide smoothly variable controlled of inductor.



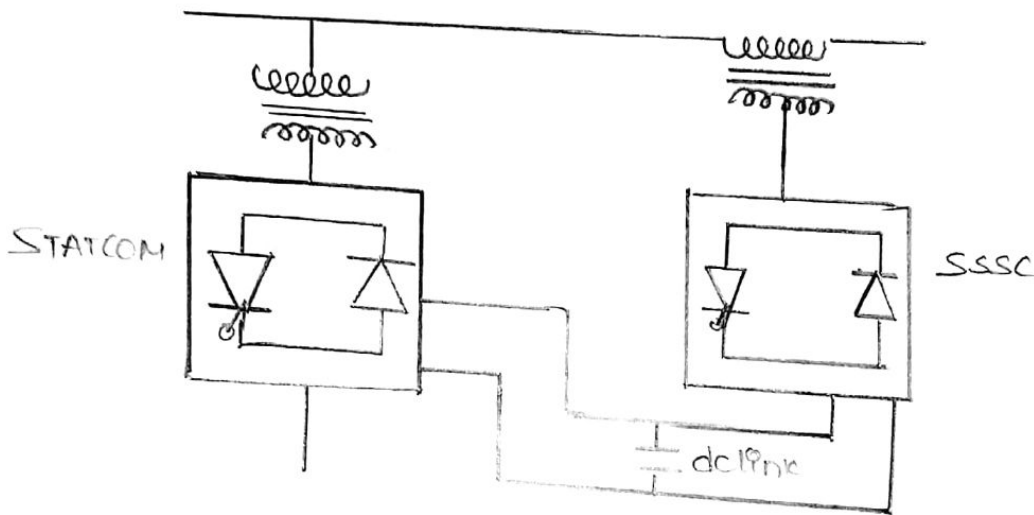
4) TCSC : Thyristor Controlled Series Capacitor :-

A capacitive reactance compensator which consisting of a series capacitive bank ^{shunted} by a thyristor controlled reactor in order to provide smoothly to control reactive capacitance variable controlled of capacitor.



Combined Series-Shunt Controller:-

1. UPFC - Unified power flow Controller
 2. TCPST - Thyristor Control phase shifting T/F
 3. TCVL - Thyristor Control voltage Limiter
 4. TCVR - Thyristor Control voltage Regulator
1. UPFC : Unified power-flow Controller:-

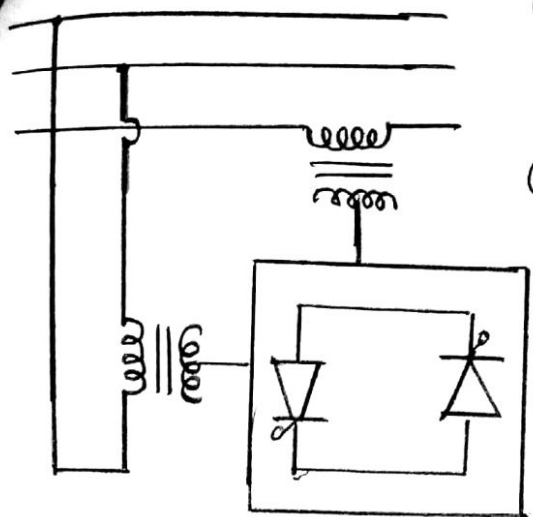


The combination of static synchronous compensator and static synchronous series compensator (SSSC) which are coupled via a common dc link to the bidirectional flow of real power between series output terminals of SSSC and shunt output terminals of STATCOM and controlled to provide real and reactive line series compensation without an external energy source.

UPFC means unconstrained series voltage injection is to able to control transmission line voltage, impedance and phase angle.

UPFC provides independently controllable shunt reactive compensation.

PST: Thyristor Controlled phase shifting I/F:-



- ① A phase shifting I/F adjusted by thyristor switched to provide variable phase angle.
- ② The phase shifting is obtained by adding a voltage vector in series with a phase. This vector is derived from other two phases via Shunt Connected I/F.

③ Thyristor Control voltage Limiter (TCVL):-

The Thyristor switched Metal oxide varistor used to limit voltage across it's terminals during transient conditions

④ TCVR: Thyristor Control voltage Regulator:-

A Thyristor Control I/F which can provide variable in phase voltage with continuous manner.

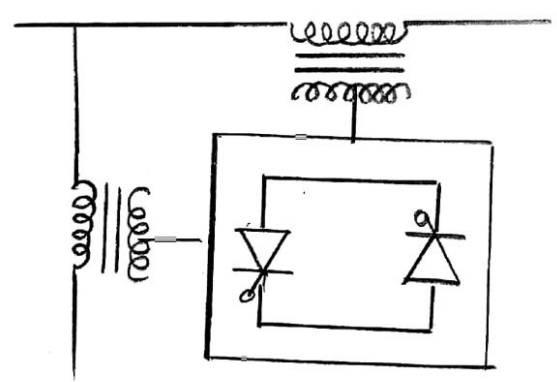


fig: TCVR

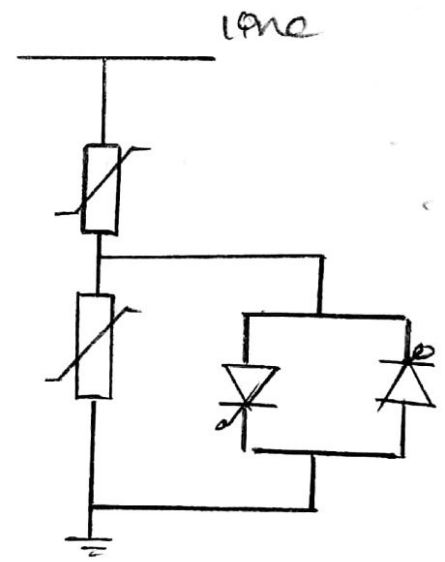


fig: TCVL

Limits the Loading Capability: There are 3 kinds of Limits

- ① Thermal
- ② Dielectric
- ③ Stability

1. Thermal: 1. Thermal Capability of an overheadline is a function of the ambient Temperature, wind condition, condition of the Conductor and Ground clearance.
2. The factor also due to variable Environment
3. Normal rating of line is generally decided based on conservative basis, serve ambient environment case.
4. Online monitoring devices that provide online real time loading Capability.

2. Dielectric: 1. From an insulation point of view many lines are designed very conservatively.
2. For an normal rating it is often to increase normal voltage by operation by 10% voltage (500kV = 550kV)
3. Care should be needed to ensure dynamic & Transient over voltages within limits.
4. FACTS Technology Can be used to ensure acceptable overvoltage and power-flow condition.

3. Stability: "The ability to maintain synchronism under all Disturbances" (Sudden, Large)

classifications:

- 1) Transient Stability
- 2) Dynamic Stability
- 3) Steady State Stability
- 4) voltage Collapse
- 5) Subsynchronous response

powerflow in a Meshed system:-

To understand the flow of power, let's consider a 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.

→ Suppose the lines AB, BC, AC have continuous ratings of 1000 MW, 1250 MW & 2000 MW respectively.

→ Emergency case ratings of twice those numbers for a sufficient length of time to allow rescheduling of power in case of loss of one of these lines.

→ one of the generating station is generating 2000 MW & the other 1000 MW a total of 3000 MW would be delivered to the load center.

→ For an impedance that line carry 5, 1600 & 1400 MW respectively. (a)

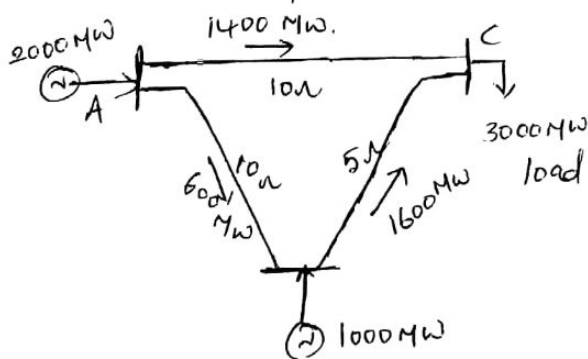


Fig (a) system diagram

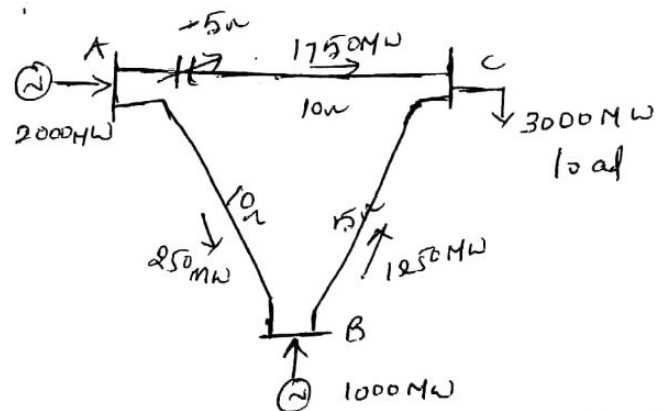


Fig (b) system diagram with TCSC in line AC

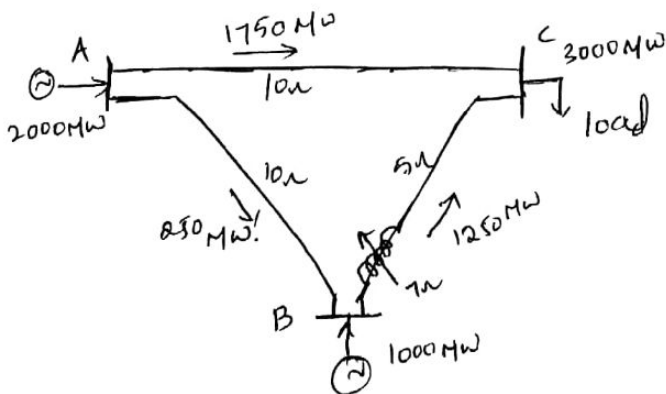


Fig (c) system diagram with TCSC in line BC

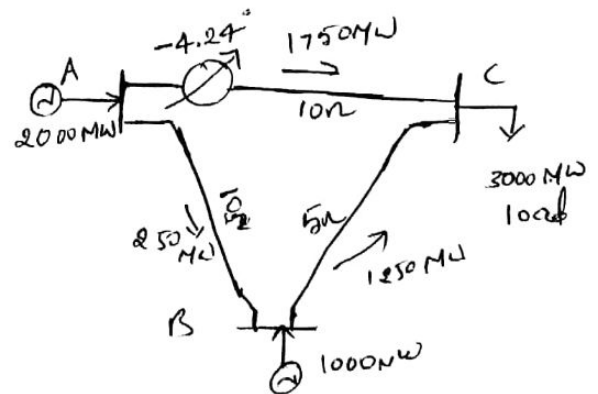


Fig (d) system diagram with TCPR in line AC.

→ fig (a) such a situation would overload line BC (loaded at 1600 MW for its continuous rating of 1250 MW), therefore generation would have to be decreased at B, & increased at A, in order to meet the load without overloading line BC.

→ in fig (b), a capacitor whose reactance -5Ω at the synchronous frequency is inserted in one line, it reduces the line impedance from 10Ω to 5Ω , so that power flow through the lines AB, BC & AC will be 250, 1250 & 1750 MW,

→ The number of operations can be limited by wear on the mechanical components, because the line loads vary continuously with load conditions.

→ Similarly results may be obtained by increasing the impedance of one of the lines in the same meshed configuration by inserting a 10Ω reactor in series with line AB, it will adjust the steady-state power flows, dampen unwanted oscillations. shown in fig (c)

→ A thyristor-controlled phase angle Regulator could be installed instead of a series capacitor (or) a series reactor in any of the three lines to serve the same purpose in fig (d). The regulator is installed in the third line to reduce the total phase-angle difference along the line from 8.15° to 4.26° .

→ Combination of mechanical & thyristor control of the phase angle Regulator may minimize cost.

Voltage source Converters:-

we have two types Converters

- ① Self Commutated Converters.
- ② Line Commutated Converter

→ self commutating converter against line commutated converter. Compare to self commutating converter, line commutating converter must have an ac source connected to an converter. It consumes reactive power, and suffers commutation failure in the inverter mode of operation.

→ The FACTS controller would be an self commutating type.
Two basic categories

→* Current source converter in which direct current always in one polarity, and the power reversal takes place through reversal of dc voltage polarity.

→* voltage source converter in which the dc voltage always in one polarity, and the power reversal takes place through reversal of dc current polarity.

→ Conventional thyristor based converter without turnoff capability, can only be current source converter, whereas, turnoff devices be voltage source converters.

→ The dc current in voltage source converter flows in either direction, the converter are bidirectional flow, so the dc voltage does not reverse, the turnoff devices need not have reverse voltage capability, such devices are called asymmetric turnoff devices. GTO, IGBT, MOSFET

→ several turnoff devices are used in high voltage applications.

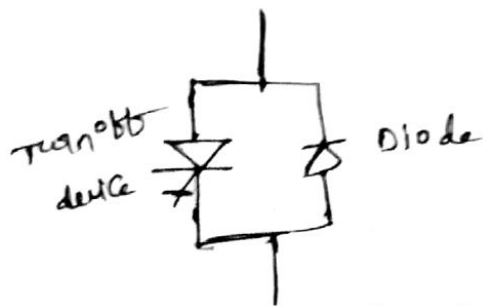


fig. (a) value for a voltage source converter.

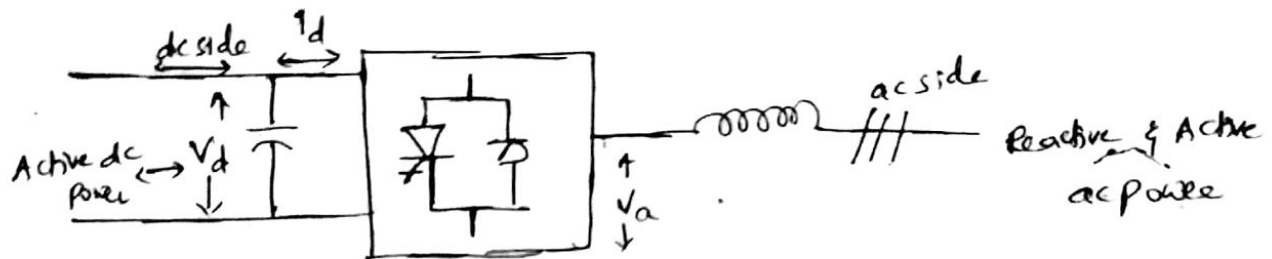


fig. (b) - voltage source converter concept

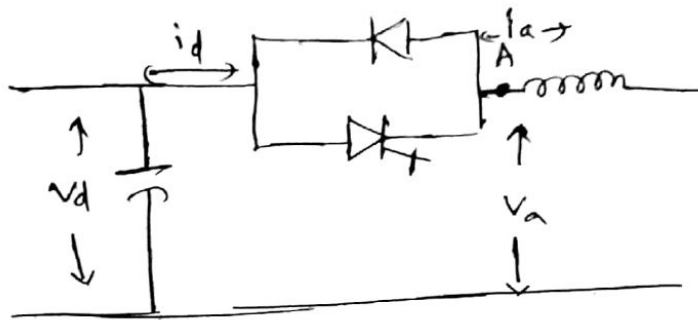


fig. (c)

fig. (c) single pulse operation.

- fig. (a) represents a value of a appropriate voltage & current rating required for the converter.
- This converter topology mainly used for supplying and consuming reactive power only and not for converting active power.
- fig. (b) The voltage source converter internal topology can be represented by a box.
 - on the dc side voltage is unipolar and is supported by a capacitor. This capacitor large enough to handle sustained charging & discharging current. That shows the switching sequence of converter valves.
 - on the ac side generated ac voltage is connected to a system via inductor. The ac voltage source with low internal impedance, The dc capacitor doesn't short circuited.

① represents single value operation.

→ DC voltage V_d is assumed to be constant, supported by a large capacitor, with the positive polarity side connected to the anode side of the turn off device.

→ when turn off device 1 is turned on, the positive dc terminal is connected to the ac terminal, A. The ac voltage would jump to $+V_d$.

→ if the current happens to flow from $+V_d$ to A, the power would

be flow from ~~A to $+V_d$~~ dc side to ac side (Invert)

→ if the current happens to flow from A to $+V_d$ it will flow the diode, even if the device is so called turn on, the power would be flow from the ac side to dc side (rectifier).

→ in rectifier action the instantaneous current flow will be positive

→ in inverter action the instantaneous current flow will be negative.

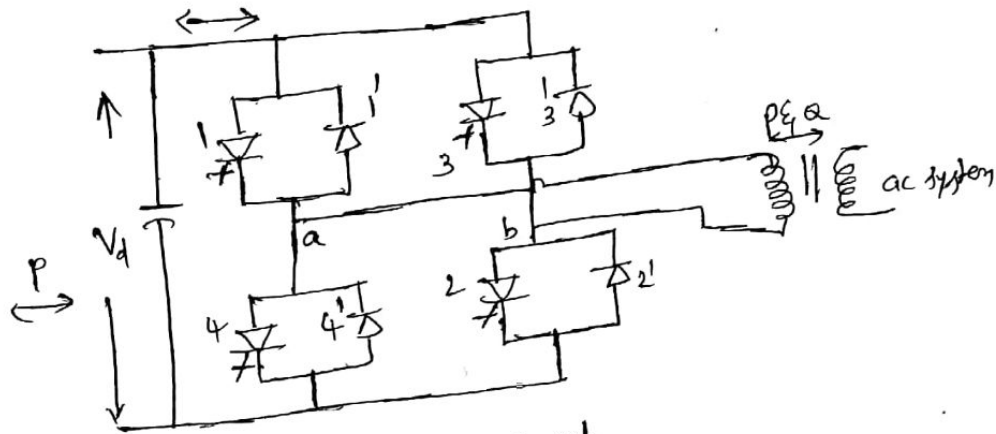
→ The filter may be used to limit the consequent current harmonics entering at the system side.

Single phase full wave Bridge Converter operation :-

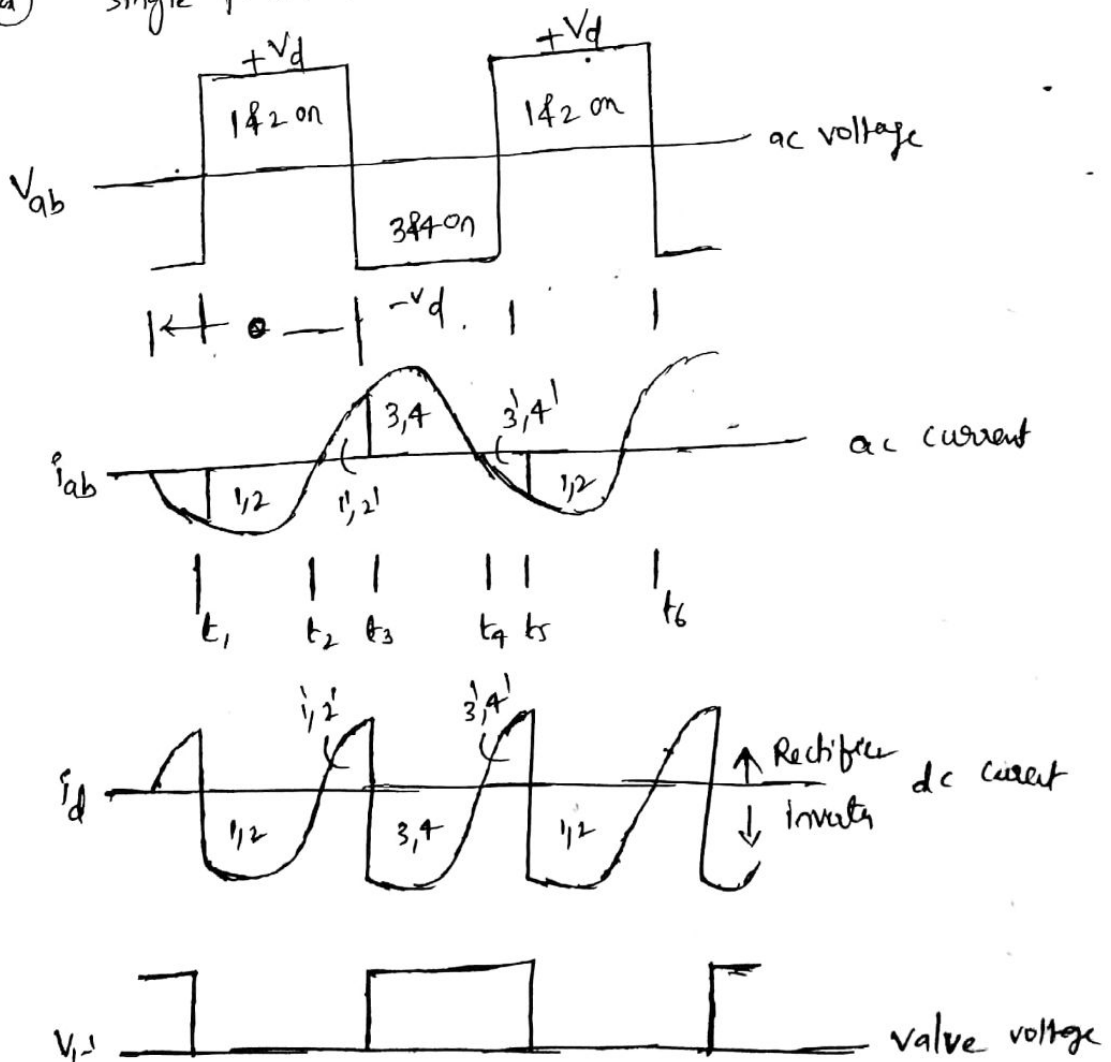
(3)

Although FACTS Controllers will generally utilize three-phase Converters, a Single phase, full wave bridge Converter may also be used in some designs.

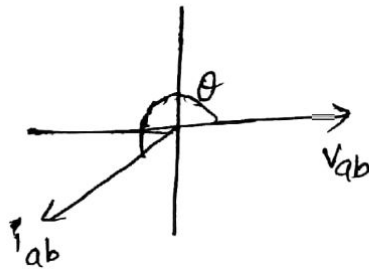
→ it is important to first understand the operation of a Single-phase bridge Converter and operation of a phase-leg to further understand the principle of voltage source conversion.



(a) single phase full wave circuit



fig(b) operation wave form.



© Phase Relationship between current and voltage.

→ fig (a) single phase full-wave bridge converter consists of four valves, (1-1') to (4-4'). dc capacitor to provide stiff dc voltage, two ac connection point a and b.

→ The designated value numbers represents turn on & turn-off dc voltage converted to ac voltage.

→ fig (b) with turn-off device 1 & 2 turned on, voltage V_{ab} becomes $+V_d$ for one half cycle, and with 3 & 4 turned on & 1, 2 turned off V_{ab} becomes $-V_d$ for the other half cycle.

→ For example, suppose that the current flow from the ac system, shown by second waveform, is a sinusoidal wave i_{ab} , angle θ leading with respect to square-wave form.

① From instant t_1 to t_2 , with turn-off device 1 & 2 on & 3, 4 off, V_{ab} is positive & i_{ab} is negative. The current flows through device 1 into ac phase a, and then out of ac phase b through device 2, with power flow from dc to ac (inverter action).

② From instant t_2 to t_3 the current reverses, i.e. becomes positive, and flows through device 1 & 2 with power flow from ac to dc (rectifier action) although device 1 & 2 are still on & voltage V_{ab} becomes $+V_d$. 1 & 2 cannot conduct in reverse direction.

From instant t_3 to t_4 , I_{g2} turned off and device 3,4 are turned on, thereby V_{ab} becomes negative while i_{ab} is still positive. The current now flows through 3 & 4 with power flow from dc to ac (inverter action).

④ From instant t_4 to t_5 , with device 3 & 4 still on, & I_{g2} off, and V_{ab} negative, current i_{ab} reverses & flows through diode 3 & 4 with power flow from ac to dc (rectifier).

Fig ①. The power flow from ac to dc with a lagging power factor.

Device	V_{ab}	Current flow	Conducting device	Conversion
I_{g2} on, 3 & 4 off	positive	negative	I_{g2}	Inverter
I_{g2} on, 3 & 4 off	positive	positive	I_{g2}	Rectifier
I_{g2} off, 3 & 4 on	negative	positive	3 & 4	Inverter
I_{g2} off, 3 & 4 on	negative	negative	3 & 4	Rectifier

Three-phase full wave Bridge Converter

Converter operation

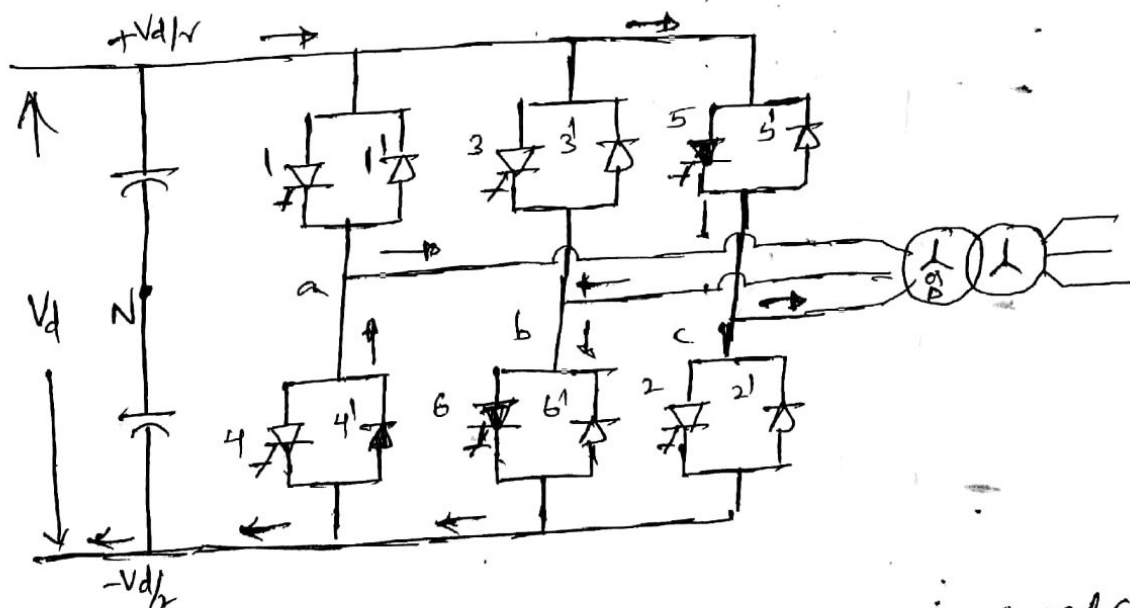
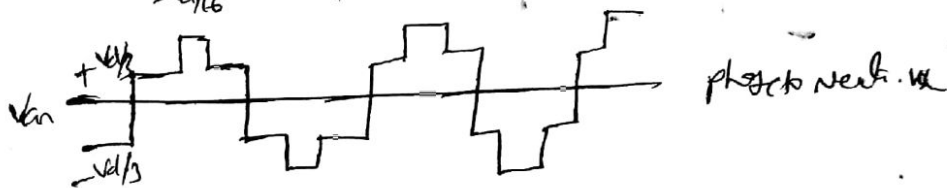
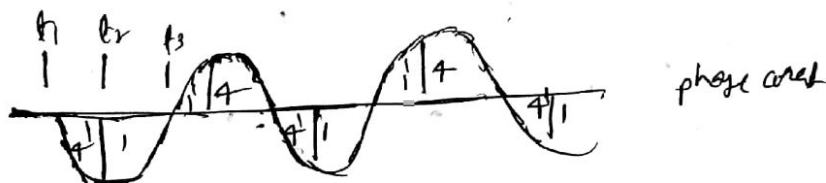
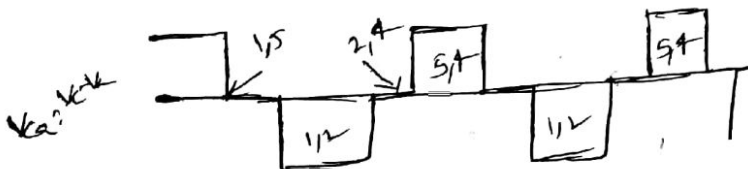
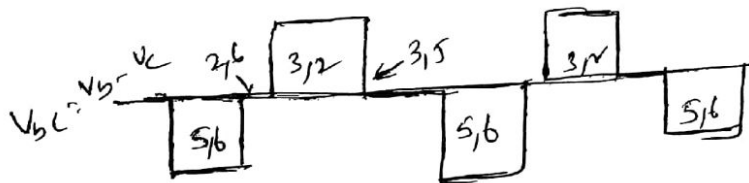
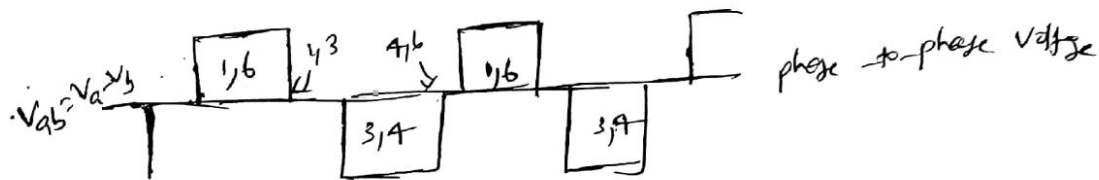
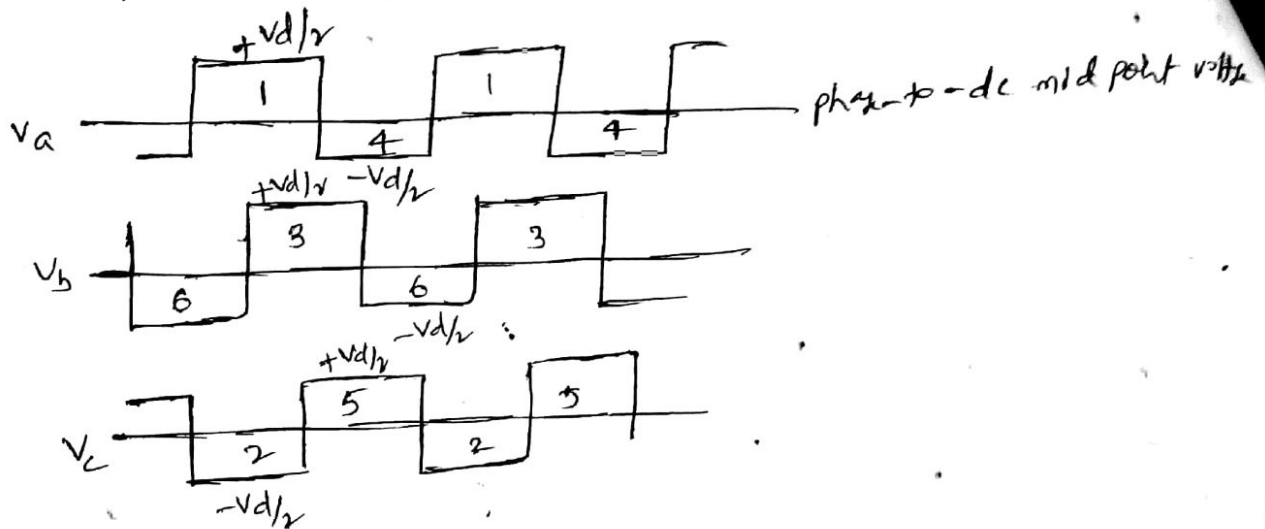


Fig ①

operation of a three-phase, full wave voltage source converter

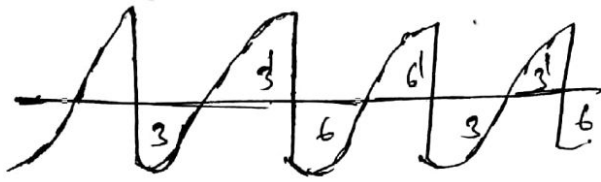
① three phase, full wave converter, ② AC wave form of a three-phase, full wave converter, ③ DC current wave form of a three-phase, full wave voltage source converter.

Fig 1 represents a three-phase full wave converter with six valves (6-6'). The designated order 1 to 6 represents the sequence of valve operation which consists of three-phase legs, 120 degrees apart. The three phase legs operate in a square wave mode.

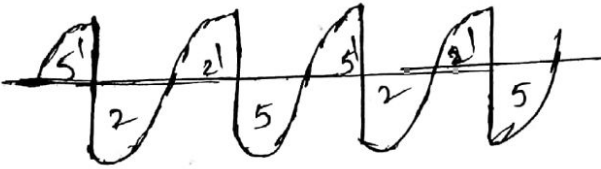




dc current from phase a



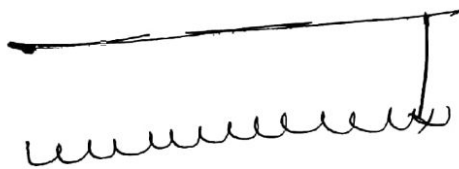
dc current from phase b



dc current from phase c



total dc by current



dc current with with positive three

Fig 3.4 (c)

- Fig 3.4 (b) Three square wave forms are the voltages of ac buses a, b & c with respect to a hypothetical dc-capacitor midpoint, N, with peak voltages of $+V_d/2$ to $-V_d/2$. These phase legs having 120° phase shift with others.
- phase-leg-3-6 switches 120° after phase leg-1-4, and phase-leg-5-2 switches 120° after phase-leg-3-6,
- The three phase-phase voltages V_{ab}, V_{bc} & V_{ca} where $V_{ab} = V_a - V_b, V_{bc} = V_b - V_c$ & $V_{ca} = V_c - V_a$.
- The wave form V_{ab} shows voltage V_d when turn-off device 1 connects a by a to the dc bus $+V_d/2$, and turn-off device 6 connects a by b to the dc bus $-V_d/2$. giving a total voltage $V_{ab} = V_a - V_b = V_d$.
- 120° later turn-off device 6 is turned off and turn-off device 3 turns on, both ac by a & b, b come connected to same dc bus $+V_d/2$, give zero voltage between by a & b.

→ Another 60 later turnoff device 5 is turned off and turned off a 4 connects by to $-V_d/2$, V_{d5} becomes $-V_d$. After 120 turnoff device 3 turned off, turnoff device 6 connects by b to $-V_d/2$. $\text{gim } V_{d5} = 0$.

→ fig ③ dc current refluxy via turnoff device 5 into phase C,

At any time, Three valves are conducting in a 3- ϕ converter. In fact, only the active power part of ac feed and part of the harmonic flow in to the dc side.

Transformer Connections for 12-pulse operation.

→ The harmonic content of the phase to phase voltage & phase to neutral voltage was discussed. The two voltages were 30 degree out of phase.

→ If this phase shift is corrected. Then for the phase to neutral voltage, i.e. V_{an} , The harmonic order $12n \pm 1$, would in phase opposition to other ph-voltage & Amplitude is $1/\sqrt{3}$ times.

→ The combined output voltage would have a 12-pulse waveform with harmonics of the order of $12n \pm 1$, i.e. 11th, 13th, 25th, 27th. with amplitude $1/n$, $1/13n$, $1/25n$, $1/27n$.

fig. 1.2, the two 6- ϕ pulse converters; involving a total of 12 phase-legs are connected in parallel on the same dc bus, and work together as a 12-pulse converter. It necessary to have two separate transformers, other wise phase shift in the non-12-pulse harmonics, i.e. 5th, 7th, 17th, 19th in the secondary will result large circulating current due to common core flux.

→ The circulating current of each non-12 pulse harmonic given by

$$I_n/I_1 = 100 (X_T \times n^2) \%$$

I_1 is the nominal fundamental current, n is relevant harmonic number and

X_T is pu transformer impedance. if X_T is 0.15 pu at fundamental frequency,

When the circulating current for 5th harmonic will be 26.6%, 7th 14.9%, 11th 5.5%, 13th, 39.1% of the rated fundamental current.

Fig 1.b → represents the 5th, 7th, 11th, 13th. Harmonic voltage cancel out, and the two fundamental voltages add up, and it is 12-pulse converter.

Fig 1.c shows it is necessary to provide control for two dc buses. have equal voltage.

→ The dc bus voltage can be increased or decreased by shifting the operation in the rectifier or inverter direction.

→ increase in pulse number would reduce the dc side current harmonics,
 → For 12-pulse converter, the harmonics of the dc side 6th, 18th, are cancelled out, and only, 12-pulse harmonics 12th, 24th... enter the dc bus.

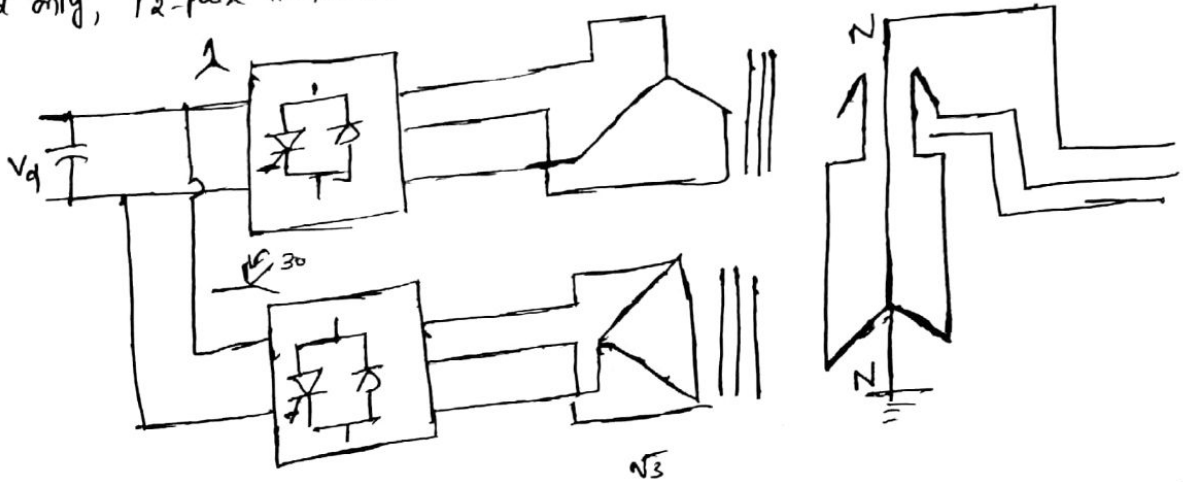
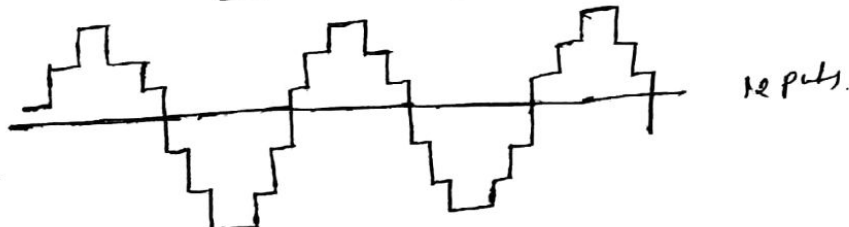
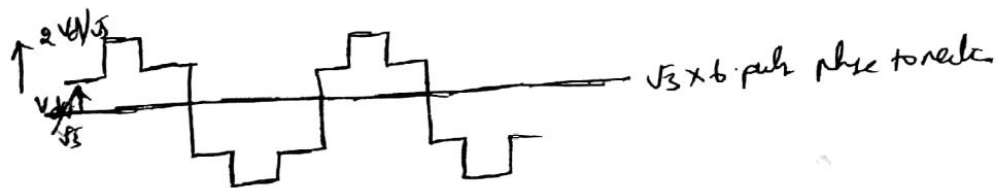


Fig 1.a - 12-pulse Converter with wye & delta secondaries



12 pulse converter with two 6-pulse converters

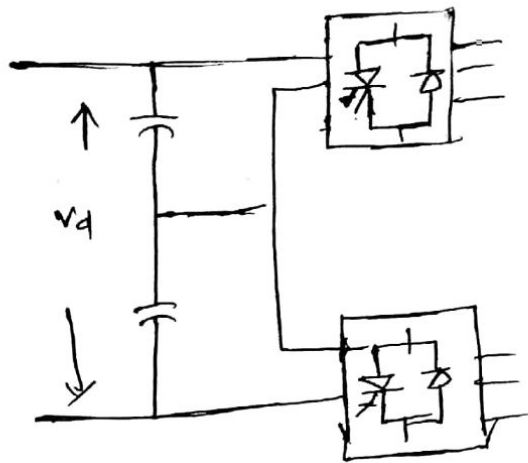


fig 1.1c show 12-pulse Converter with two fully Connected Sin pulse Converter.

24 & 48-pulse operation:-

- Two 12-pulse Converters, phase shifted by 15 degrees from each other, can provide a 24-pulse Converter, obviously with much lower harmonics on ac side & dc side..
 - its ac voltage would have $24n \pm 1$ order Harmonics. i.e. 23rd, 25th, 47th, 49th Harmonics with magnitudes of $\frac{1}{23rd}$, $\frac{1}{25th}$, $\frac{1}{47th}$, $\frac{1}{49th}$ respectively.
 - The question is now is how to arrange this 15 degree phase shift.
 - one approach is to provide 15 degree phase shift windings on the two transformers of one of the two 12-pulse converters.
 - Another approach is to provide phase shift windings for +7.5 degree phase shift on the two transformers of one 12-pulse converter and -7.5 degree on the two transformers of the other 12-pulse converter.
- fig 2.2a separate transformer requires the same design & leakage inductance.
- All four sin-pulse Converters can be connected on the dc side in parallel. alternatively all four sin-pulse Converters can be connected in series of high voltage.
 - primary of all four transformer can be connected in series as shown in fig 2.2b in order to avoid harmonic circulation current corresponding the 12-pulse order i.e. 11th, 13th, 23rd, 25th..

even a 24-pulse converter with out ac filter could have voltage harmonics which are higher than acceptable level.

→ The alternative course is go to 48-pulse operation with eight six pulse groups. with one set of transformer of one 24-pulse converter phase-shifted from the other by 7.5°. (or) one set shifted by $+3.75^\circ$ and other by -3.75° . all eight transformer primaries may be connected in series.

→ The primary of the two 24-pulse converter may be connected in parallel, circulating current will be acceptable.

→ For oil p.u impedance, & the 3rd Harmonic, the circulating current would be 1.94 only. The circulating current can be limited by higher transformer impedance.

→ in 48-pulse operation ac filter should not necessary.

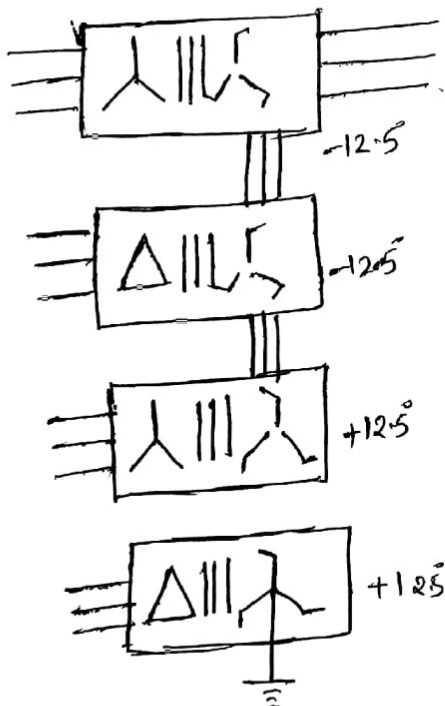


Fig 2.9 24-pulse converter transformer connection with 12-pulse converter in series on the ac side

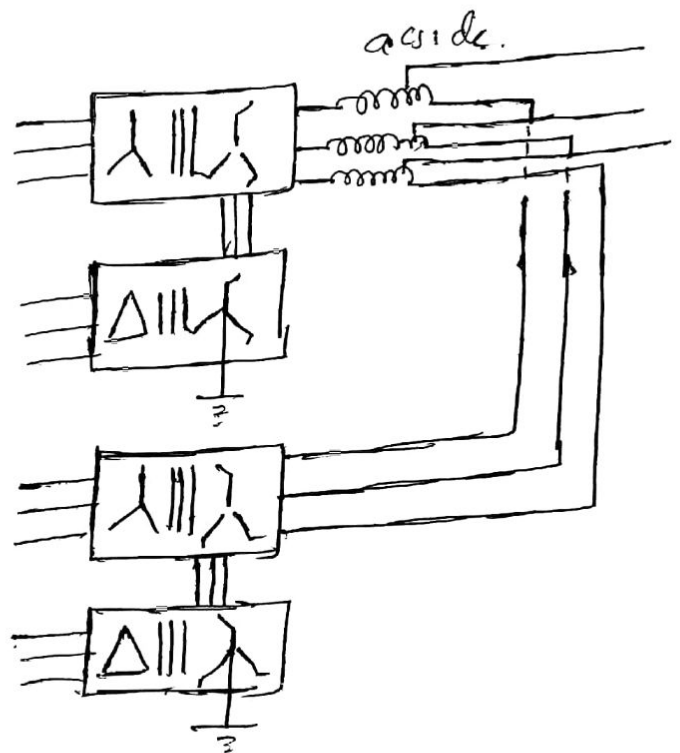


Fig 2.6 24-pulse converter transformer connected with two 12-pulse converter in parallel on the ac side.

Three-level for voltage sourced Converter:

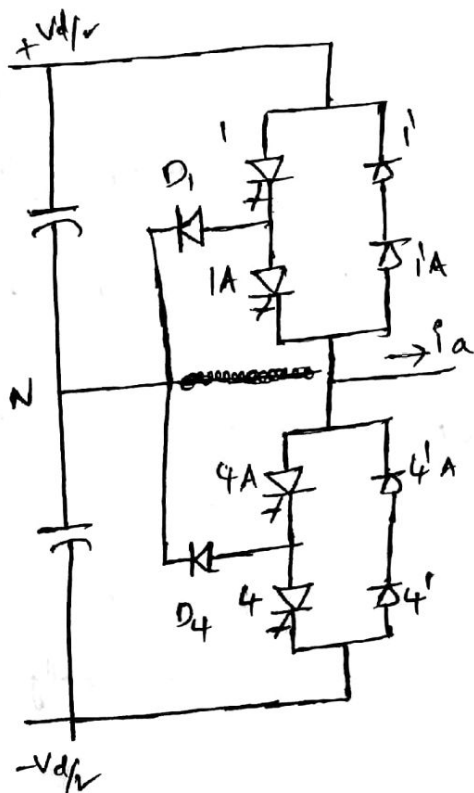
(i) operation of three-level converter:

→ it is desirable to vary the magnitude of a.c output voltage without having to change the magnitude of d.c voltage.

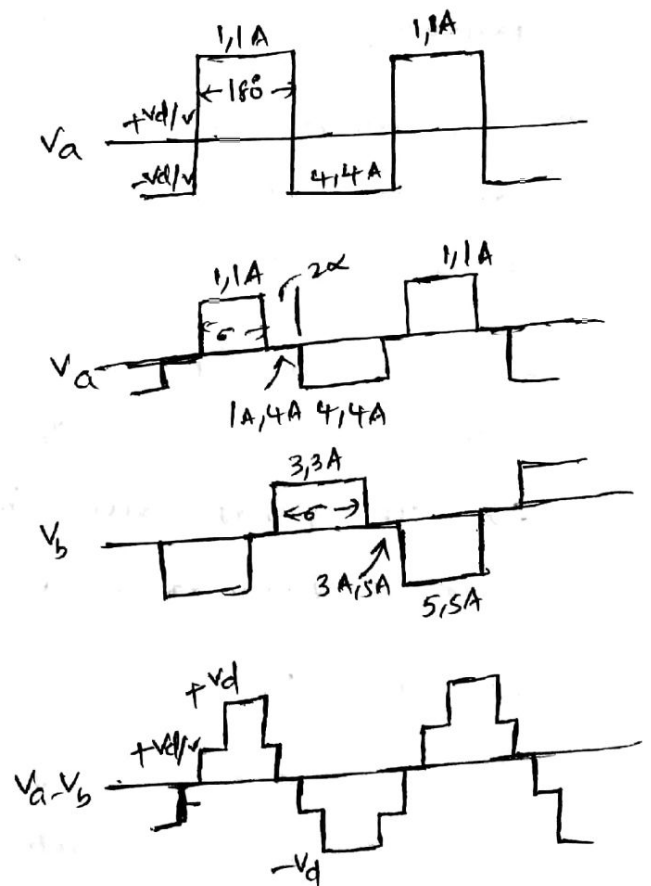
→ The Three level converter is one concept that can accomplish that to some extent. one phase-leg of a Three level converter is shown in fig 1(a)

→ The other two phase-legs (not shown) would be connected across the same d.c bus bars and the clamping diodes connected to the same midpoint of the d.c capacitor.

→ it is seen that each half of the phase leg is split into two series connected valves. i.e. $1-1'$ is split into $1-1'$ & $1A-1'A$. The midpoint of the split valves is connected by diodes D_1 & D_4 to the midpoint N as shown.



(a) one phase-leg of three level converter



(b) o/p a.c voltage

- By doubling the number of valves from two to four per phase leg, addition to providing two extra diode valves.
- The addition of the diode clamping valves D_1, D_4 per phase leg in H-bridge adds to the Converter Cost. and diode clamp at the mid point of ϕ also sharing voltage b/w two valve-halves.
- a Converter Continuous safe operation with one failed device in string of series connected devices, may require some extra devices.

o/p wave forms:

The o/p voltage corresponding to one three-level phase leg.

- ① The first wave form shown is a full 180 degree square wave obtained by the closing of device 1 & 1A to give $+V_{d/2}$ for 180° , and the closing of device 4 & 4A for 180° to give $-V_{d/2}$ for 180° .
- ② The second wave form shown in which the upper device 1 is turned off & device 4A is turned on an angle α earlier than they were due in the 180° square wave operation. only device 1A & 4A on, & the diodes D_1, D_4 clamp the phase voltage V_a to zero & the current is flowing.
- ③ The continuous for a period 2α until device 1A is turned off, device 4 is turned on, & the voltage jumps to $-V_{d/2}$ with both the lower devices 4 & 4A turned on & upper device 1 & 1A turned on. & The voltage made up of $\phi = 180^\circ - 2\alpha$.
- The Converter is referred to as three level because the d.c voltage has three levels. i.e. $-V_{d/2}, 0, +V_{d/2}$.
- The turnoff device handling instantaneous inverter action & their parallel diodes handle any instantaneous rectifier action.
- The phase-leg current flows into the mid-point of the two capacitors.
- The current is mainly of third harmonic and is substantially independent of the converter pulse number.

Fundamental & Harmonic voltages of a Three level Converter

→ The Three level Converter buys is the flexibility to rapidly vary the ac voltage (8) to provide defined zero voltage notch to eliminate the specified Harmonic.

→ The ac voltage pulse width duration σ per half cycle.

$$v = \frac{4}{\pi} (V_{d/2}) \left[\sin \frac{\sigma}{2} * \sin \left(\omega t + \frac{\sigma}{2} \right) - \frac{1}{3} \sin \frac{3\sigma}{2} + \sin 3 \left(\omega t + \frac{\sigma}{2} \right) + \frac{1}{5} \dots \right]$$

$$V_n = \frac{4}{\pi} (V_{d/2}) \left[\frac{1}{n} \sin \frac{n\sigma}{2} * \sin n \left(\omega t + \frac{\sigma}{2} \right) \right]$$

RMS value is given by

$$V_n = \frac{2\sqrt{2}}{\pi} (V_{d/2}) \frac{1}{2} \sin \frac{n\sigma}{2}$$

Fundamental rms voltage is given by

$$V_1 = \frac{2\sqrt{2}}{\pi} (V_{d/2}) \sin \frac{\sigma}{2}$$

(iii) Three level ~~phase~~ Converter with parallel legs:

→ Another method of achieving a three level converter, which is to connect two phase legs, in parallel per phase. showing in figure (Q.1a).

→ The two legs are parallel through an inductor & the ac connection is made at the mid point of their inductor, & their pulse sets and phase shifted by an angle α' in the opposite directions, (total of 2α).

→ The ac terminal voltage of the two phase legs, with respect to a hypothetical dc midpoint, are shown fig 2b.

① The first two wave forms, shifted from each other by an angle 2α :

② The net ac terminal voltage, with respect to the dc mid point, is the average of the two voltages, and is shown by third wave form.

→ it consists of half cycle pulse p/w variable duration $\sigma \approx 180 - 2\alpha$.

③ The inductor voltage is given by difference of the ac voltage of the two legs, shown by fourth waveform.

④ greater the required range of control, larger would be the inductor size.

⑤ MVA rating is directly proportional inductor voltage V_L .

- it is natural to suppose one can go to higher levels, i.e. five level,
- The major problem of voltage balancing between the capacitors.
- it is not reasonable to assume that the current flow each level is balanced in five

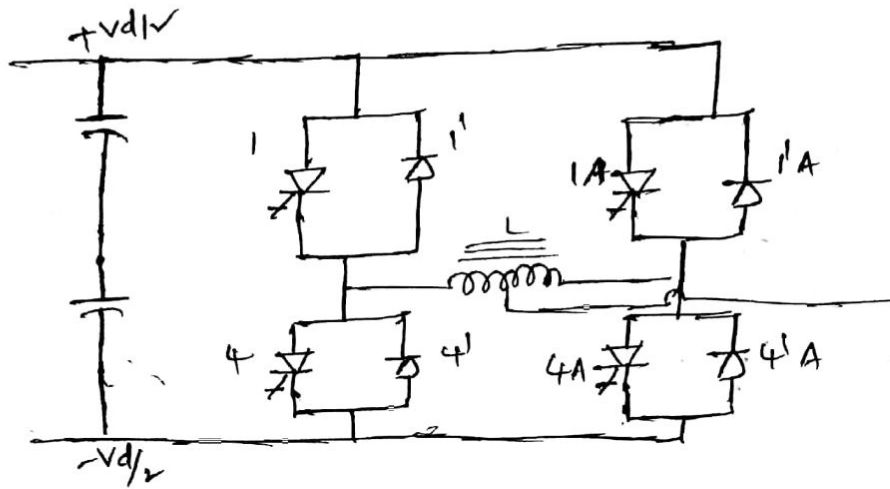


Fig 2.a one phase leg with two parallel legs.

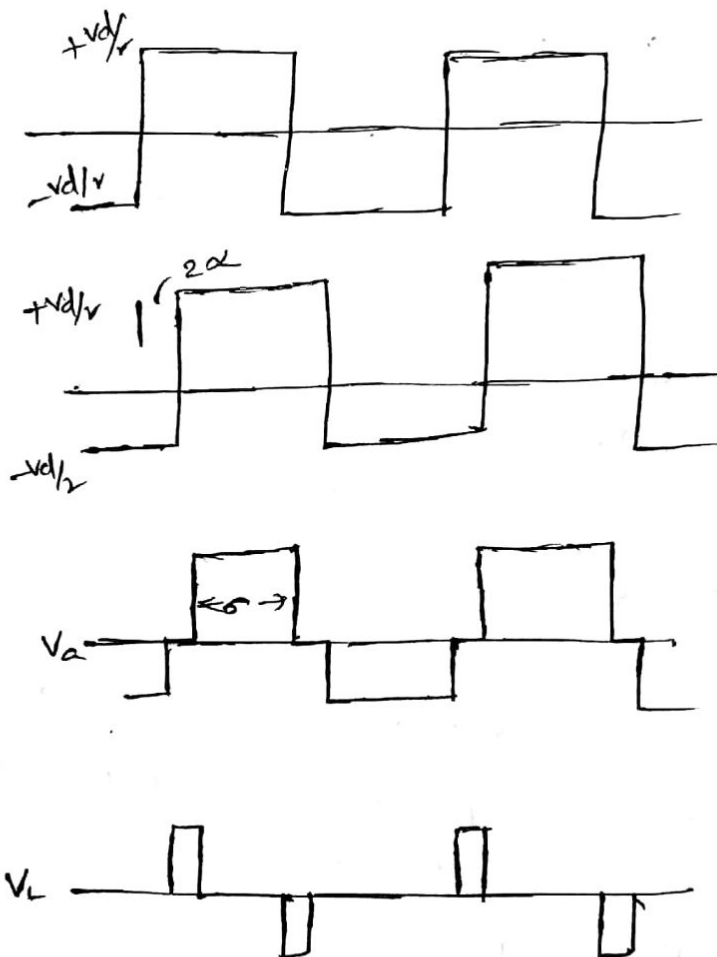


Fig 2.b wave form for the two parallel legs.

Width Modulation Converter (PWM):-

③

In two level (or) multi level Converters, there is only one turn on, turn off per device per cycle.

- With these Converters, the ac output voltage can be controlled, by varying the width of the voltage pulses, and the amplitude of the dc bus voltage.
- Another approach is to have a multiple pulses per half cycle, and then vary the width of the pulses to vary the amplitude of ac voltage.
- By varying the ac voltage and to reduce the lower order Harmonics.
- more pulses means more switching losses. There are Resonant PWM Converter topologies that incorporate Current-zero (or) voltage-zero type soft switching, in order to reduce switching losses. So such Converters are used for low power. but not suitable for high power bcz high equipment cost.
- PWM Converters for low voltage & low power in the range of tens of watts, PWM frequency is in the order of KHz.

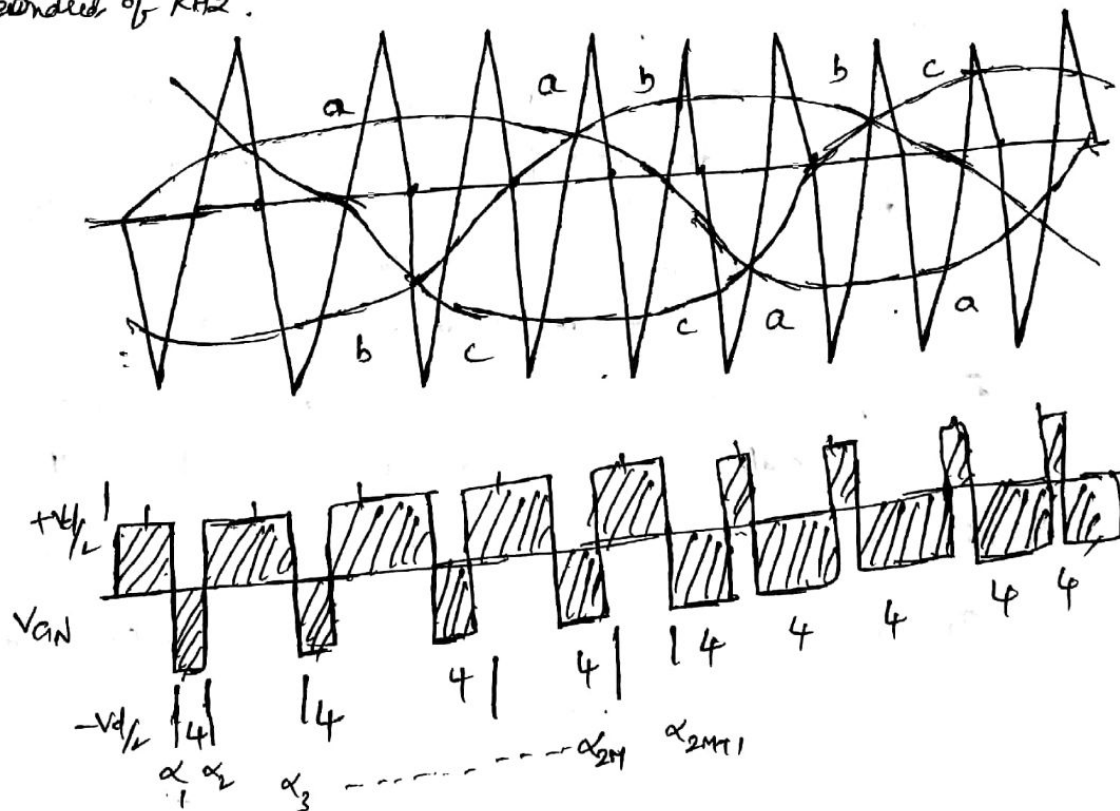
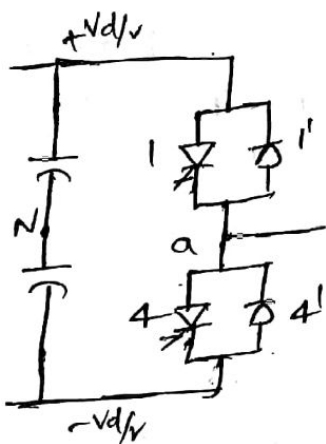


Fig 3.3 Operation of PWM converter with switching frequency of nine times the fundamental (a) A phase-by-phase PWM waveform

- Consider a phase-leg shown in fig 3.9. a Three phase bridge converter. fig 2.10a shows comparison of two types of control signals.
- Three signals of main-frequency sine wave representing three phases, and a sawtooth wave signal of nine times the main frequency (540Hz for 60Hz main).
- Turn on & turn off pulses to the device corresponding to the comparison of sawtooth wave with sine wave of corresponding wave.

① The negative slope of sawtooth wave crossing the sine wave of phase a, results in turn-on pulse for device 1 and turn-off pulse for device 4.

② The positive slope of sawtooth wave crossing the sine wave of phase a, results in turn-off pulse for device 1 & turn-on pulse for device 4.

③ The output ^{voltage} waveform contains a fundamental frequency component & harmonics.

④ The output voltage pulses are symmetrical about the zero crossing of the sine wave, because the sawtooth frequency is an odd integer multiple of the main frequency.

⑤ With a fixed sawtooth wave, increasing the magnitude of sine wave will increase conduction time of devices and to decrease the conduction time of devices during positive half cycle. and vice versa negative half cycle. The o/p ac voltage will increase with increase in the magnitude of sine wave & will decrease with decrease in the magnitude of the control sine wave.

⑥ As the control sine-wave peak equal the peak of the sawtooth wave, the middle notch in the ac output voltage disappears.

⑦ It is clear that the ac output voltage can be controlled from zero to maximum.

⑧ The sine wave itself can be modified with notches. i.e. to create other effects on the waveform.

Concept of Current Sourced Converter:-

② A Current source Converter in which the dc current ^{flow is} always of the polarity, and the power flow reverses with the reversal of dc voltage.

③ A voltage source Converter in which the dc voltage always has one polarity, and the power flow reverses takes place with reversal of dc current.

Fig: ① represents the difference b/w the C-SC & VSC

Fig ①-a represents the Converter box for the voltage source Converter, symbolically shown with a turn-off device with a reversed diode, .

Fig ①-b represents the converter box without a specific type of device.

The C-SC may be based on diodes, conventional thyristors.

Three types of current source converters.

- ① Diode Converter
- ② Line-commutated Converter
- ③ self-commutated converter.

① Diode Converter:- Fig (2-a) which simply converts ac voltage to dc voltage, and utilizes ac system voltage for commutation of dc current from one valve to another.

The diode based line commutating converter just converts ac power to dc power without any control and also in doing, consumes reactive power on the ac side.

② Line Commutated Converter's

It is based on conventional thyristors (with gate turn-on but without gate turn-off capability). Fig 2-b utilizes ac system voltage for commutation of current from one valve to another.

This Converter can Convert & Control active power in either direction, Consumes Reactive power on the ac side. it can't supply reactive power.

⑤ " Self Commutated Converter :-

which is mainly based on turn-off devices (GTOs, MTOs, IGBTs, etc). in which commutation of current from valve to valve takes place with device-turnoff action and provision of ac capacitors.

- whereas in a VSC the commutation of current is supported by a stiff dc bus with dc capacitor.
- in a CSC, the ac capacitors provide stiff ac bus for supplying the fast changing pulses needed for commutation.

Adv:- The Converter with turn-off devices (self commutating) is that they offer greater flexibility including PWM mode of operation.

- when Reactive power management is not a problem, i.e. where controlled reactive power supply is not required.

→ The line commutated Converter over self commutated Converter for conversion of ac to dc and dc to ac, HVDC tr, line commutated Converter exclusively used in where the reactive power is managed through switched capacitors.

→ The superconducting Reactor itself a current source converter.

→ The conventional thyristor based Converter handle two to three times ^{the power} more than the next most powerful devices (GTOs, MTOs).

→ The DC voltage in CSC can be in either direction, The Converter valves must have both forward & reverse blocking capability. These are usually made a symmetrical device. It can make and can make with peak ^{blocking} voltage as high as 12 kV.

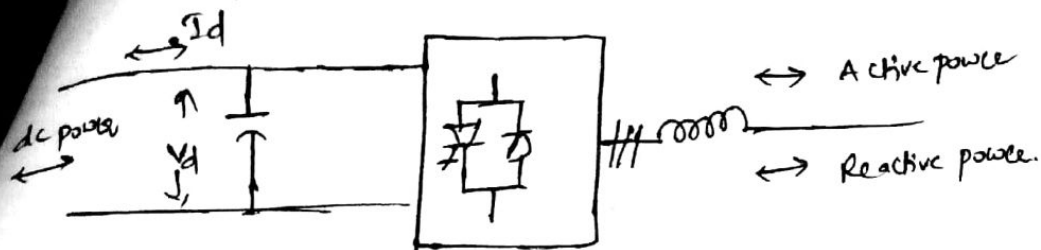


fig: 1-a voltage source converter.

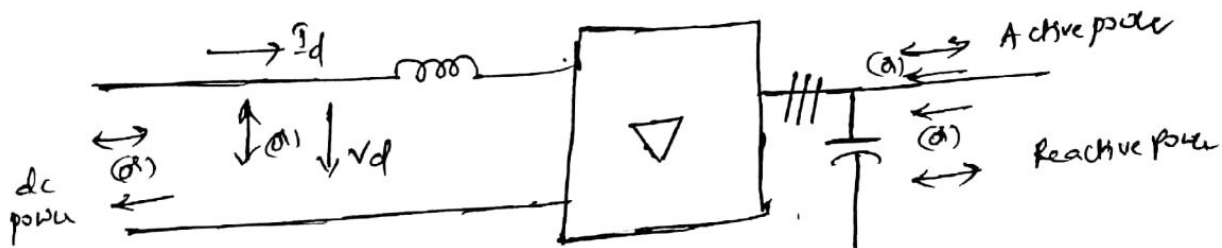


fig: 1-b Current source converter.

fig ①: Voltage source & current source converter

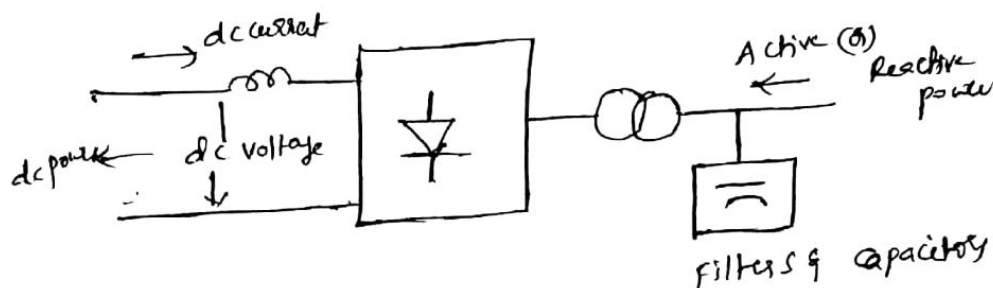


fig: 2-a diode Rectifier.

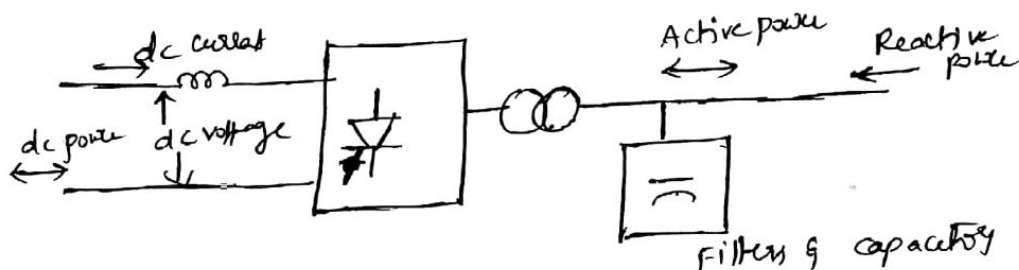


fig 2.b thyristor line-commutated converter

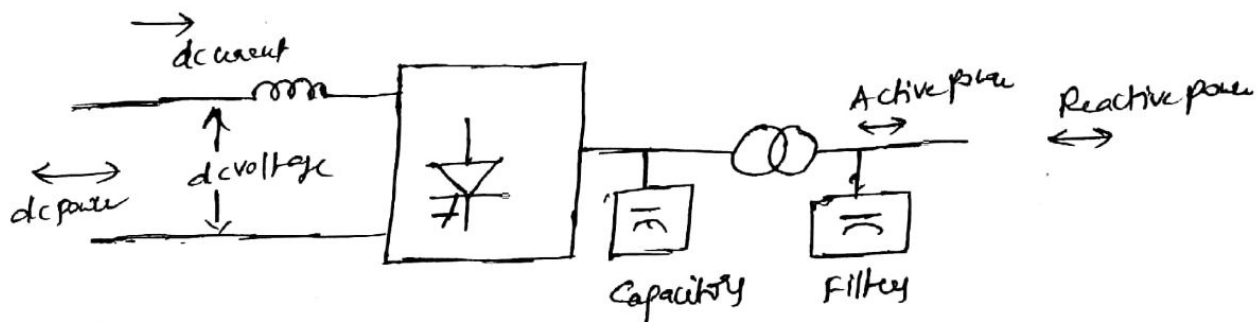


fig: 2.c self commutated converter

fig ②: types of current source converter.

A Comparison b/w Current-sourced versus voltage-sourced Converters.

There are some Adv & Dis Adv of Current sourced versus voltage-sourced Converters.

- Diode based Converters are ^{the} lowest cost Converters, if control of active power by the converter is not required.
- if the leading reactive power is not required, then a conventional thyristor based converter provides a low-cost converter with active power control. It can serve as a controlled lagging reactive power load.
- The current sourced converter does not have high short circuit current, as does the voltage sourced converter.
- For CSC the rate of rise fault during external & internal fault can be limited by dc reactor. For VSC the capacitor discharge current would rise rapidly and damage valves.
- The 6-pulse CSC does not generate third harmonic voltage, its transformer primary ~~is~~ a 12-pulse converter does not have to be connected ⁱⁿ series for harmonic cancellation. For 24-pulse operation with phase shift.
- In a current stiff converter, the valves are not subject to ~~dv/dt~~ due to the presence of the ac capacitor.
- AC capacitors required for the current-stiff converter can be quite large & expensive.
- Continuous losses in the dc reactor of a CSC are much higher than than the losses in the dc capacitor. Losses can be reduced by loss penalty.
- These harmonics as well as the presence of dc reactor can result in over voltage on the valves & transformer.
- With the presence of capacitor, which are subjected to commutation charging & discharging, this converter will produce harmonic voltages at a frequency.

Static Shunt Compensation

Objectives of shunt Compensation:-

- ① increase transmission power by reducing the inductive reactance.
- ② Reactor is connected to minimize the over voltage at light load condition.
- ③ switched capacitor maintain the voltage level at full load condition.

$$\boxed{\uparrow P = \frac{V^2}{X_L} \sin \delta}$$

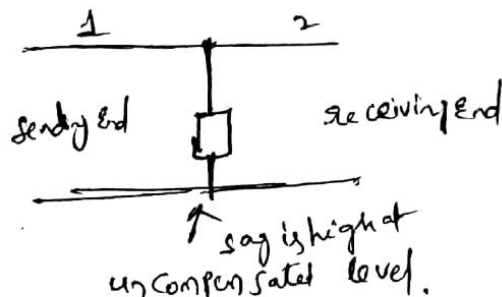
- ④ dynamic voltage control to improve the transient stability and damp power oscillations.

Objective of shunt Compensation:-

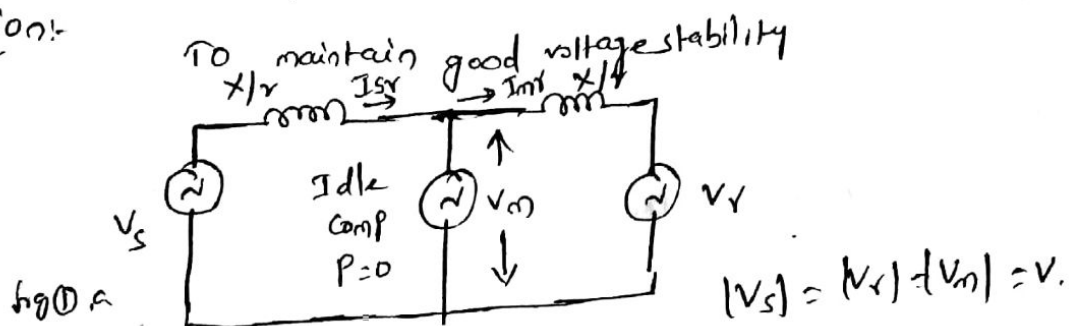
① midpoint voltage regulation for line segmentation:-

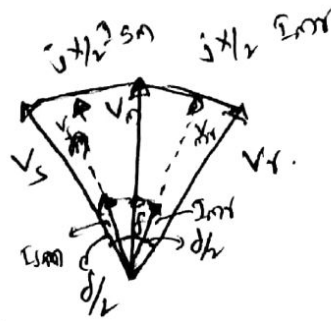
Consider the simple two-machine transmission model in which an ideal V_{ax} compensator is shunt connected at the mid point of the line. as shown in fig.

→ The line is represented by series line inductance. The compensator is represented by a sinusoidal ac source V_m in phase with the midpoint voltage V_m , with an amplitude identical to that of sending end receiving end voltage. ($V_s = V_r = V_m = V$).



segmentation:-





$$\cos \delta/4 = \frac{V_{SM}}{V_M} = \frac{V_{SM}}{V}$$

$$V_{SM} = V_{SM} = V \cos \delta/4 \rightarrow (1)$$

$$\sin \delta/4 = \frac{X/4 I_{SM}}{V_M} = \frac{X/4 I_{SM}}{V}$$

$$I = I_{MR} = I_{SM} = \frac{4V}{X} \sin \delta/4$$

Real power $P = V_{SM} I_{SM}$

$$= V \cos \delta/4 I_{SM}$$

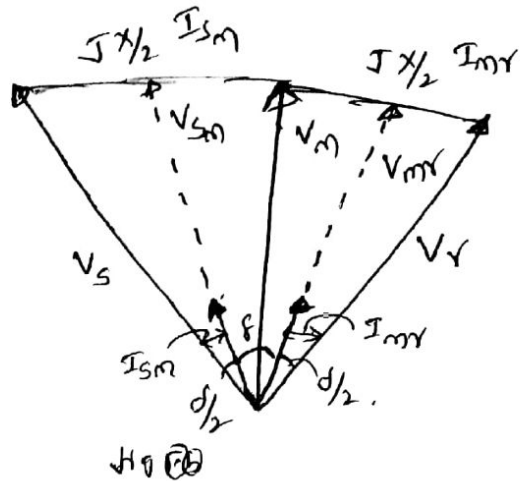
$$= VI \cos \delta/4 \quad (I_{SM} = I)$$

$$= V \left[\frac{4V}{X} \sin \delta/4 \right] \cos \delta/4$$

$$P = \frac{2V^2}{X} \sin \delta/4 \cos \delta/4$$

$$= \frac{2V^2}{X} \sin 2 \times \delta/4$$

$$P = \frac{2V^2}{X} \sin \delta/2$$



Reactive power

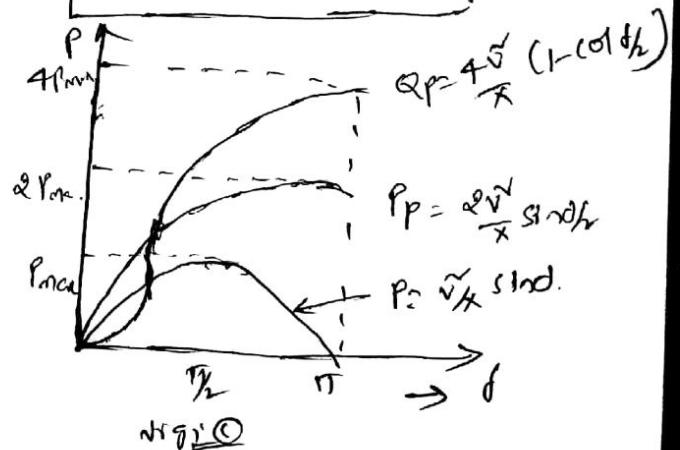
$$Q = VI \sin \delta/4$$

$$Q = V \left[\frac{4V}{X} \sin \delta/4 \right] \sin \delta/4$$

$$Q = \frac{4V^2}{X} \sin^2 \delta/4$$

$$= \frac{4V^2}{X} (1 - \cos 2(\delta/4)) \quad (\sin^2 \theta = 1 - \cos 2\theta)$$

$$Q = \frac{4V^2}{X} (1 - \cos \delta/2)$$



Ex 9.0: (a) Two machine system with an ideal midpoint reactive compensator.

(b) corresponding phasor diagram

(c) power transmission V_s angle characteristics.

→ The first segment, with an impedance $X/2$, carries power from the sending end to the midpoint, and the second segment also with impedance $X/2$, carries power from midpoint to receiving end.

→ The mid point of the tr line is the best location of the compensator. This is bcz the voltage sag along the uncompensated line is the largest at the mid point. It can be broken into two segments, carries the same max. power.

End of the line voltage support to prevent voltage instability:- (2)

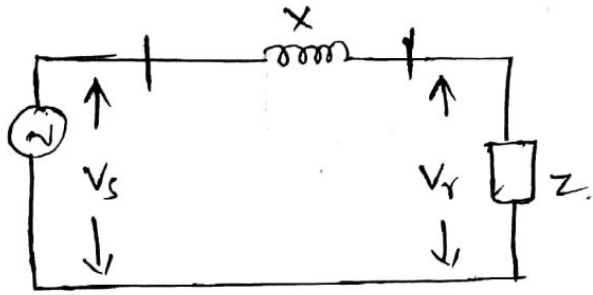


fig (a) Variation of voltage stability limit of a radial line with load and load power factor

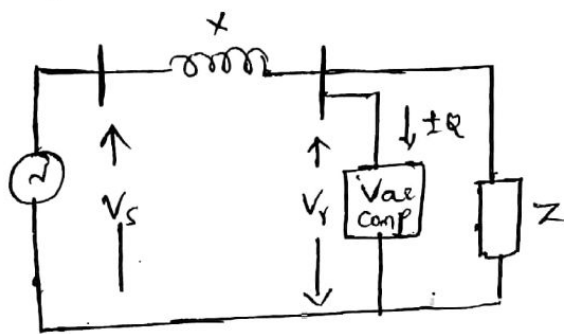
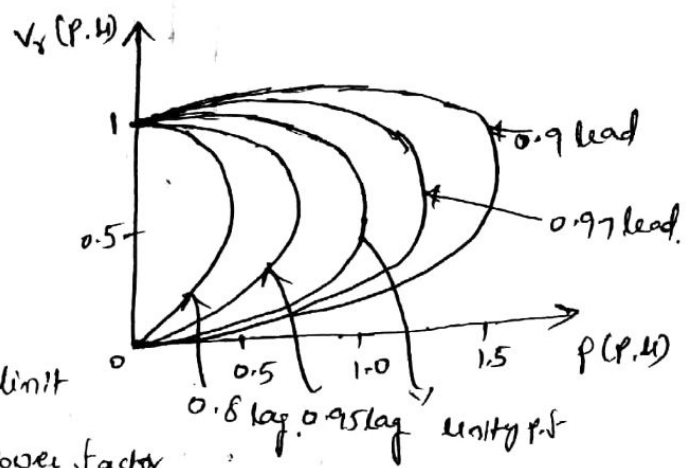
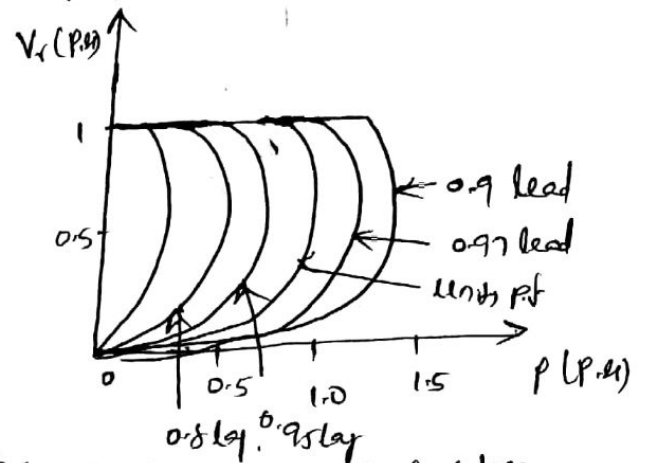


fig (b) The extension of this limit by reactive shunt compensation.



- The voltage stability is less for lagging loads.
- The voltage stability is more for leading loads.
- A simple radial system with feeder line reactance of X and load impedance Z . The normal terminal voltage V_r ~~varies~~ power P plot at various load power factors, ranging from 0.8 lag and 0.9 lead.
- It should be noted that voltage stability limit decreases with inductive loads, & increase with capacitive loads.
- The shunt reactive compensation can effectively increase the voltage stability limit by varying supply reactive load & regulating terminal voltage ($V - V_r = 0$).
- When a large load area is supplied from two (or) more generating plants with independent ties. The loss of one of the power sources could suddenly increase the load demand on the remaining part of the system, causing severe voltage depression that could result in an ultimate voltage collapse.

② Improvement of Transient stability:-

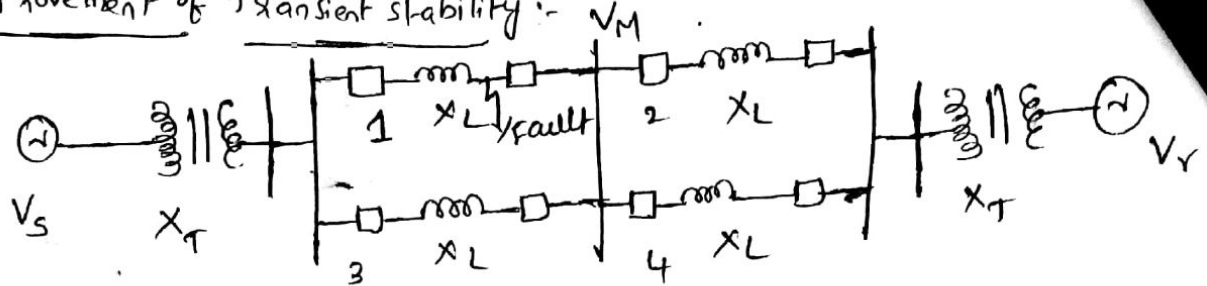


Fig: (a) Two Machine two Area system.

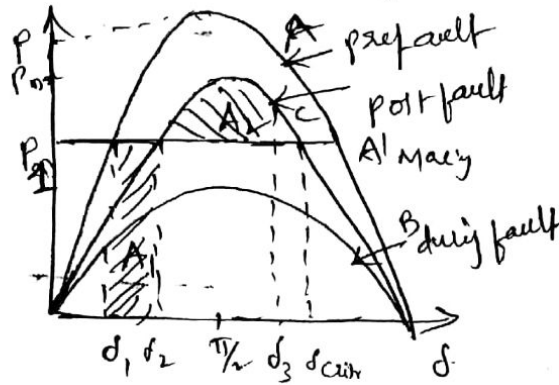


Fig (b)
during fault, $P_e < P_m$ (accelerate generator)

After fault: $P_m < P_T$ ($-P_e > P_m$) de accelerate generator

due to some k.r.c δ_3 increases to δ_{crit} .

- The reactive shunt compensation can significantly increase the maximum transmittable power..
- The potential effectiveness of shunt on transient stability improvement can be conveniently evaluated by Equal Area Criteria.
- Fig (a) shows simple two machine system Fig (b) shows power & shunt.
- The system is characterized by the P vs δ curve "a" and is operating at angle δ_1 to transmit power P_1 when fault occurs at line segment.
- During the fault the system is characterized by the P vs δ curve "b" and over this period, TEP decreases significantly while mechanical input power to the sending end generator remains constant to P_1 .
- The generator accelerates and its angle increases from δ_1 to δ_2 ∴ protective breakers disconnect the faulted line segment and the sending end generator absorbs accelerating energy. Separated area A₂.

At angle δ_2 on curve C. The Transmitted power exceeds mechanical power ($P_e > P_m$).
 P_1 and the sending end generator starts decelerating. The area represented by A_2

→ The Area A_{margin} , between δ_3 and δ_{crit} represent the transient stability margin of the system.

→ Shunt Compensation provide effective voltage support. & increase the transmission capability of post fault system and thereby enhance transient stability.

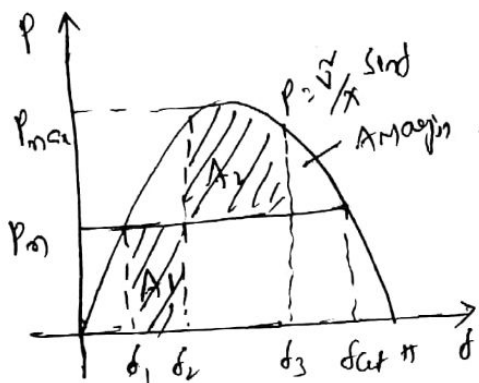


Fig C Transient stability without Compensation

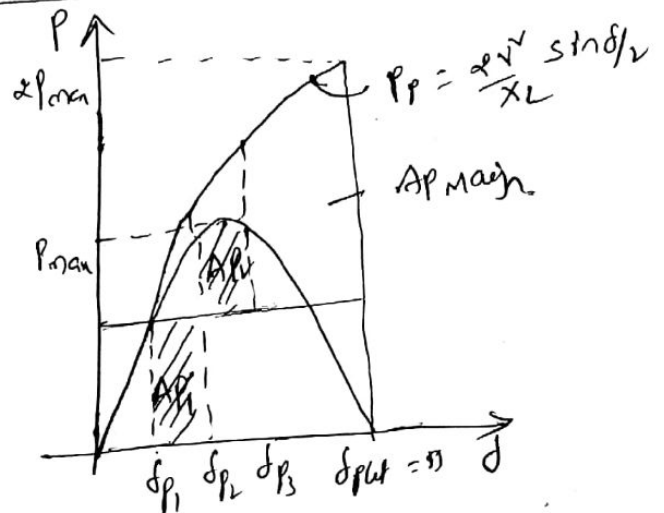


Fig d Transient stability with Compensation

$P_m \rightarrow$ constant power

- The dynamic behaviour of the system can be illustrated from fig C & d.
- The fault both of them Transient power P_m (Mechanical power) at angles δ_1 & δ_p .
- During the fault the Transmitted power becomes zero, while mechanical input power to the generator remains constant (P_m).
- The sending end generator accelerates from steady state angles δ_1 & δ_p to angles δ_2 & δ_{p2} ; when the fault clears. The accelerating energies are represented by A_1 & A_{P1} . After fault clearing the TEP exceeds mechanical input power and the sending end machine decelerates, but accumulated K.E. forces increase until a balance b/w the accelerating & decelerating energies concerned to areas A_1 , A_{P1} & A_2 , A_{P2} . The Transient margin areas represented by A_{margin} , $A_{Pmargin}$. The uncompensated system has a sufficient transient stability margin, shunt compensation increases the Transmittable power without decreasing the margin.

(d) power oscillation damping:-

→ In the case of an underdamped power system, any minor disturbance can cause the machine angle to oscillate around its steady state value at the natural frequency of the total electro-mechanical system.

→ The lack of sufficient damping can be a major problem in some power systems, and in some cases, it may be the limiting factor for the transmittable power.

→ Power oscillation is a sustained dynamic event, it is necessary to vary the applied shunt compensation, and thereby the voltage of the p.s. line to counteract the accelerating & decelerating swings of the disturbed machine(s).

→ During fault $\frac{df}{dt} > 0 \rightarrow (P_e < P_m)$ The generator accelerates and δ increases

→ After fault $\frac{df}{dt} < 0 \rightarrow (P_e > P_m)$ The generator decelerates and δ decreases

The var output can be controlled in a "Bang-Bang" manner. (Continuous - narrow valley).

Fig (a) shows the undamped and damped oscillations of angle δ around the steady state value δ_0 .

Fig (b) shows the undamped & damped oscillations of the electrical power P around the steady state value P_0 .

Fig (c) The reactive power output Q_p of the shunt connected var compensator.

→ ~~The Transmitted~~ The capacitive (fve) output of the compensator increases, the mid point voltage and hence the transmitted power $\frac{df}{dt} > 0$.

→ The capacitive output of the compensator decreases, the mid point voltage and hence the transmitted power $\frac{df}{dt} < 0$.

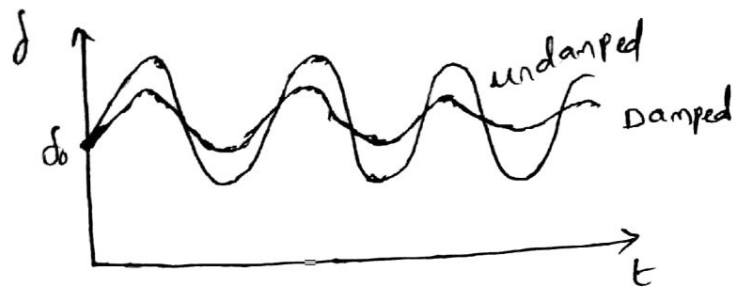


Fig (a) generator angle.



Fig (b) Transmitted power.

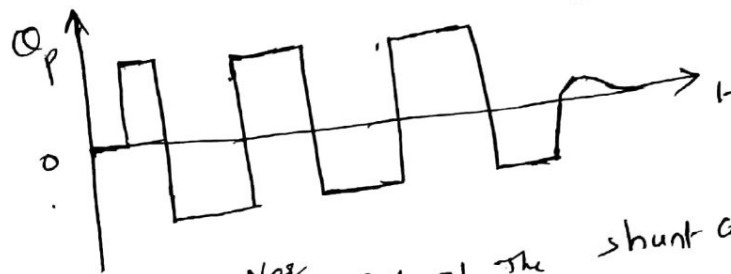


Fig (c) $V_{cr} \times$ output of the shunt compensator

Summary of Compensator requirements:

- ① The Compensator must stay in synchronous operation with the ac system at the compensated bus under all operating conditions including major disturbances.
- ② The Compensator must be able to regulate the bus voltage for bus support and improved transient stability. ③ control it for power oscillation damping.
- ③ For a line connecting two systems, the best location for Vcr compensation is in the middle, whereas for a radial feed to a load the best location is at the load end.

Methods of Controllable VAR generation:

- Capacitors generate reactive power, inductors absorb reactive power connected to an ac power source.
- Continuously variable var generation (or) absorption for dynamic system compensation was originally provided by under- or over excited rotating ^{sk} machines.
- In 1970s high power, line commutated thyristors in conjunction with capacitors, inductors have been employed in various circuit configurations to produce variable reactive power.
- Using appropriate switching control, the var output can be controlled continuously from maximum capacitive to maximum inductive output at a given bus voltage.
- Recently gate turn-off thyristors & other power semiconductor with internal turn-off capability have been used in switching converter circuits to generate (or) absorb reactive power with out use of ac capacitors & inductors.
- The ideal synchronous condensers, in which the magnitude of the internally generated ac voltage is varied to control the var output.
- In case of static var generator (SVG) whose output is varied so as to maintain control specific parameter (V, f) of the electrical power system.
- SVG draws controllable reactive current from an alternating power source.
- different types of var generator can be operated with same external control to provide compensation function. The external characteristics control functional capabilities. (voltage, regulation, P.f.c, P.D).
- modern static var generators based on high power semiconductor switching circuits.
- SVGs are used to realize the variable reactive power.

Variable impedance type static var generator:-

The performance & operating characteristics of the impedance type var generator are determined by their major Thyristor controlled components TCR & the TSC.

① Thyristor Controlled Reactor & Thyristor Switched Reactor (TCR & TSR):-

- The TCR is shown in figure. It consists of a reactor of inductance L & a bidirectional Thyristor valve (a) a switch.
- A large Thyristor can block voltage from 4000 to 9000 V and conduct current 3000 to 6000 A.
- In a practical valve many Thyristors (10 to 20) are connected in series to meet required blocking voltage levels at a given power rating.
- The valve can be brought in conduction by simultaneous application of gate pulse to Thyristors. The valve will block immediately after ac current crosses zero.

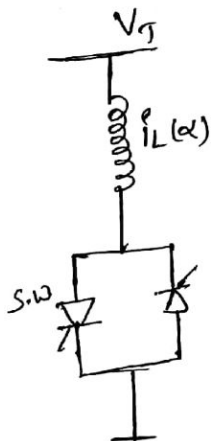
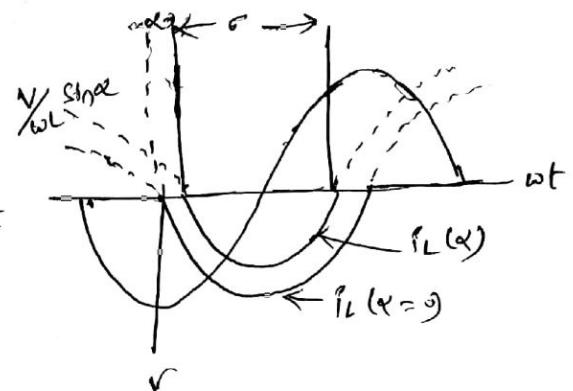
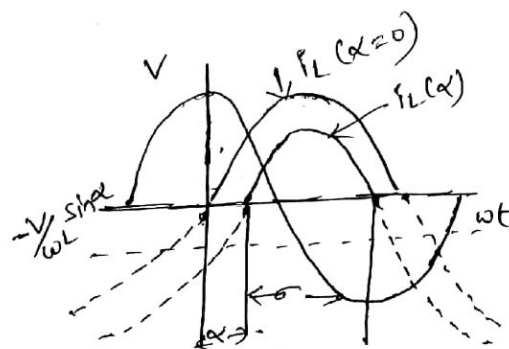
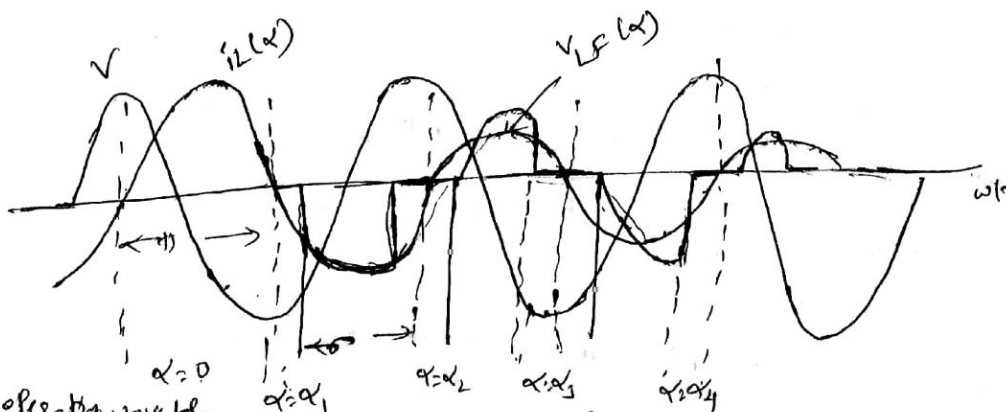


fig: TCR



fig(5) firing delay angle control.



fig(6) operating waveforms

The i_L can be controlled from max to zero by the delay angle control. The closer of value is delayed with respect to peak value of v_i in each half cycle. Thus, duration of current conduction can be controlled.

→ when $\alpha = 0$, i_L will be same as in the steady state.

→ when the gating of the valve is delayed by angle α ($0 < \alpha < \pi/2$) w.r.t to v_i

$$v = V \cos \omega t$$

$$i = \frac{1}{L} \int v dt$$

$$i = \frac{1}{L} \int_{\alpha}^{\omega t} V \cos \omega t dt$$

$$i = \frac{V}{\omega L} [\sin \omega t]_{\alpha}^{\omega t} = \frac{V}{\omega L} (\sin \omega t - \sin \alpha)$$

$$i_L = \frac{V}{\omega L} \sin \omega t$$

$\sigma =$ conduction angle.

$$\sigma = \pi - 2\alpha$$

when $\alpha = 0$ $\sigma = \pi$

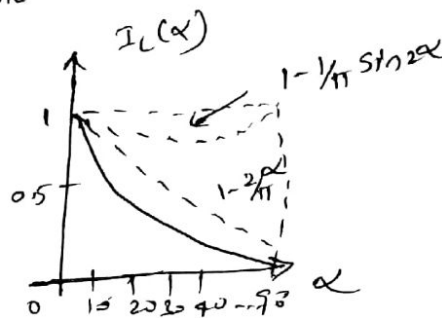
$\alpha = \pi/2$ $\sigma = 0$

→ By increasing delay angle, the conduction period (σ) & reactive power decreases.

$$i_L(\alpha) = \frac{V}{\omega L} (\sin \omega t - \sin \alpha)$$

$$i = V_B$$

$$B = \frac{1}{\omega L} [\sin \omega t - \sin \alpha]$$

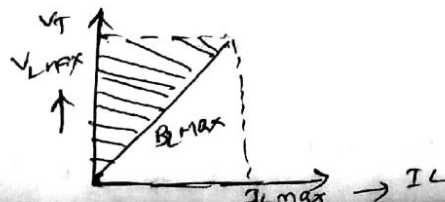


admittance: $B_L(\alpha) = \frac{1}{\omega L} [1 - \frac{2}{\pi} \alpha - \frac{1}{\pi} \sin 2\alpha]$

TSR: If the TCR switching is restricted to a fixed delay angle α , usually $\alpha = 0$, it becomes TSR. It provides a fixed inductive admittance and thus, when connected to the ac system Reactive $\propto V$.

→ TSR can provide reactive admittance controllable in a step like manner. At $\alpha = 0$,

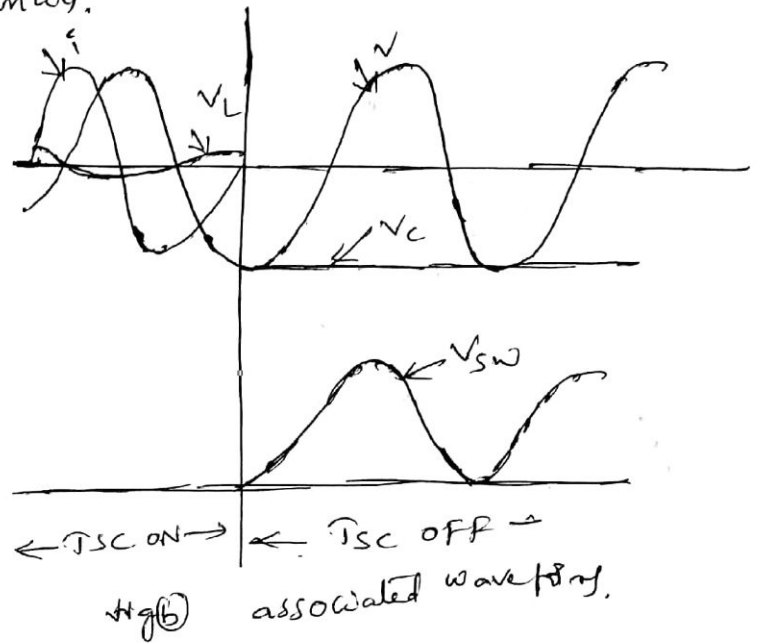
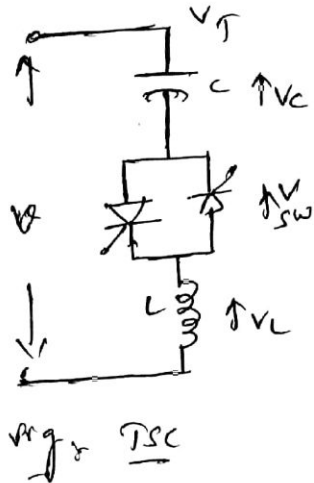
$i_{s,s}$ will be sinusoidal.



② Thyristor Switched Capacitor (TSC):-

It consists of a capacitor, bidirectional Thyristor valve & a small surge current limiting reactor.

→ This reactor primarily limits the surge currents in the Thyristor valve under abnormal conditions, & to avoid Resonance with ac system impedance at a particular frequency.



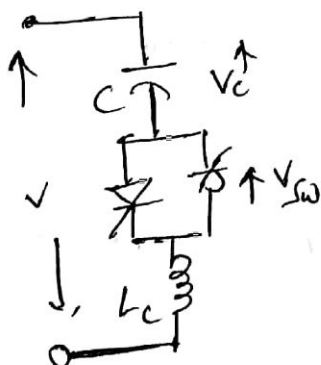
Under steady state condition, when the valve is closed, TSC is connected to sinusoidal volt.

$$i(\omega t) = \frac{V_m \omega}{\omega^2 - 1} \omega \cos \omega t; \quad n = \sqrt{\frac{X_C}{X_L}} = \frac{1}{\sqrt{\omega^2 L C}}$$

$$|V_C| = V_m \frac{\omega}{\omega^2 - 1}$$

→ Depending on switching the capacitor should be charged & discharged.

disadv: due to charging & discharging of capacitor, the transient will be take place.



Case (1) $V_C \leq V$

Then $V_C = V$

(a) $V_{SW} = 0$

Case (2) $V_C > V$

Then $\alpha = 0$

and $V_{SW} = \min$

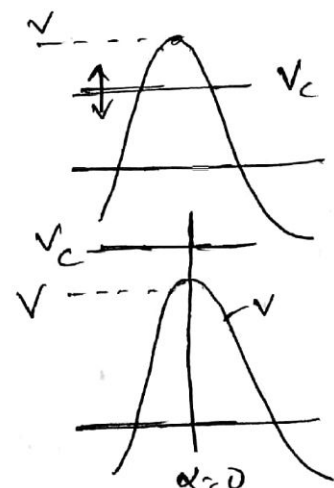


Fig: Condition for transient - free switching of the TSC with different

If the Residual Capacitor voltage is lower than V . Then correct instant of switching is the instantaneous AC voltage equal to capacitor voltage.
 Case (ii) If the Residual capacitor voltage is equal to higher than peak AC voltage then the correct switch is at the peak of the AC voltage at which the thyristor value voltage is minimum.

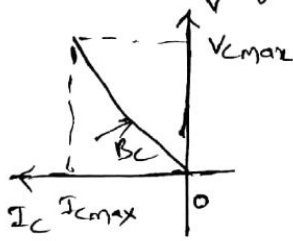


Fig. operating $V-I$ area of a single TSC.

V_{max} : voltage limit

I_{max} = current limit

BC = Admittance of Capacitor

③ Fixed Capacitor, Thyristor-controlled Reactor Type VAr generator: (FC-TCR)

→ A Basic Arrangement of a fixed capacitor with a thyristor controlled Reactor is shown in figure (FC-TCR).

→ The current in the reactor is varied by the previously discussed method of firing delay angle control.

→ The Capacitive Impedance are used to generate reactive power, it provides low impedance at selected frequencies to shunt the dominant harmonics by TCR.

→ By varying delay angle ' α ' we can generate Inductive current.

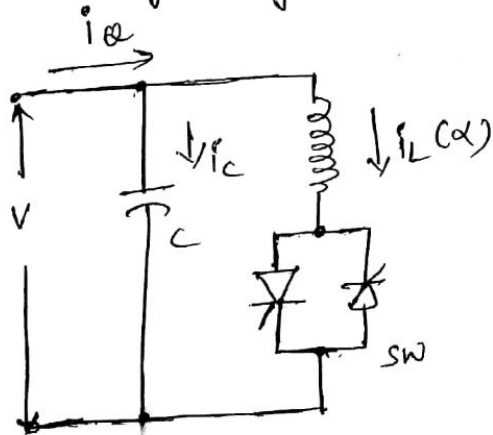


Fig. Basic FC-TCR type static VAr generator

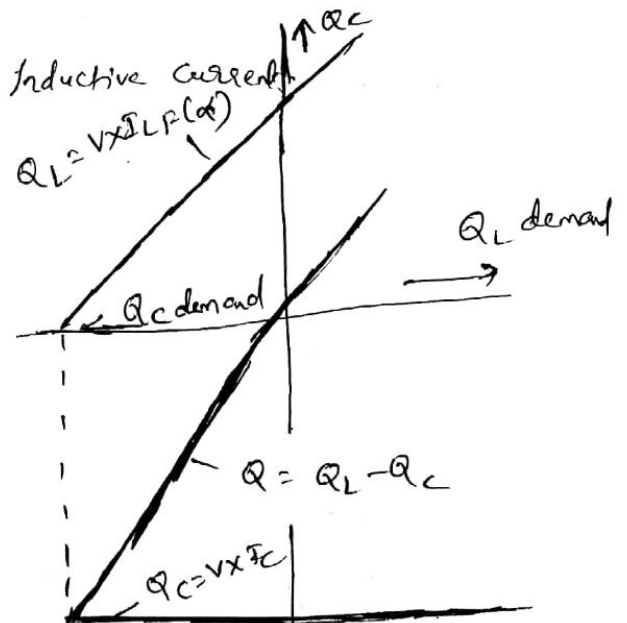


Fig. VAr Demand vs VAr output characteristics.

- At maximum Capacitive var output, the Thyristor controlled rectifier ($\alpha = 90^\circ$).
- To decrease capacitive output, the current in the reactor is increased by decreasing delay angle α' .
- At zero var output, the capacitive & inductive currents become equal and thus the capacitive & inductive vars cancel out.
- further decrease of angle α , the inductive current becomes larger than the capacitive current, resulting in a net inductive var output.
- The control of the thyristor controlled reactor (FC-TR) type var generator needs four basic functions.
- The first function is synchronism timing. This is usually provided by a phase locked loop circuit that runs in synchronism with ac system voltage and generates appropriate timing pulses with respect to the peak of that voltage.
- The second function is reactive current to fire angle conversion. This can be provided by real time circuit implementation of the mathematical relationship b/w the amplitude of fundamental CR current I_{CR} and delay angle α .
- The third function is the computation of the required fundamental reactor current I_{PL} . The requested output current I_Q defined by the amplitude reference input I_{Qref} to the var generator control.
- The fourth function is thyristor firing pulse generation. This is accomplished by firing pulse generator which produces necessary gate current pulses.

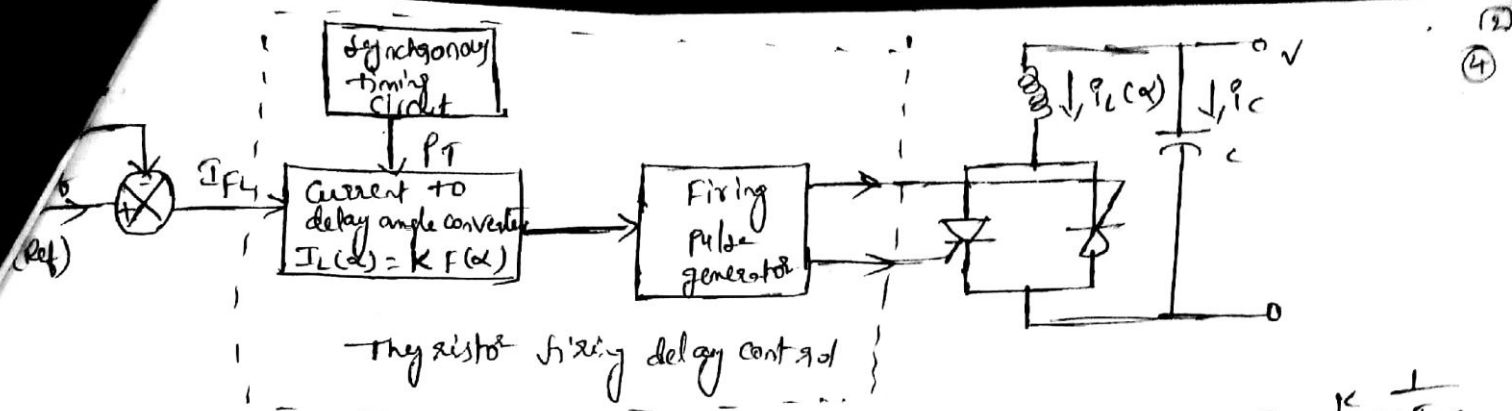


Fig (a)

$$G(s) = K \frac{1}{1 + T_d s}$$

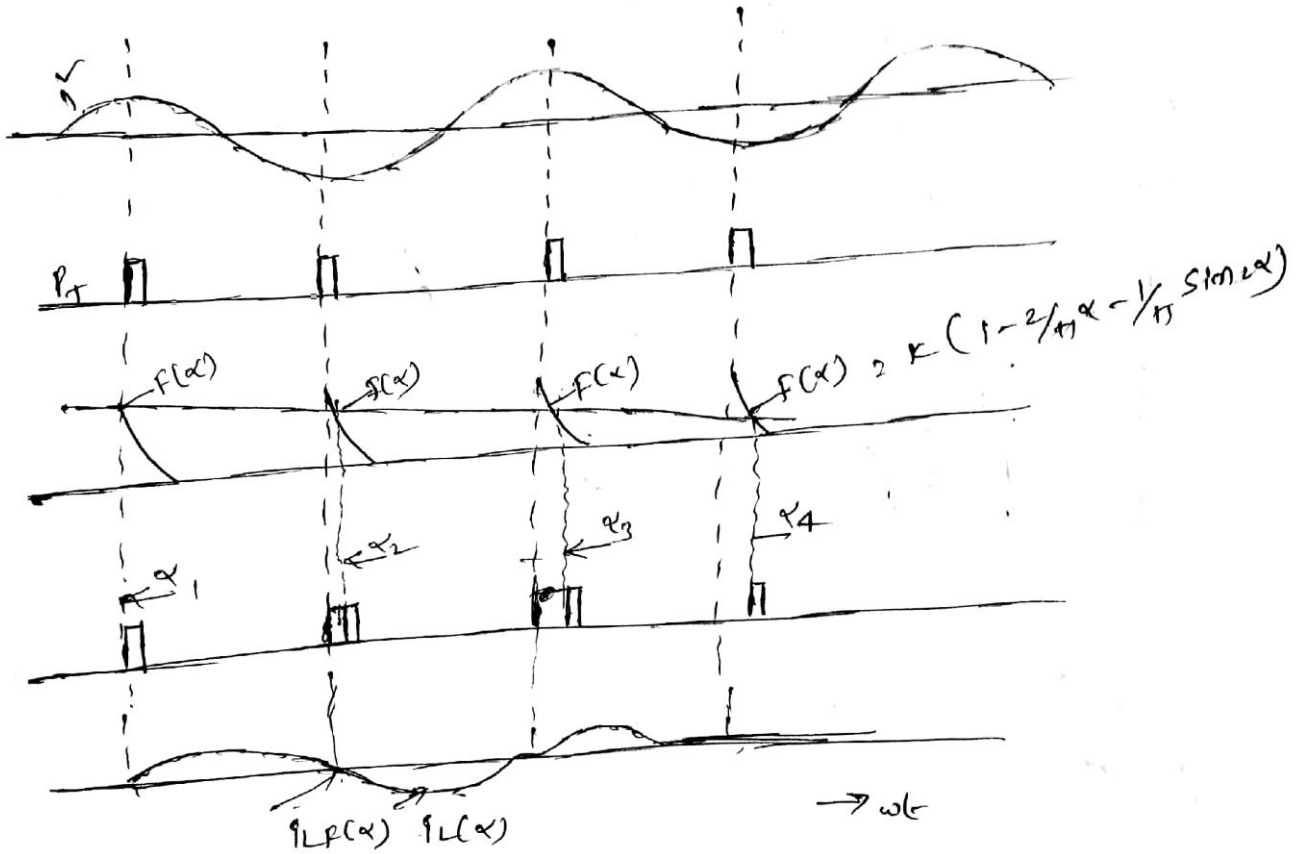
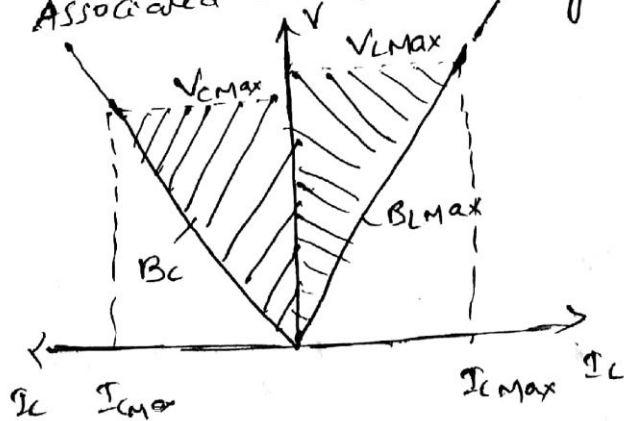


Fig (b)

Fig (a) functional control scheme for the FC-TCR Type static var generator

Fig (b) Associated wave forms relating the basic operating principle



V_{Cmax} = Voltage limit for Cap

V_{Lmax} = Voltage limit for TCR

I_{Cmax} = Capacitive current limit

I_{Lmax} = Inductive current limit

B_{Lmax} = max inductive admittance

B_c = admittance of capacitor

Fig: - operating v-i area of the FC-TCR type var generator

④ Thyristor-Switched Capacitor, Thyristor-Controlled Reactor type Vargenerator (TSC-TCR)

→ TSC-TCR was developed primarily for dynamic compensation of power transmission system with the intention of minimizing stand by losses.

A basic single-phase TSC-TCR arrangement is shown. For a given output range, it typically consists of n TSC branches and one TCR

→ The number of branches n , is determined by including operating voltage level, maximum Var output, current rating of the thyristor valves, installation cost.

→ The circuit

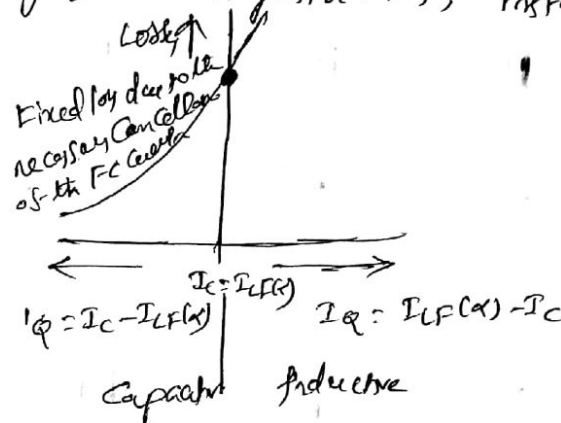
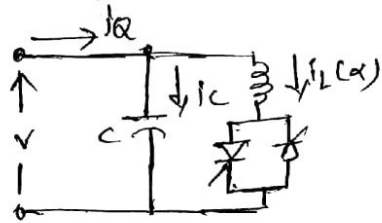


Fig. ① Loss versus Var output characteristics of the FC-TCR type static var generator.

The operation of the TSC-TCR generator shown in fig. ②

→ The total capacitive output range is divided into n intervals. In the first interval, the output of var generator is controllable in the zero to Q_{max}/n range, where Q_{max} is the total rating provided by all TSC branches.

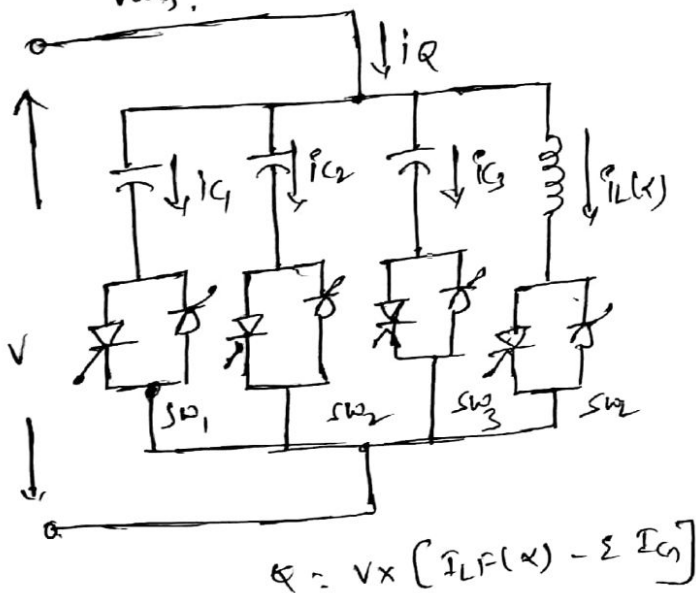
→ In this interval, one capacitor bank is switched in, and, simultaneously, the current in the TCR is set by the appropriate firing delay angle.

→ So that the sum of the var output of TSC (negative) and that of the TCR (positive) equals the capacitive output required.

→ In the second, 3rd & n th intervals, the output is controllable in the Q_{max}/n to $2Q_{max}/n$, $2Q_{max}/n$ to $3Q_{max}/n$... and $(n-1)Q_{max}/n$ to Q_{max} range by switching in the second, 3rd, ... n th capacitor banks.

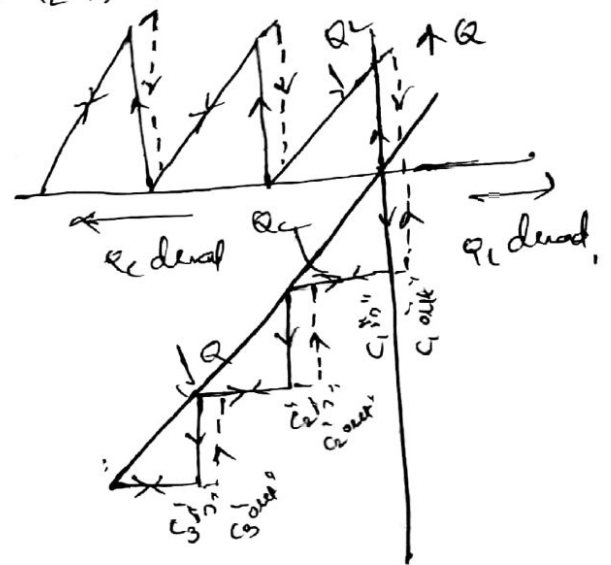
5) However to ensure that the switching conditions at the end points of the intervals are not indeterminate, the var settings of the TCR have to be some what large in practice than that of one TSC in order to provide enough overlap (hysteresis) b/w the switching in and switching out var levels.

→ The Var Demand vs Var output characteristics shown here for TSC-TCR type var generator. As seen the capacitive var output Q_c is changed in a step like manner by the TSC to approximate the var demand with a net capacitive var surplus, and the relatively small inductive var output of the TCR, Q_L is used to supply capacitive vars.



(a)

Fig 2 (a) Basic TSC-TCR type static var generator



(b)

Fig 2 (b) Var Demand vs Var output characteristics

surplus → Additional

TSC-TCR provide Three major function.

- ① Determine the number of TSC branches needed to be switched in to approximate required capacitive output current, and inductive current needed to cancel, surplus capacitive current
- ② Controls the switching of TSC branches in a transient-free manner
- ③ Varies the current in the TCR by firing delay angle control.

Switching Converter type Var generators:

- The aim of this approach is to produce a variable reactive impedance that can be adjusted to meet the compensation requirement of the transmission network.
- When SSCs operated without an energy source, and with appropriate controls to function as a shunt connected reactive compensator, it is termed as analogously to the rotating synchronous compensator.
- up to now we discussed about dc to ac converter, (a) just converter, where as the latter one is referred to as frequency changer, (b) frequency converter, (c) cyclo converter. It can convert change of ac power of one frequency to ac power of another frequency.
- In the case of dc to ac converter, the dc terminals are usually considered as "input" and therefore voltage-sourced and current-sourced converter are distinguished according to whether these are shunted by a voltage source (a) by a current source.
- Converters presently employed in FACTS controllers are the voltage-sourced type, current-sourced type converter may also be used in future.

Basic operating principles:-

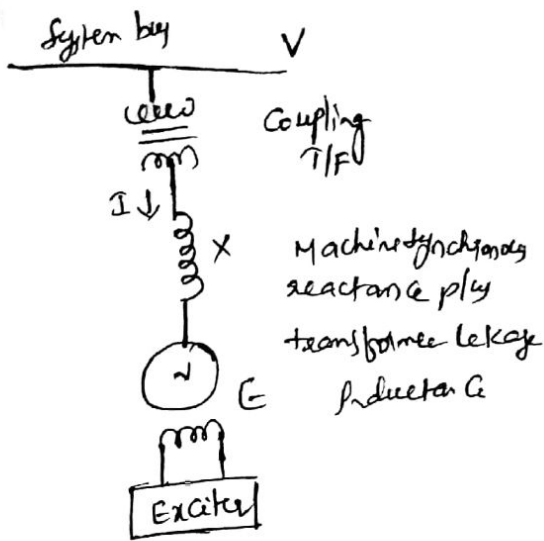
The basic principle of reactive power generation by a voltage-sourced converter is akin to that of the conventional rotating synchronous machine shown.

- The 3- ϕ , induced electromotive forces (EMFs), e_a, e_b, e_c of the synchronous rotating machine is in phase with system voltages, V_a, V_b, V_c .
- The reactive current I drawn by the synchronous compensator is determined by magnitude of the system voltage V , that of terminal voltage E :

$$I = \frac{V - E}{X}$$

The Q exchanged can be

$$Q = \frac{V^2 - E^2}{X}$$



→ over excited synchronous motor acts as a synchronous condenser.

Fig. Reactive power generation by a rotating synchronous compensator

→ By controlling excitation of the machine, the reactive power flow can be controlled.

→ Over Excitation Condition: $E > V$. results in leading current, the machine seen as capacitor by the ac system.

→ Under Excitation Condition: $E < V$. results in lagging current, the machine seen as inductor by the ac system.

→ Normal Excitation: $E = V$, results in unity power factor.

The basic voltage controlled scheme for reactive power generation is shown.

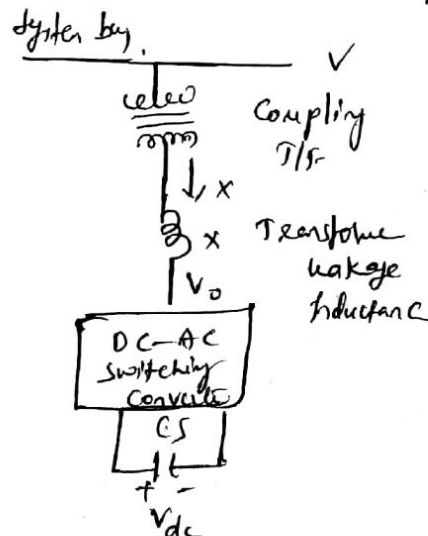


Fig. Reactive power generation by rotating & voltage source switching converter

→ The amplitude of the output voltage is equal to system voltage.

The reactive power exchange is zero.

→ The three phase output voltage is generated by a voltage-sourced d.c to a.c converter operated from an energy storage capacitor.

→ All the practical converters are employed in transmission, single phase H-bridge, 3- ϕ , two level six pulse bridge, 3- ϕ , three level, 12-pulse bridge shown.

→ The values are used in elementary converter readily 3 to 10 of series connected semiconductor devices. eg:- GTO Thyristor with Reverse-parallel.

→ They are producing square wave, quasi-square, PWM output voltage.

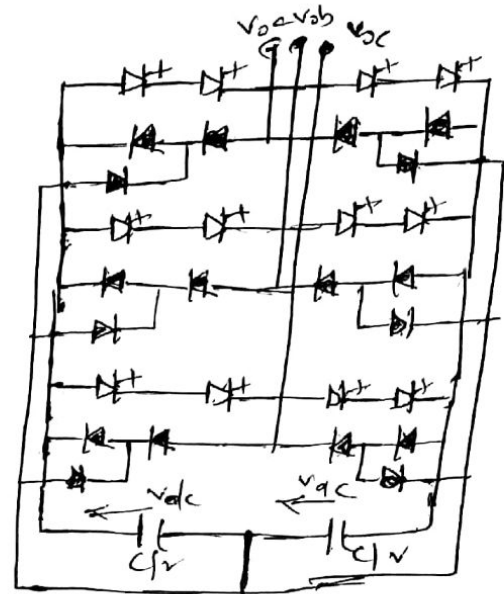
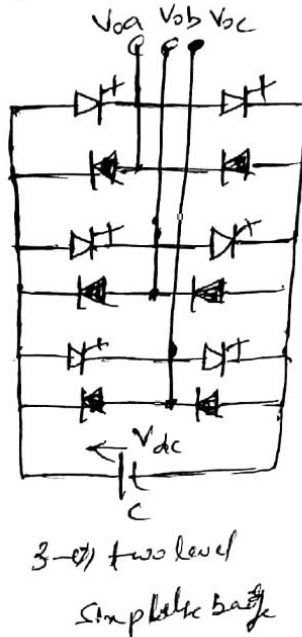
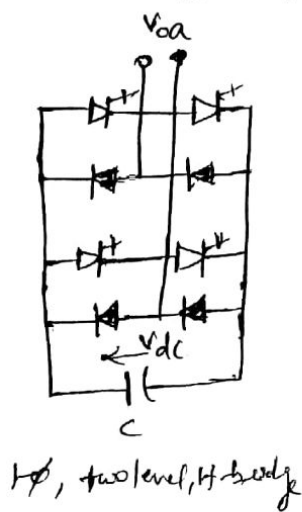


Fig 1 Basic Converter Schem for reactive power generation.

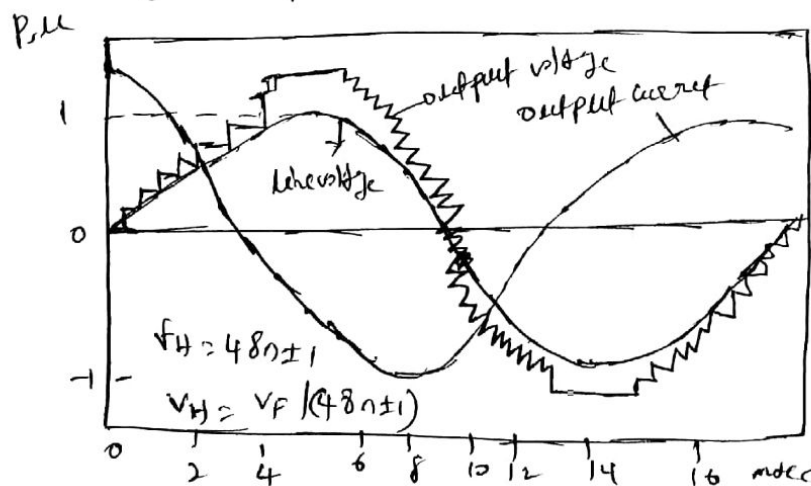


Fig 2 Typical output voltage & current waveforms of 48-pulse converter generating reactive power.

Hybrid Var generators:- Switching Converter with TSC & TCR

7

- The Converter based Var generator can generate (or) absorb the same amount of var. reactive power; in other words, it has the same control range of capacitive & inductive var output.
- Many applications may call for a different var generation & absorption range. This is done by combining FC & TSC & TCR.
- The combination of a converter based var generation with a fixed capacitor is shown in fig (1) (a). This arrangement can generate vars in excess of the rating of converter, shifting the operating range into the capacitive region. The associated V-I characteristic shown in fig (1) (b).
- Also possible to operate static var generator further into the absorption region by combining the converter with shunt reactor shown in fig (2) (a). The V-I characteristic shown in fig (2) (b).
- whereas fixed capacitor (or) reactor shift the operating range of converter based var generation more into the capacitive (or) into inductive region without changing magnitude of MVA's.
- TSC & TCR actually increase the total control range of var output.
- The change in V-I characteristics are clearly dependent on the MVA rating of the converter related to the total controlled MVA.
- Hybrid var generators employing a converter with fixed & TCR, & TSC banks, may be used for the purpose of MVA rating. an optimal/lossy vs var output characteristics is a given approach.

Summary of static Var generator

The basic characteristics of the main static Var generator schemes are summarized,

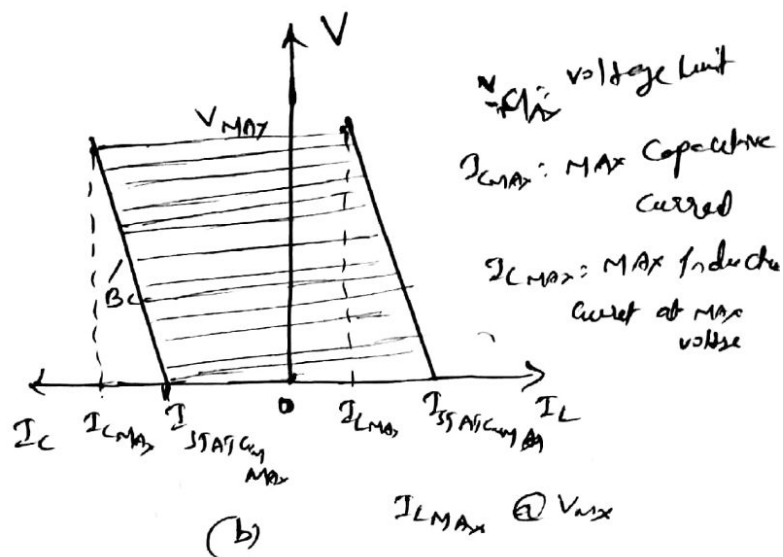
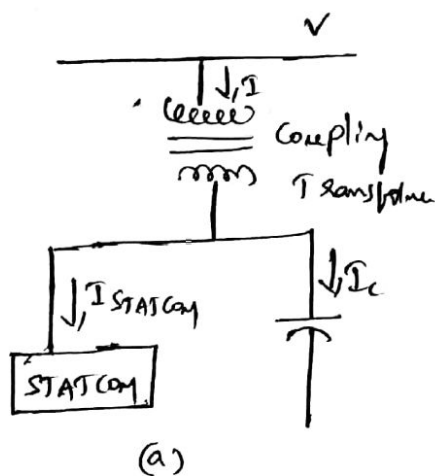


fig 10a Combined converter based & fixed capacitor type var generator
 (b) associated operating v-i area.

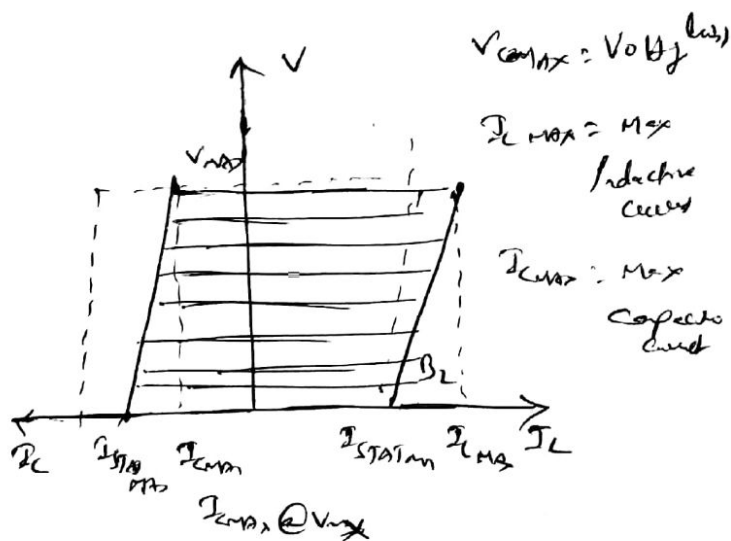
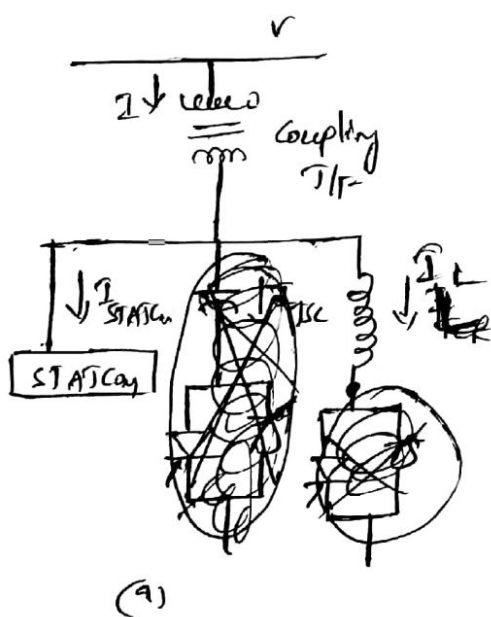


fig 10b Combined converter based & fixed reactor type var generator
 (b) associated operating v-i area.

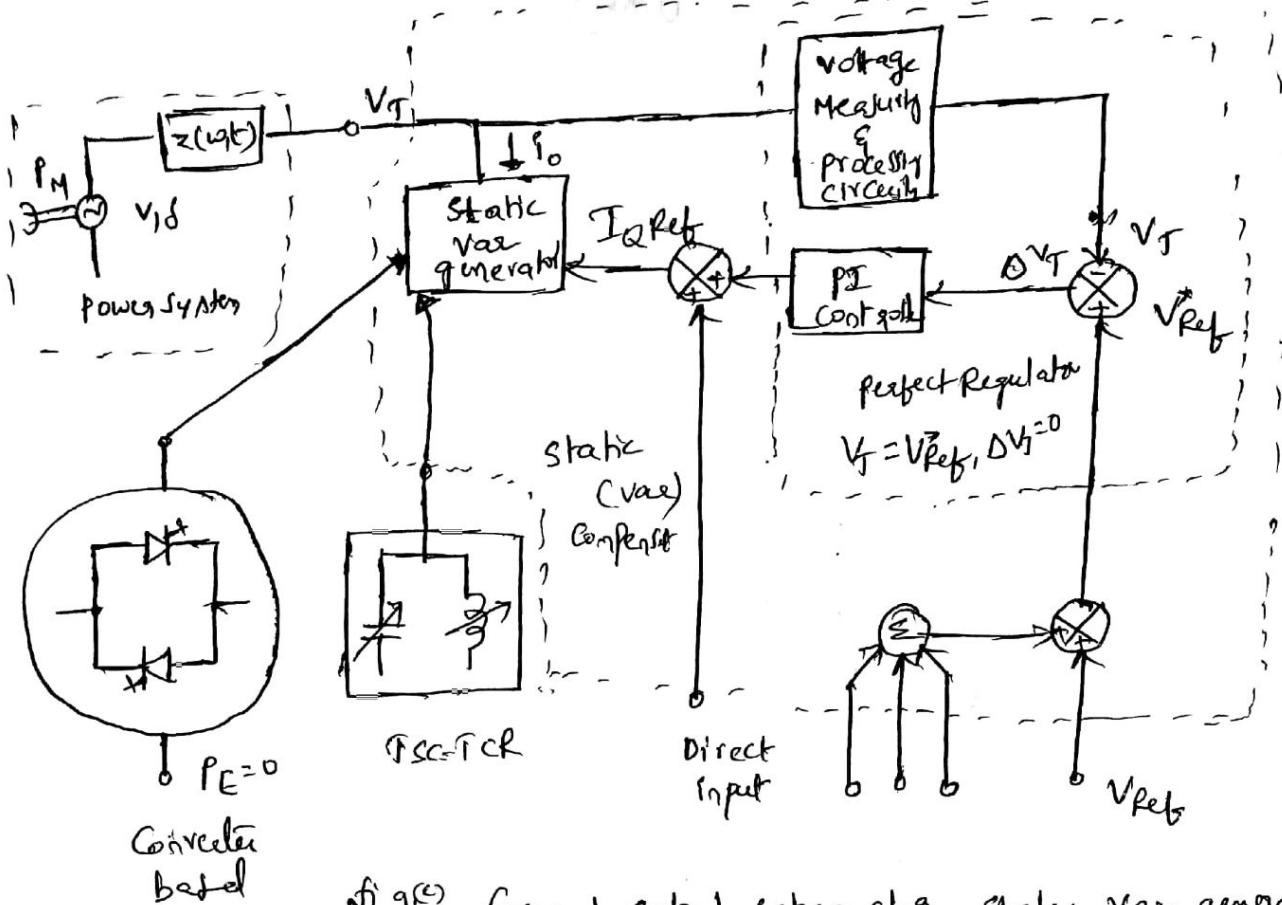


fig. 1 General control scheme of a static var generator

- A general control scheme, converting a static var generator into a Transmission line Compensator .. is show in fig (1).
- The power system, at the terminal of the compensator, is represented by a generator with generally varying rotor angle δ , internal voltage V , and source impedance Z that is a function of angular frequency ω & time t .
- The terminal voltage V_t of the power system can be characterized by a generally varying amplitude V_t & angular frequency ω .
- The output of the static var generator is controlled so as to maintain that the amplitude I_0 of the reactive current I_0 drawn from the power system follows the current reference I_{qref} .
- The var generator operated as Perfect terminal voltage regulator.
- The amplitude V_t of the terminal voltage V_t is measured & compared with voltage reference V_{ref} . The error ΔV_t is processed & amplified by PI controller to provide current reference I_{qref} to the var generator.

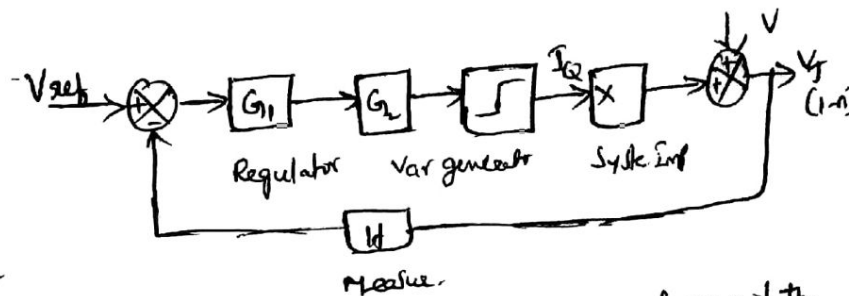
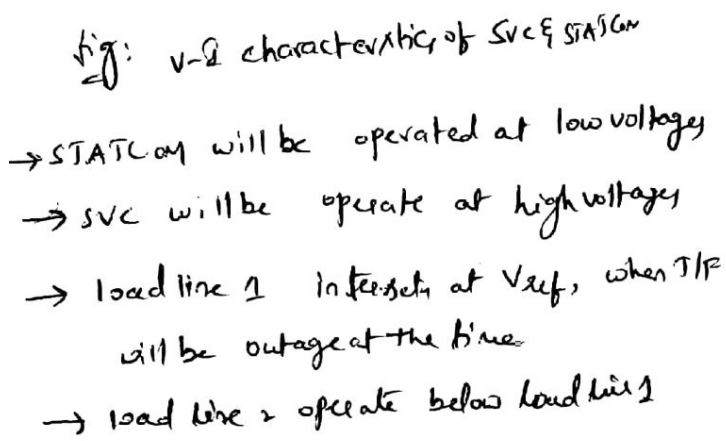


Fig. 1 Basic tr function block diagram of the static (var) compensator

$$V_f = V \cdot \frac{1}{1 + G_1 G_2 H X} + V_{ref} \cdot \frac{G_1 G_2 X}{1 + G_1 G_2 H X}$$

let $v_{ref} = 0$

$$\frac{\Delta V_1}{\Delta V} = \frac{1}{1 + G_1 G_2 H X} = \frac{1}{1 + G_1 G_2}$$

$$G_1 = \frac{1}{1 + T_1 s}$$

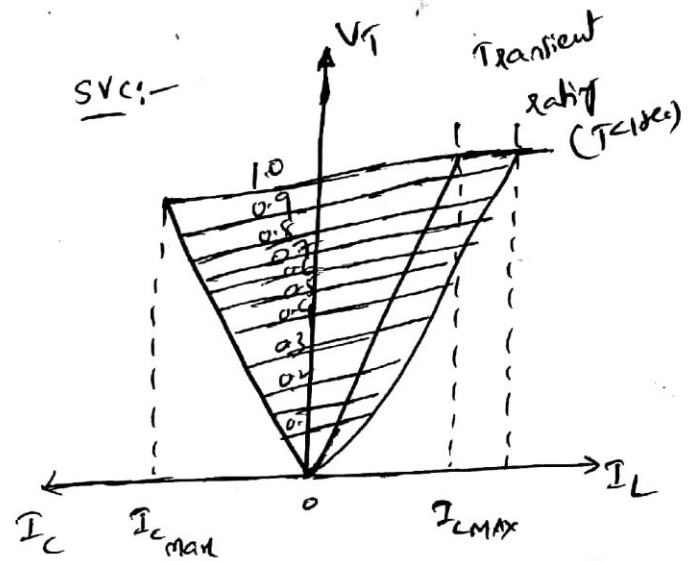
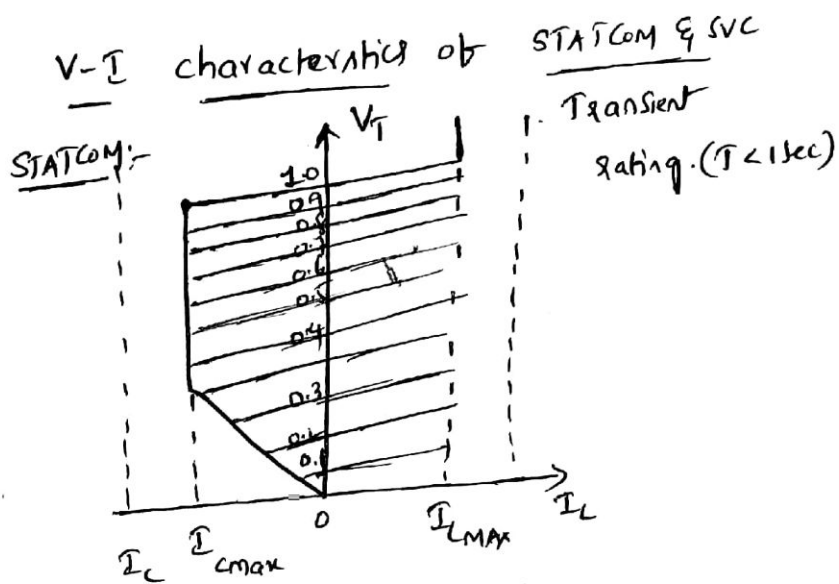
$$a_2 = \bar{e}^T d s$$

$$g = g_1 g_2 = \frac{\gamma_L}{17.15} \cdot e^{T ds}$$

$$H = \frac{1}{1 + T_2 s}$$

Comparison b/w SVC & STATCOM:-

- The Basic operating principle of statcom which can be a converter based VAR generator function as shunt connected synchronous voltage source.
- static VAR compensator which can be a Thyristor Controlled Reactor (TCR) & Thyristor switched capacitor (TSC) function as shunt connected control reactive impedance..



- STATCOM operate at full output current
- Transient stability is more.

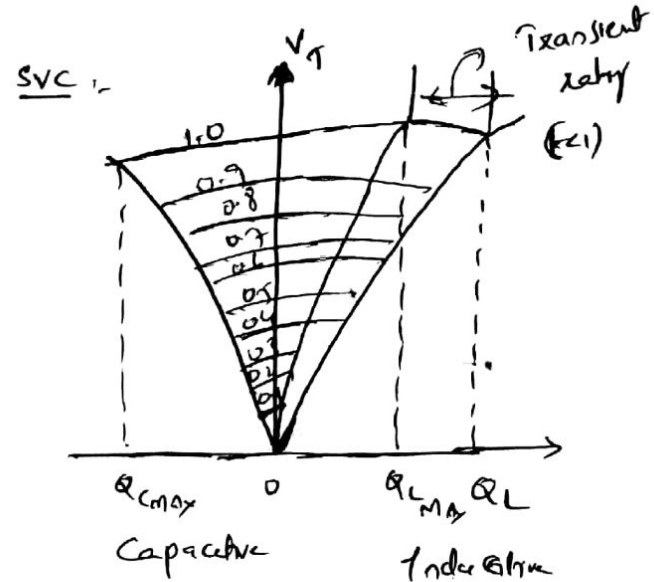
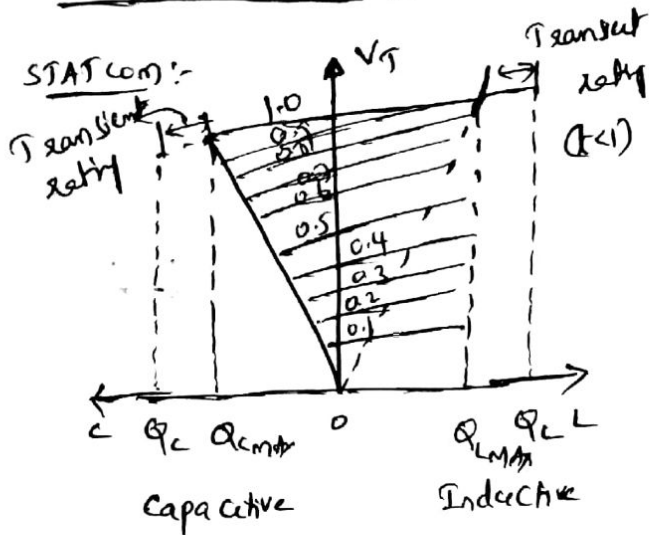
Points:-

- 1) STATCOM can be operated over its full output current range even at very low values typically about 0.8 p.u system voltage level.
- 2) The maximum capacitive (or) inductive o/p currents of the statcom can be maintained independent of AC system voltage.
- 3) The SVC will be composed of TSC & TCR. The maximum attainable compensating current of the SVC decreases linearly with the AC system voltage. Its max var o/p decreases with square of this voltage as shown in the figure.

4) STATCOM is superior to this SVC is provide a voltage support under large system disturbances.

5) The capability of providing max compensating current at reduced system voltage enables the statcom to perform a variety application for same dynamic compensation of a SVC of considerably higher rating.

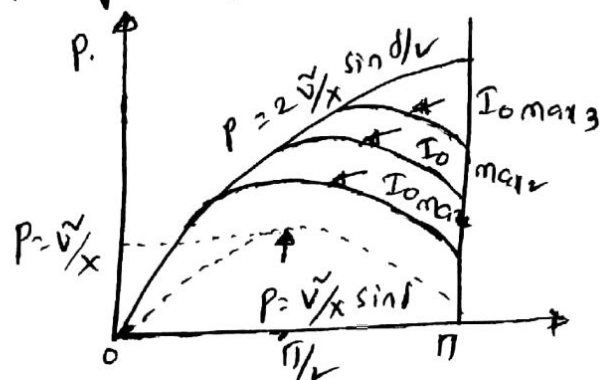
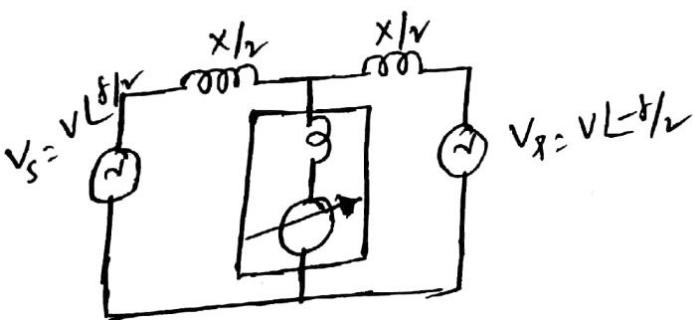
V-Q characteristic:-

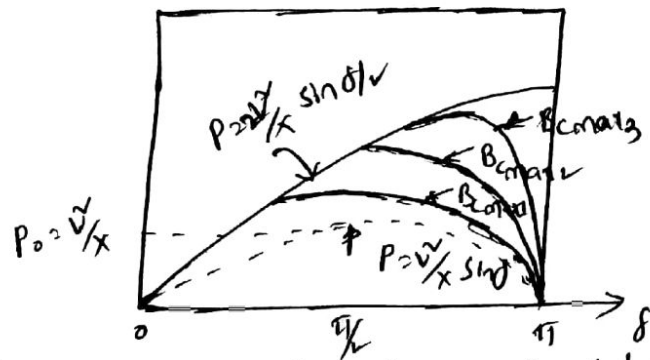
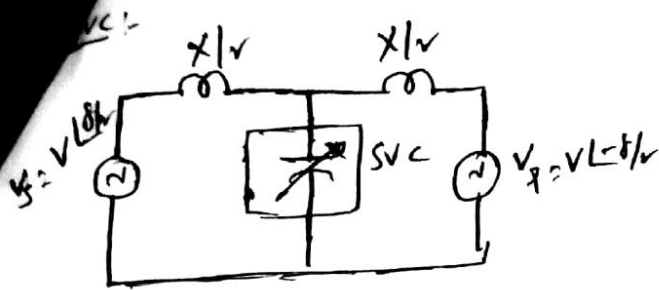


- 1) STATCOM has an increased Transient rating in both the capacitive & inductive.
- 2) The max attainable Transient over current of the statcom in the capacitive region is determined by the maximum current turn off capability of the power semi conductors employed.

Transient stability:-

- STATCOM has more transmittable power capability than SVC
- STATCOM has more Transient stability margin than SVC

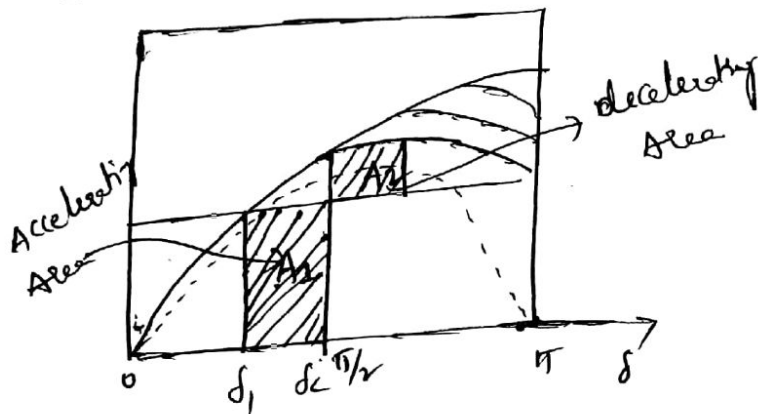




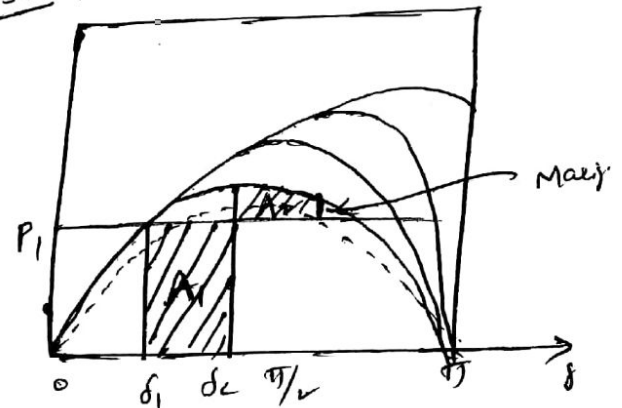
→ The ability of statcom to maintain full capacitive d/p current at low system voltage also makes it more effective than the SVC. in improving the Transient stability.

→ The Effectiveness of the statcom in increasing the transmittable power as shown in the figure.

STATCOM:-



SVC:-



- 1) The Transient stability Margin obtained with the statcom due to the better support of the mid point voltage greater than with SVC.
- 2) The Transmittable power can be increased with the shunt compensation provided by a statcom rather than by an SVC (or) for the same stability margin the rating of the statcom can be decreased below that of the SVC.

Response time:-

1) STATCOM having less response time compared to SVC bcz statcom has a semiconductor device.

2) The attainable response time and the Bandwidth of the closed voltage regulation loop of the statcom are also better than that of SVC.

3) The time constant T_d is typically from 200 μ s to 350 μ s for a statcom. & b/n 2.5 ms & 5 ms for the SVC

Capability to exchange real power:-

- The station has capable of drawing controlled real power from an energy source at its DC terminals and delivering an AC power to the system.
- By equipping the station with an energy storage device of suitable capacity, effective control strategies for the modulation reactive & real and real of power can be executed in the improvement of transient for the damping of power oscillation.

loss vs V_{ref} of characteristics:-

- The loss contribution of power semiconductor & related components to the total compensator losses is higher for the station than for the SVC.

But: The power semiconductor devices with internal turn off capability have higher conduction losses than conventional thyristor.

Objectives of Series Compensation:-

- 1) Series Compensation is highly effective in both power flow control in the line & improving the stability.
- 2) The effect of series compensation on the basic factors determining attainable maximum power transmission, steady state power limit, transient stability, voltage stability & power oscillation damping.

Concept of series Capacitor compensation:-

$$P = \frac{V_s V_r}{X} \sin \delta$$

→ The basic idea of behinds series Capacitive Compensation is to decrease the over all effective series transmission impedance through from sending end to receiving end.

→ $P = \frac{V_s V_r}{X} \sin \delta$ relationship characterizing the power P_r over a

single line

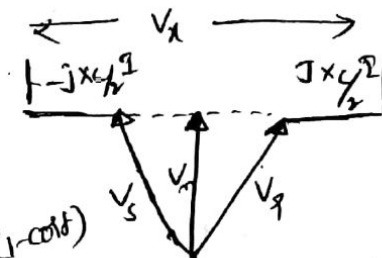
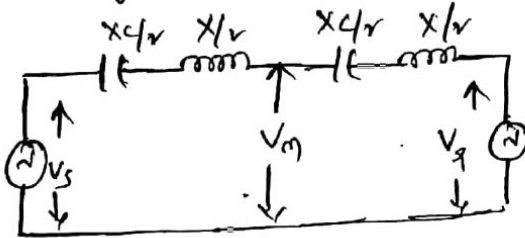


fig: two machine model with

series capacitive compensation

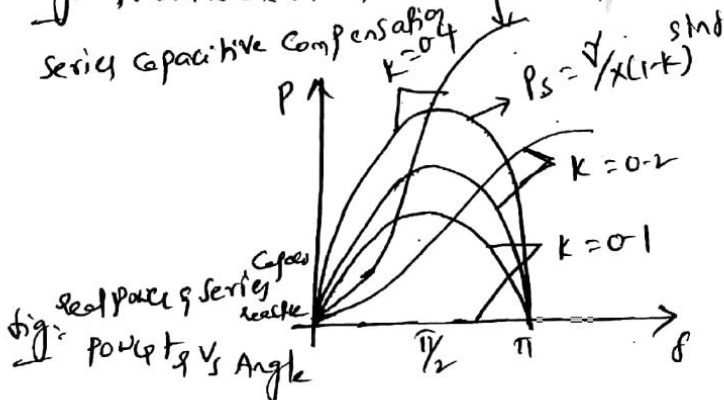


fig (b): phasor Diagram

The effective transmission impedance

$$X_{eff} = X - X_c$$

$$= (1 - k)X$$

$$\text{where } k = \frac{X_c}{X} \quad (0 \leq k < 1)$$

k = degree of series compensation

Assumption

$$V_S = V_R = V$$

$$I = \frac{QV}{(1-k)X} \sin \delta/2$$

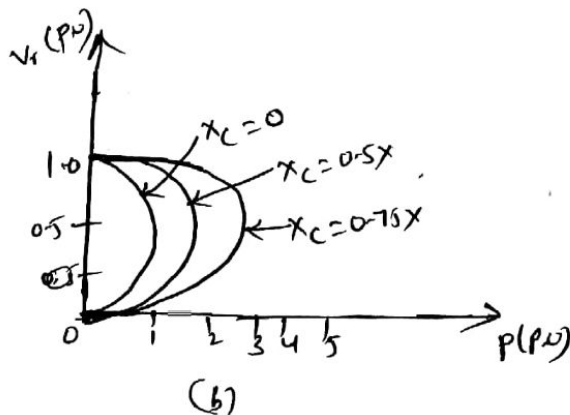
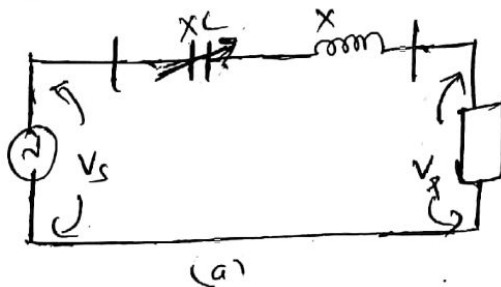
$$P = V_m I_m = \frac{V^2}{(1-k)X} \sin \delta$$

$$Q_C = I^2 X_C = \frac{QV^2}{X} \frac{k}{(1-k)^2} (1 - \cos \delta)$$

By variation of 'k' the reactive, Active power increase (Pm).

Note:- For the same end voltage the magnitude of the total voltage across the series line inductance $V_X = 2VX$ is increased by the magnitude of the opposite voltage (Q_C) developed across the series capacitor. This results cause an increase the line current.

Voltage stability:-



Fig(a) Transmittable power & voltage stability limit of a radial transmission line as a function of series capacitive compensation

→ There is no oscillation at load side that is possible in series compensation. The load side voltage should be constant.

$$P = \frac{V}{X} \sin \delta$$

→ Series capacitive compensation can also be used to reduce the series reactive impedance to minimize the receiving end relation and the possibility voltage collapse.

→ Inductive load will be nullified by the capacitive load.

→ Shunt compensation does it supplying reactive load demand and regulating terminal voltage.

→ Series capacitive compensation does it by cancelling a portion of line reactance and thereby an effect providing a stiff voltage source for the load.

→ for increasing the voltage stability limit in over head tr. series compensation is much more effective than shunt compensation of the same MVA rating.

Improvement of Transient stability:-

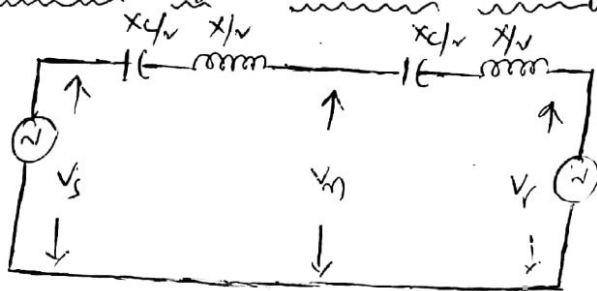


fig:- two machine system with series capacitive compensation.

→ The powerful capability of series line compensation to control the transmitted power can be utilized much more effectively to increase the transient stability limit & to provide power oscillation damping.

- The equal area criterion introduced to investigate the capability of Ideal shunt Compensator to improve the transient stability, is used again here to access the relative increase of the transient stability Margin attainable by series Capacitive Compensation.
- The Dynamic behaviour of the systems is illustrated in figures fig (a) & (b). As seen prior to the fault both of them transmit power P_m at angles δ_1 & δ_{s1} .
- During the fault, Transmitted electric power becomes zero while the Mechanical input power to the generator remain constant P_m . Therefore the sending end generator accelerates from the steady state angle δ_1 & δ_{s1} to angles δ_2 & δ_{s2} .
- when the fault clears the accelerating energy represented by area A_1 & A_{s1} .
- After fault clearing, the Transmitted electric power exceeds the Mechanical input power & therefore sending-end Machine decelerates.
- However a Balance b/w the accelerating & decelerating energies represented by areas A_1 , A_{s1} & A_2 , A_{s2} is reached at maximum angles δ_3 & δ_{s3} ^{swing}.
- The Margin of Transient stability represented by areas A_{Margin} & $A_{sMargin}$.
- Fig (a) & (b) clearly shows a substantial increase in the transient-stability Margin in the series Capacitive Compensation can provide by partial Cancellation of series Impedance of the ℓ_2 line.
- The increase in the transient stability Margin is proportional to the degree of series Compensation.

→ The practical Series Capacitive Compensation does not usually exceed 75% for a number of reasons, including load balancing with parallel paths, high fault current.

→ often the compensation is limited to less than 30% due to sub synchronous concerns.

→ without compensation the margin is very less.

→ with compensation the margin is high.

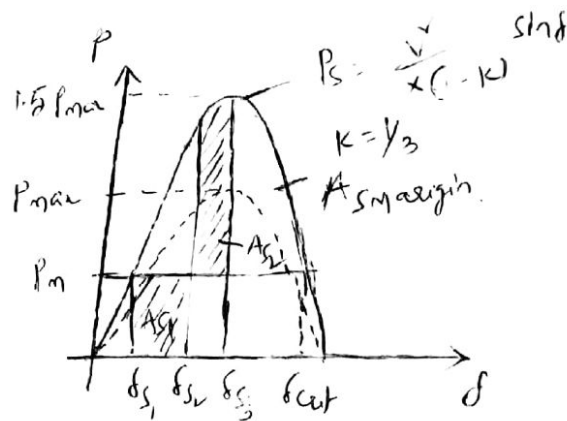
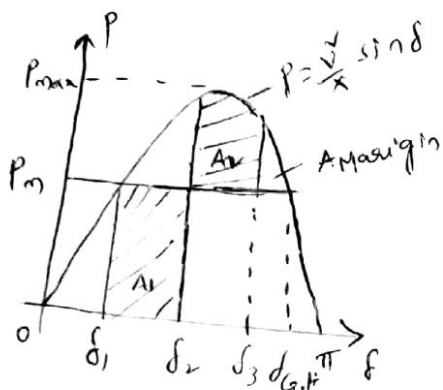


Fig - Equal area criterion to illustrate the Transient stability Margin for a Simple two Machine System (a) without compensation (b) with a series capacitor.

during fault:-

$$P_m > P_e \rightarrow \text{Machine accelerated}$$

(P_m constant, P_e decreases)

After fault:-

$$P_m < P_e \rightarrow \text{Machine decelerated}$$

(P_m constant, P_e increases)

Power Oscillation Damping:-

Power oscillation depends on δ , & also faults.

$$P = \frac{V_1 V_2}{X} \sin \delta$$

K = degree of series compensation

- Controlled series compensation can be applied effectively to damp power oscillations.
- When the rotationally oscillating generator accelerating and δ increases ($\frac{d\delta}{dt} > 0$), the electric power P_e must increase to compensate for the excess mechanical input power.
- When the generator decelerates and angle δ decreases ($\frac{d\delta}{dt} < 0$), the electric power must be decreased to balance the insufficient mechanical input power.

fig (a) shows the undamped & damped oscillations of angle δ around the steady-state value δ_0 .

- K is maximum when $\frac{d\delta}{dt} > 0$ & the ^{line} impedance is minimum, the transmitted line power is maximum.
- K is zero when $\frac{d\delta}{dt} < 0$ & the line impedance is maximum, the transmitted line power is minimum.

$$K = \frac{X_c}{X} \uparrow \rightarrow Z \downarrow \rightarrow V \uparrow \rightarrow P \uparrow$$

$$K = \frac{X_c}{X} \downarrow \rightarrow Z \uparrow \rightarrow V \downarrow \rightarrow P \downarrow$$

$\uparrow$ $\frac{d\delta}{dt} > 0$, $P_m > P_e$ during fault, accelerated

$\downarrow$ $\frac{d\delta}{dt} < 0$, $P_m < P_e$ post fault, decelerated

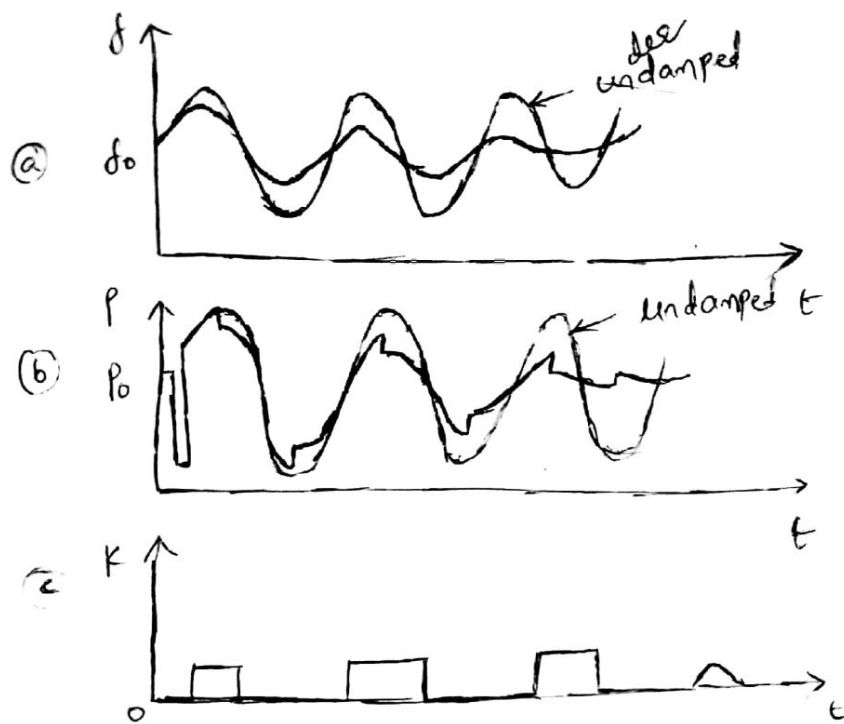


fig (a) generator angle (b) transmitted power (c) degree of series compensation.

fig. wave form illustrating power oscillation damping by controllable series compensation.

Functional requirements:-

- series Compensators is primarily applied to solve power flow problems.
- These problems may be related to the length of the line (d) the structure of the tr n/w.
- The length of the line can be shortened to meet power transmission requirements by fixed compensation of the line.
- Network structure related problems, which typically result in power flow unbalance, as well as power flow in parallel paths, loop flows.
- Series compensation can also be used to minimize the end voltage variations of radial lines & prevent voltage collapse.
- series compensation provides counteract to machine swings, transient stability, improvement of post-fault systems & highly effective in power oscillation Damping.
- structured & controlled series compensation can be applied with-out danger of subsynchronous resonance to achieve full utilization of tr lines.
- it can manages power flow over predefined paths, line loadings.
- series Compensators provide to meet above functional requirements, can be done by both Thyristor Controlled impedance type & Converter based, voltage source type compensators.

Variable Impedance test on Series Compensators:-

1) GTO Thyristor Controlled Series Capacitor (GSC):-

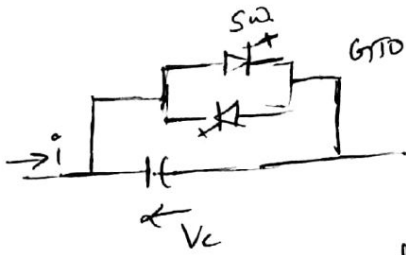


Fig:- GTO Controlled Series Capacitor.

→ It consists of a fixed capacitor in parallel with a GTO thyristor.

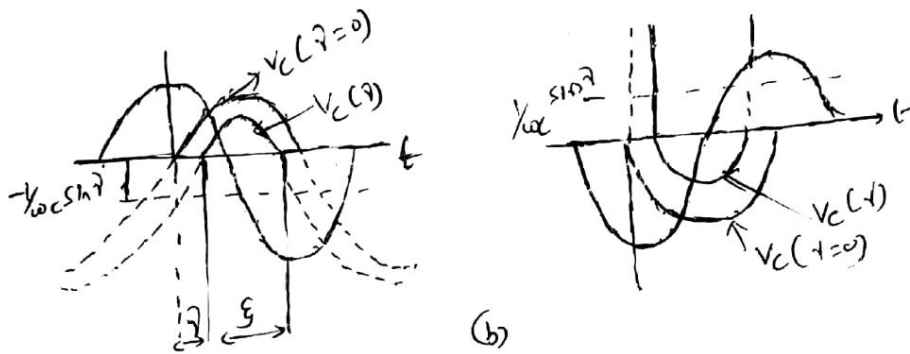
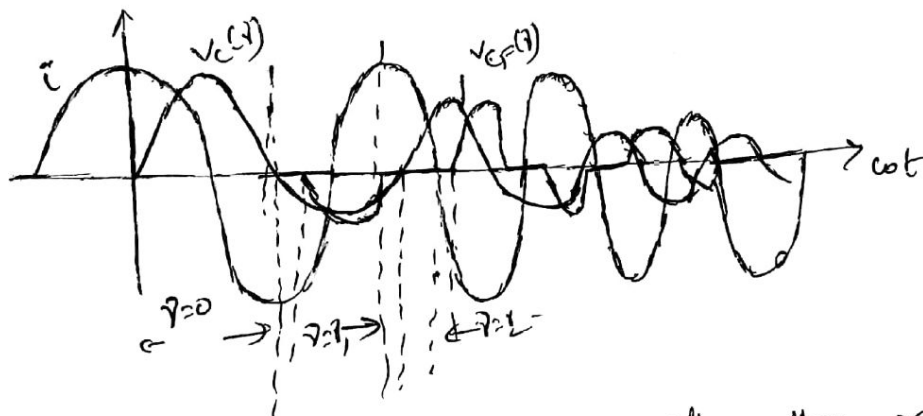


Fig:- principle of turn-off delay angle control.



(c) and attainable compensating voltage waveforms.

→ The objective of the GSC Controlled The voltage across the capacitor at a given line current i . when the GTO value ω is closed. voltage across the capacitor is zero. when the value is open V_c is maximum.

→ When the opening value is delayed by the angle ' γ ' with respect to the crest of the line current. (2)

The capacitor is expressed with defined line current $i(t) = I \cos \omega t$

$$\begin{aligned} V_c(t) &= \frac{1}{C} \int_0^{\omega t} i(t) dt \\ &= \frac{1}{C} \int_0^{\omega t} (I \sin \omega t) dt \\ &= \frac{I}{\omega C} (\sin \omega t - \sin \gamma) \end{aligned}$$

$$V_c(t) = \frac{I}{\omega C} \sin \gamma$$

$$V_{CF}(\gamma) = \frac{I}{\omega C} \left(1 - \frac{2}{\pi} \gamma - \frac{1}{\pi} \sin 2\gamma\right)$$

$$x_c(\gamma) = \frac{1}{\omega C} \left(1 - \frac{2}{\pi} \gamma - \frac{1}{\pi} \sin 2\gamma\right)$$

I is Amplitude of line current

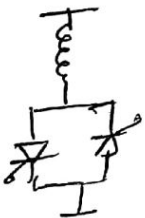
C = Capacitor of GTO Thyristor

ω = angular frequency of phase shift.

Duality b/w TCR & GCS:

TCR

- ① TCR is a switch in series with reactor



- ② TCR is supplied from a voltage source
- ③ TCR is stipulated to close a current zero

GCS

- ① GCS is a switch in shunt with capacitor



- ② GCS is supplied from current source.

- ③ The GCS is at voltage zero

④ TCR is controlled by a turn on delay angle (α) with respect to applied voltage, which defines the conduction interval of the value.

⑤ TCR controls current in a fixed inductor from a constant voltage source, by presenting a variable reactive admittance of the load to the source.

④ The GCS is controlled by a turn off delay (β) with respect to the peak of the current which defines the blocking interval of the value.

⑤ GCS control the voltage developed by a current source across a fixed capacitor. Thereby presenting variable reactive impedance to this source.

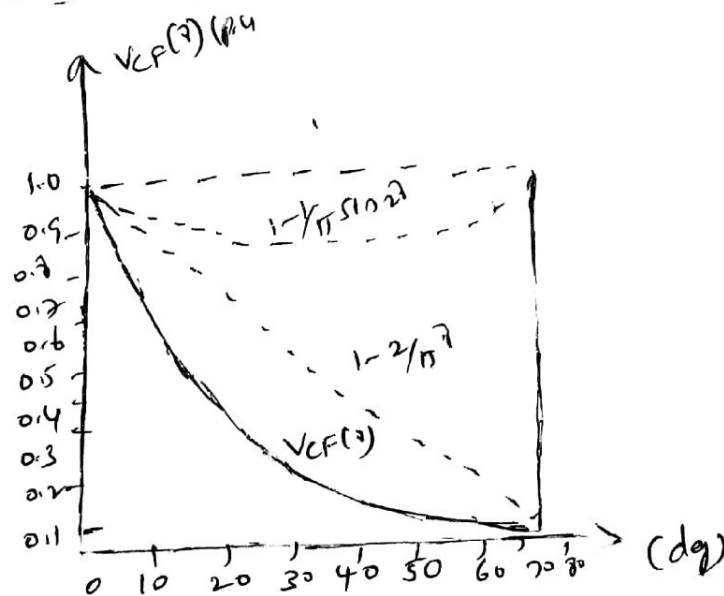


Fig: Fundamental component of the series capacitor voltage V_s , the turn off delay angle β

$$VCF(\beta) = \frac{1}{\pi} \left(1 - \frac{2}{\pi^2} - \frac{1}{\pi} \sin 2\beta \right)$$

Thyristor switched series capacitor (TSSC):-

→ it consists of number of capacitors, each shunted by an appropriately rated by pass value composed of a string of reverse parallel connected Thyristors in series.

The operating principle of TSSC is straight forward: The degree of series compensation is controlled in a step like manner by increasing or decreasing the no. of series capacitors inserted.

→ A capacitor is inserted by turning off, and is bypassed by turning on the corresponding thyristor value.

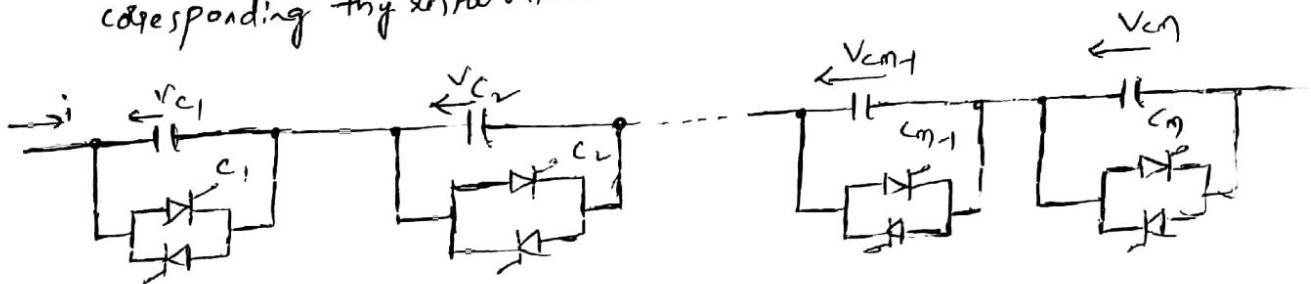


fig: Basic Thyristor-Switched Series Capacitor Scheme.

→ A Thyristor valve commutates naturally i.e. turns off when current crosses zero. Thus a capacitor can be inserted into the line by Thyristor valve only at the zero crossing of the line current.

→ Since the insertion takes place when line current zero. A full half cycle of the line current will charge the capacitor from 0 to maximum, and the opposite polarity half cycle of the line current will discharge it from its maximum to zero.

→ The TSSC can control the degree of series compensation by an inserting & bypassing series capacitor but it cannot change the natural characteristics of the classical series capacitor compensated line.

→ The basic $V-I$ characteristics of the TSSC with four series connected compensator modules operated to control the compensating voltage is shown.

→ The Average, rated Compensating voltage, $V_{Cmax} = 4X_C I_{min}$. The decreasing line current over a defined interval $I_{min} \leq I \leq I_{max}$.

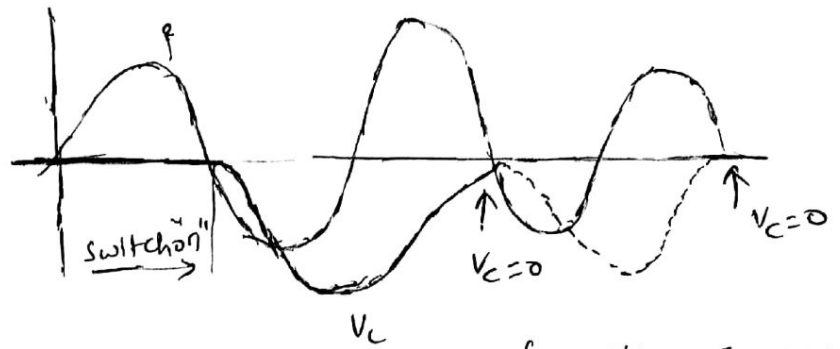
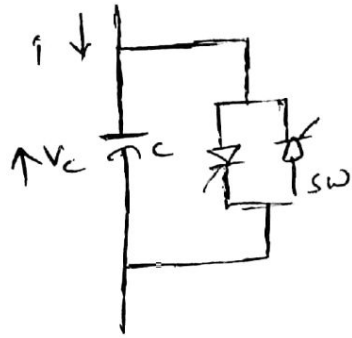


fig: illustration of capacitor offset voltage resulting from the restriction of inserting at zero line current.

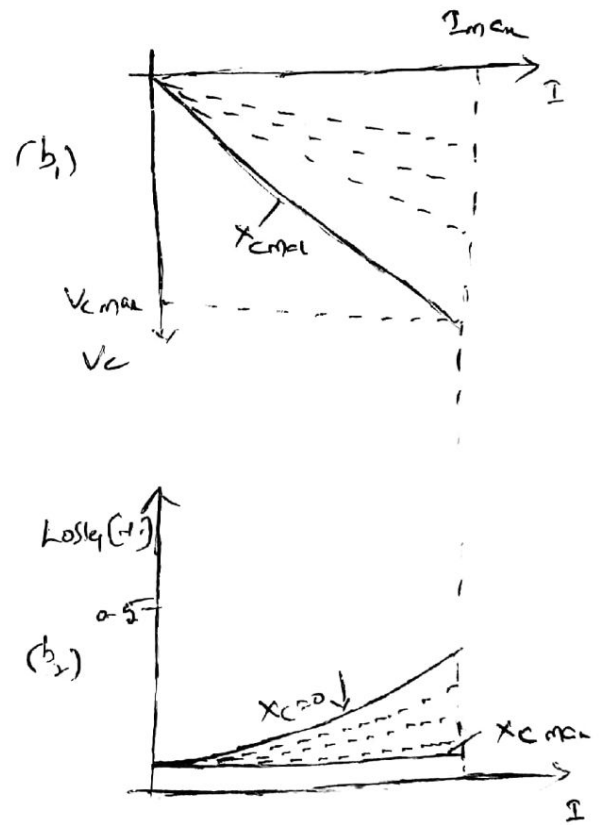
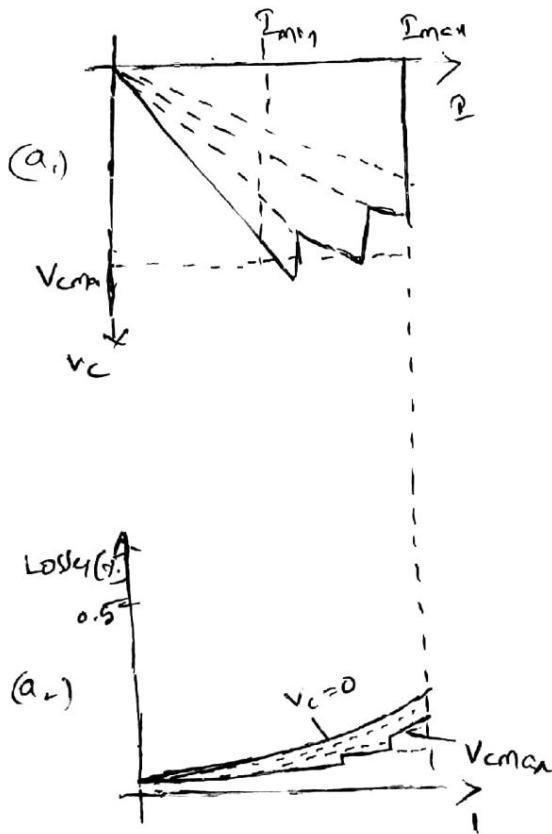
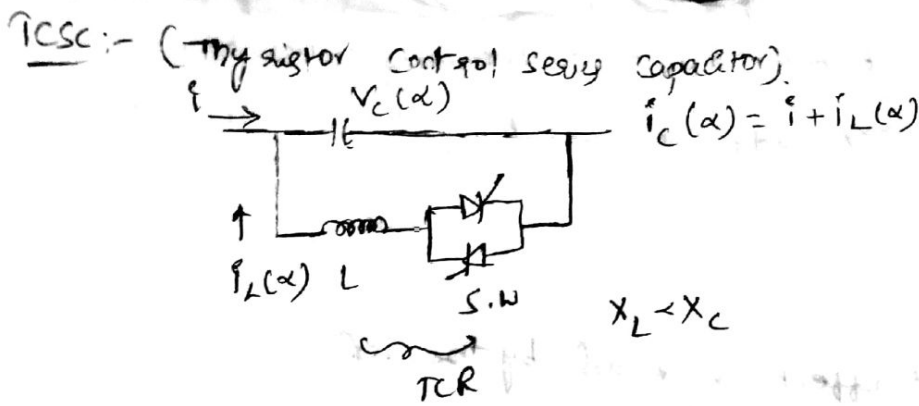


fig: $V-I$ characteristics of the SSC when operated in voltage control (a₁) and reactance control (b₁) mode, the associated loss vs. line current characteristics a₂ & b₂ respectively.



It consists of the series compensating capacitor shunted by a TCR

This arrangement is similar to structure of the TSSC. & the impedance of the reactor X_L is ~~smaller~~ smaller than that of X_C . It can be operated in an ON/OFF manner like the TSSC.

→ The basic idea of TCSC is to provide continuously variable capacitor by means of partially cancelling the effective compensating capacitor like the TCR.

→ Since the TCR is a continuously variable reactive impedance controllable by delay angle α . The steady state impedance of the TCSC is that of a parallel LC ckt.

→ It consists of a LC ckt and consisting of fixed capacitive impedance X_C & variable inductive impedance $X_L(\alpha)$

$$X_{TCSC}(\alpha) = \frac{X_C X_L(\alpha)}{X_L(\alpha) - X_C}$$

$$X_L(\alpha) = X_L \frac{\pi}{\pi - 2\alpha - \sin \alpha} \quad (X_L \leq X_L(\alpha) \leq \infty)$$

→ TCSC provides a tunable parallel LC ckt to the current. i.e. substantially a constant alternating current source. As the impedance of the controlled reactor ($X_L(\alpha)$) is varied from its maximum to its minimum, the TCSC increases its minimum capacitive impedance

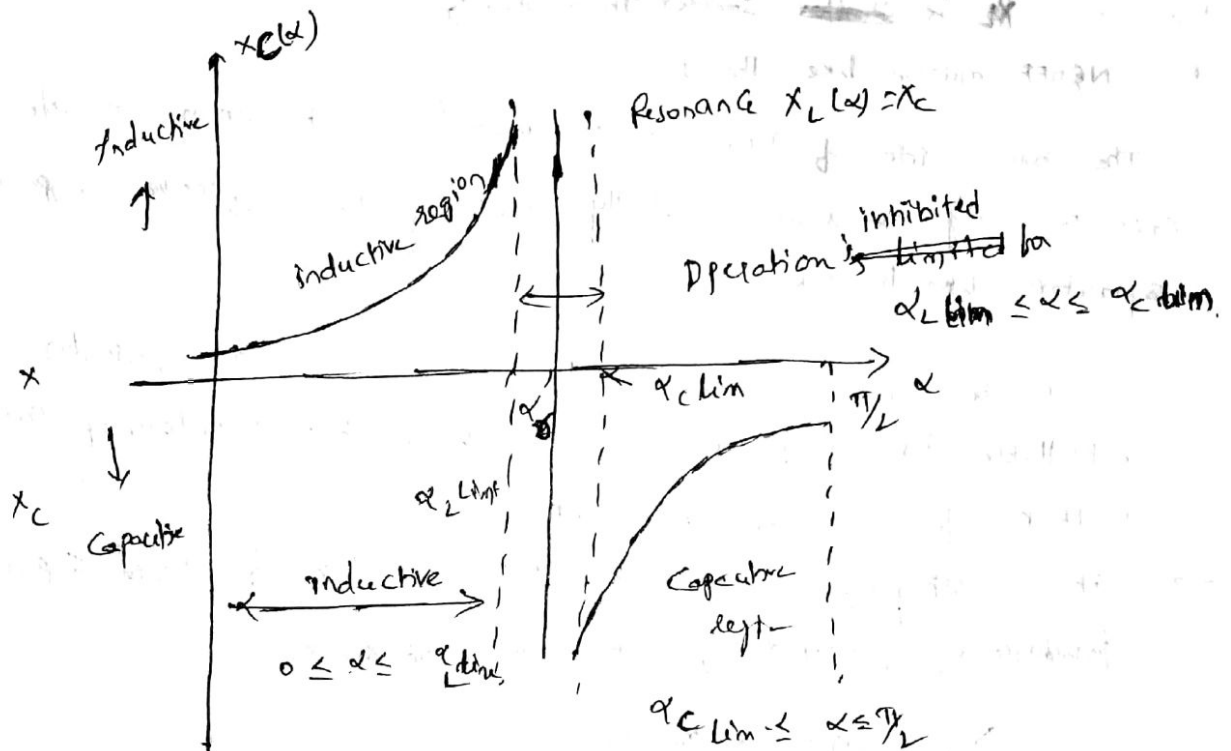
$$X_{C, TCSC, min} = X_C = \frac{1}{\omega C} \text{ until parallel resonance}$$

→ $X_{TSC}(\omega)$ Theoretical becomes infinite. decreasing $X_L(\omega)$ for the impedance of $TSC(\omega)$ becomes inductive reaching its minimum value of

$$\frac{X_L X_C}{X_L - X_C} \text{ at } \alpha = 0$$

→ where the capacitor is effect by passel by the TSC.

→ Therefore usually, TSC provide in which the impedance of the Reactor X_L is smaller than that of the X_C .



Here TSC has two operating regions around the tuned circuit resonance

- ① If the $\alpha_{C \text{ limit}} \leq \alpha \leq \pi/2$ range where $X_{TSC}(\omega)$ is capacitive
- ② & The other $0 \leq \alpha \leq \alpha_{L \text{ limit}}$ range $X_{TSC}(\omega)$ is inductive

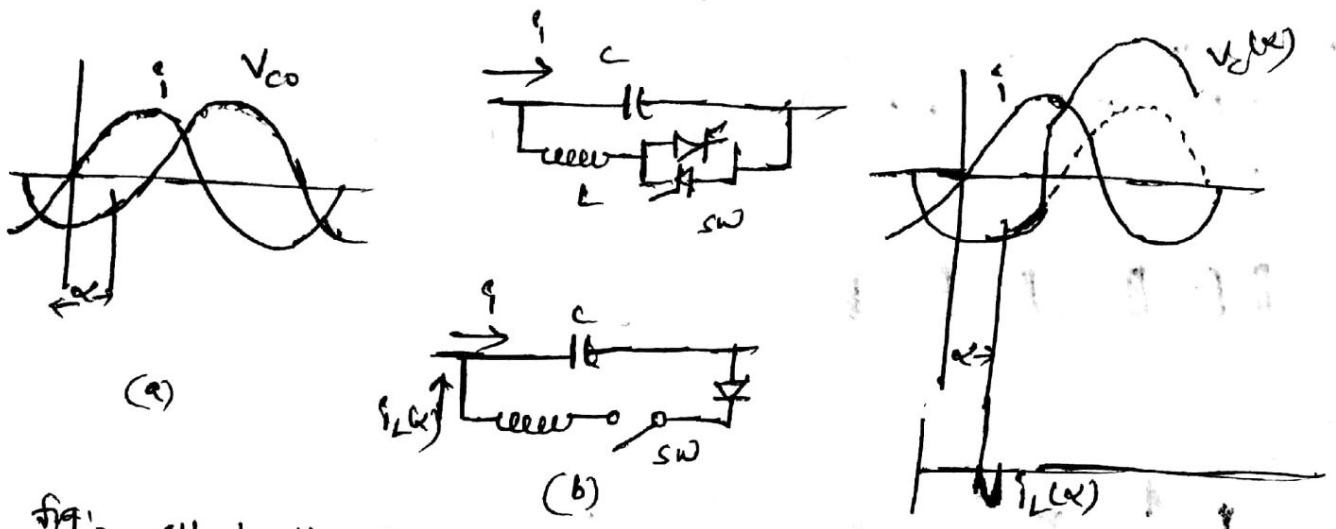


Fig. 1. Illustration of capacitor voltage reversal by TCR (a)

a) line current & corresponding capacitor voltage b) equivalent ckt of TCR at the firing instant α , c) the resulting capacitor voltage & related TCR current.

→ In fig (a) Assume that the thyristor valve, SW , is initially open & the prevailing line current & produced voltage V_{co} across the fixed series compensating capacitor

→ Suppose that TCR is to be turned on at α , measured from the negative peak of the capacitor voltage. At this instant of turn-on, the capacitor voltage is negative, the line current is positive, & the charging the capacitor in positive direction.

→ During the resonant half cycle of the LC ckt formed by the switch closing. $(X_L < X_C)$. The resonant charge reversal produces a dc offset for the next half cycle of the capacitor voltage.

→ The Reversal of the capacitor voltage is clearly the key to the control of the TCR.

→ The time duration of the voltage reversal is dependent primarily on X_L/X_C . But also on magnitude of the line current.

→ Small X_L produces large short-duration current pulses in the thyristor valve, increase of its current rating & its voltage rating.

→ X_L/X_C ratio is used 0.133.

→ In practice the TCR would likely be in 0.1 to 0.3 range.

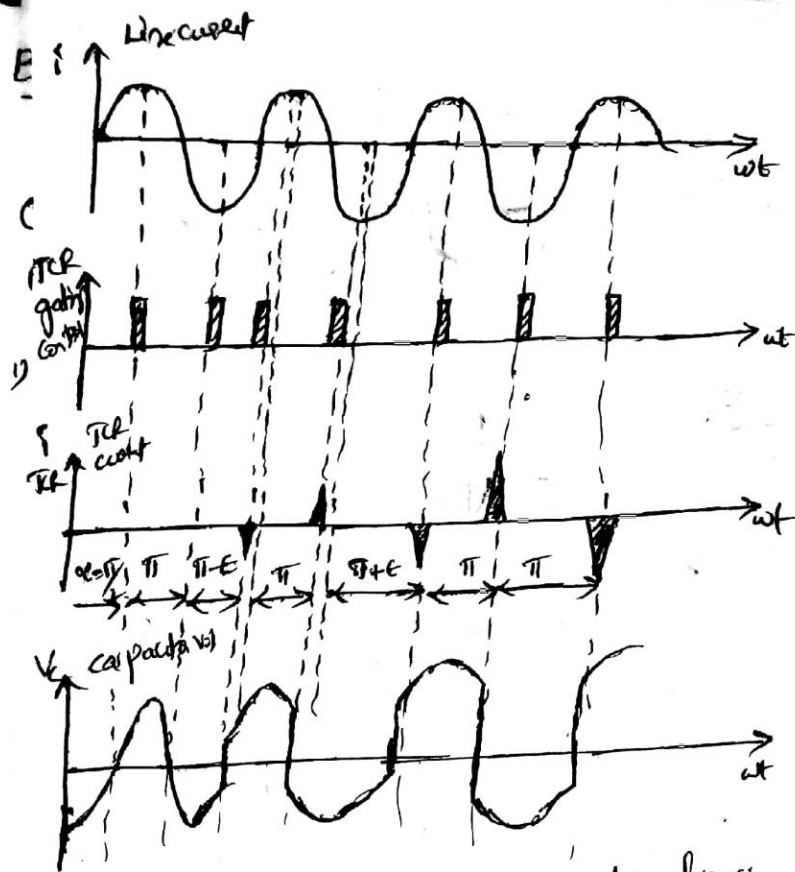


Fig: Increase of the capacitor voltage by advancing the voltage reversal from $\alpha = \pi$ to $\alpha = \pi - \epsilon$

→ The compensating voltage V_C line current $(V-I)$ characteristics of basic TSC system

→ In the capacitive region the minimum delay angle α_{lim} , sets the limit of the maximum compensating voltage up to the value of line current (I_{min}) at the maximum rated voltage V_{max} ,

→ In the inductive region, the maximum delay angle α_{lim} , limits the voltage at low line current & the maximum rated current at high line current.

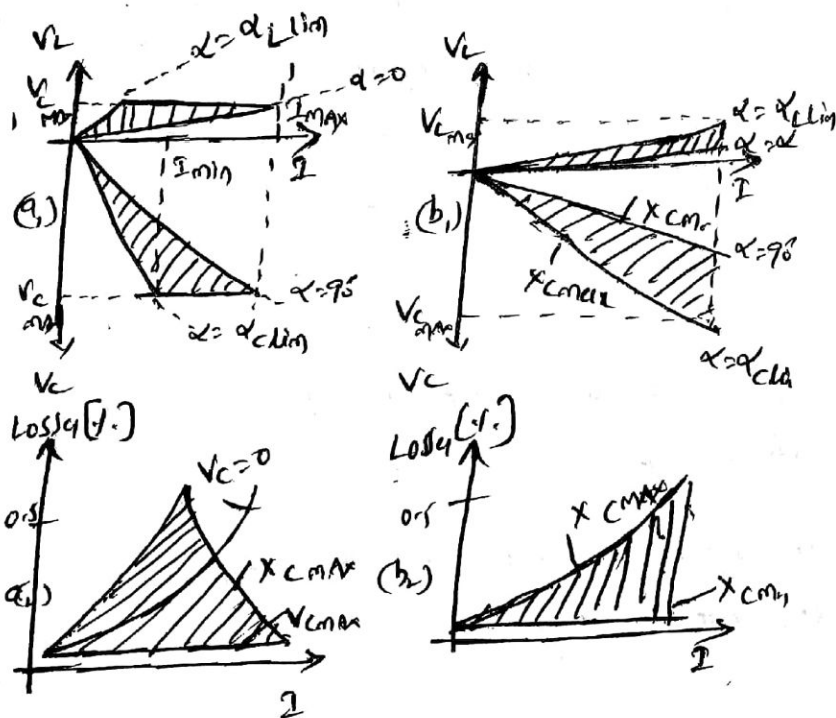


Fig:- $V-I$ characteristics of the TSC when operated in voltage control (a) & reactance control (b) mode, and the associated loss vs line current characteristics (c) & (d) respectively.

Bc Switching Converter type series Compensators:-

SVS:-

$$V = V \sin(\phi + \beta)$$

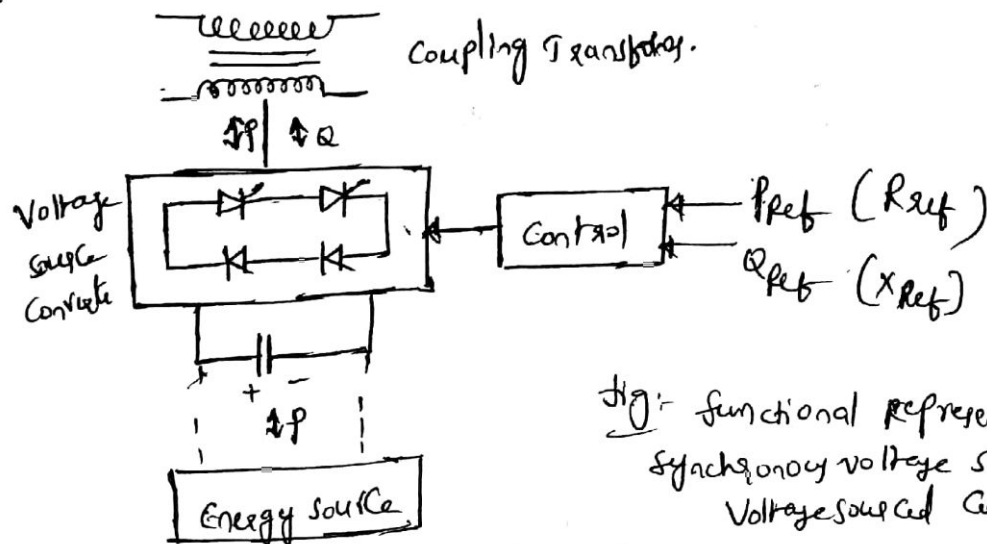


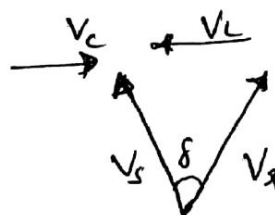
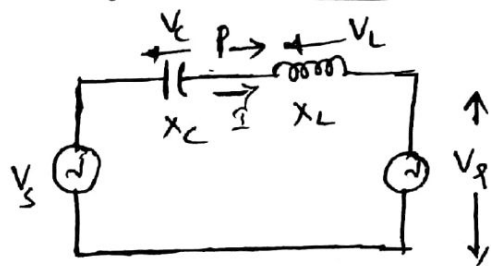
Fig:- functional representation of the synchronous voltage source based on a voltage source converter.

- We can maintain control voltage by varying inductive / capacitive.
- SVS can be operated with a relatively small dc storage capacitor like a SVC. to exchange reactive power in AC system @ with an external dc power supply like a static generator. with an energy storage device to also exchange independently controllable real power.
- SVS shown in figure. references Q_{ref} & P_{ref} define the amplitude 'P' & phase angle (ϕ) of the output generated voltage necessary to exchange the desired active & reactive power at the AC output.
- If the SVS operated strictly for reactive power exchange V_{ref} set to zero.
- The function of the series capacitor is to produce voltage at the fundamental AC system frequency in co-ordinated with the I_L line current.
- In order to increase the voltage across the inductive line impedance. increase the line current & transmit the power.

SSSC:-

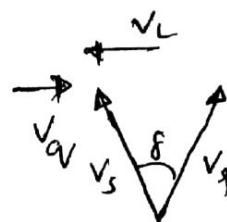
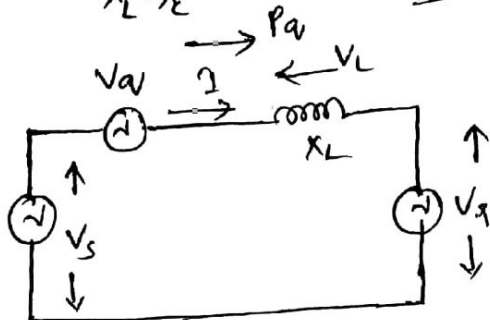
- The SVS can be able to maintain the constant compensating voltage the presence of variable line current.
- The injected voltage $\vec{V}_q', \vec{V}_c'$ decrease the voltage across inductance line impedance.

Static synchronous series compensator :- (SSSC)



$$P = \frac{V}{X_L - X_c} \sin \delta$$

fig: Basic two machine $V_s = V_r = V$ system with a series capacitor compensated line and associated phasor diagram.



$$P_q = \frac{V}{X_L - \frac{V_q}{I}} \sin \delta$$

fig: Basic two machine system with a synchronous voltage source replacing the series capacitor

V_q = synchronous voltage source

$$V_c = -jX_c I = V_q$$

→ The phasor diagram shows that but a given line current

The voltage across the series capacitor forces the opposite polarity voltage across the series line reactance. to increase by the magnitude of the capacitor voltage.

→ The series capacitor compensation works by increasing the voltage across the impedance of the given physical line which in turn increases the corresponding line current but a transmitted power may be consistent to consider series capacitive compensation by a means of reducing line impedance.

→ The same steady state power transmission can be established the series compensation is provided by a synchronous AC voltage source shown in fig. whose op matches the voltage of series capacitor.

$$V_q = V_c = -jI X_c = -jK X I, \quad K = \frac{X_c}{X}; \quad K = \text{degree of series compensation}$$

V_c = The injected compensated voltage

I = The line current

X_c = The reactance of the series capacitor

X = line reactance.

Transmitted power Vs Transmission Angle characteristics:- (SSSC)

- The SSSC injects the compensating voltage in series with line irrespective of the line current.
- The Transmitted power P_T versus the transmission angle δ relation therefore becomes a parametric function of the injected voltage V_q .

It can be expressed for two machine system

$$P = \frac{V}{X} \sin \delta + \frac{V}{X} V_q \cos \frac{\delta}{2}$$

- The normalized power P Vs angle δ plots as a parametric function of V_q are shown in fig (a) $V_q = \pm 0.353$ & ± 0.707
- In fig (b) the parametric function of the degree of series compensation K . $\delta = 90^\circ$, $K = 1/5$ when $V_q = 0.353$ & $K = 1/3$ when $V_q = 0.707$.
- Comparison of the corresponding plots shown in fig (a) & fig (b). clearly shows that the series capacitor increases the Transmitted power by fixed percentage of that transmitted by the uncompensated line at given δ .
- The SSSC can increase it by a fraction of the max power Transmission by the uncompensated line, independent of δ , in the range of $0 \leq \delta \leq \pi/2$.

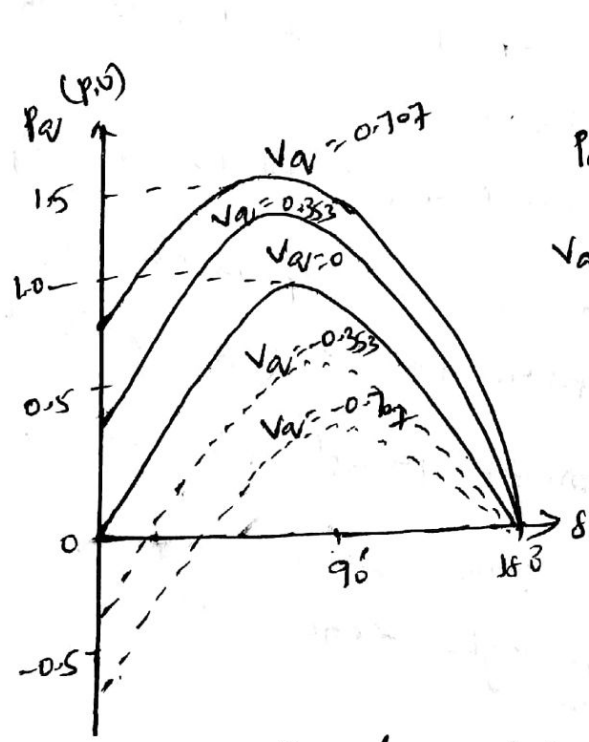


Fig (a) P_T power Vs δ Angle provided by the SSSC as a parametric function of the series compensating voltage

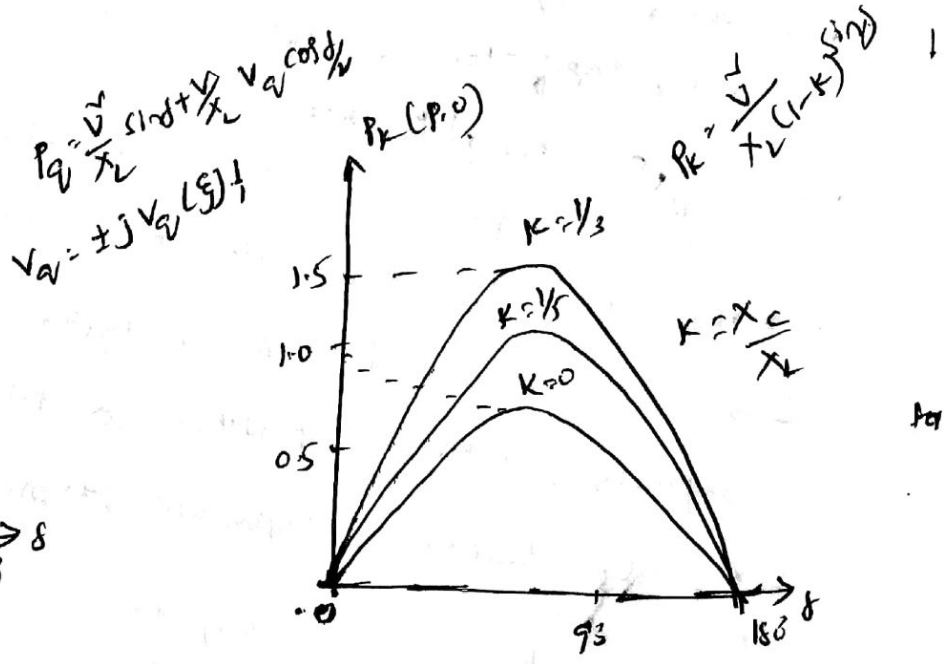


Fig (b) P_T power Vs δ angle attainable with series capacitive compensation as a parametric function of the degree of compensation

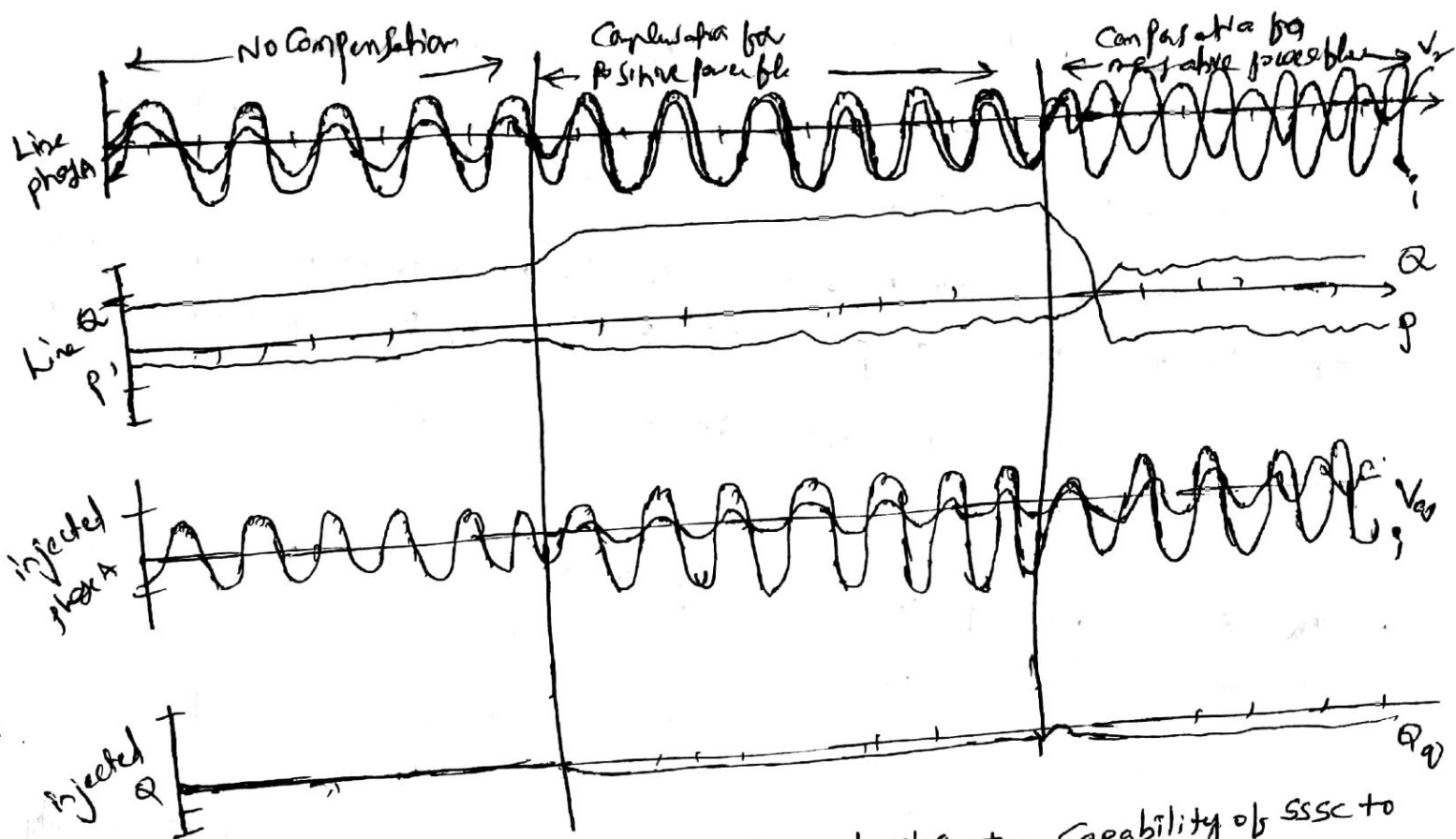


Fig (C) oscillograms from TNA simulation showing the Capability of SSSC to control AC voltage as well as reverse real power flow.

- The SSSC can Decrease, as well as increase the power flow to same degree simply by reversing the polarity of the injected AC voltage.
- The reversed (180° phase shifted) voltage adds directly to the reactive voltage drop of the line if the reactive line impedance was increased.
- In Fig (C) the plots shown at $\delta = 10^\circ$, the line current I together with the receiving end voltage $V_1 = V_2$ for phase A,
- The Tx power together with the reactive power supplied by receiving end
- SSSC exchanged with AC system for no compensation ($V_q = 0$)
- purely reactive compensation for positive power flow ($V_q = I X \pm |V_1 - V_2|$)
- purely reactive compensation for negative power flow ($V_q = I X + |V_1 - V_2|$)
- SSSC has excellent response time & that the Transition from positive to negative power flow through zero voltage injection is perfectly smooth & continuous.

Basic operating Control scheme of SSSC:-

we have two types of control schemes

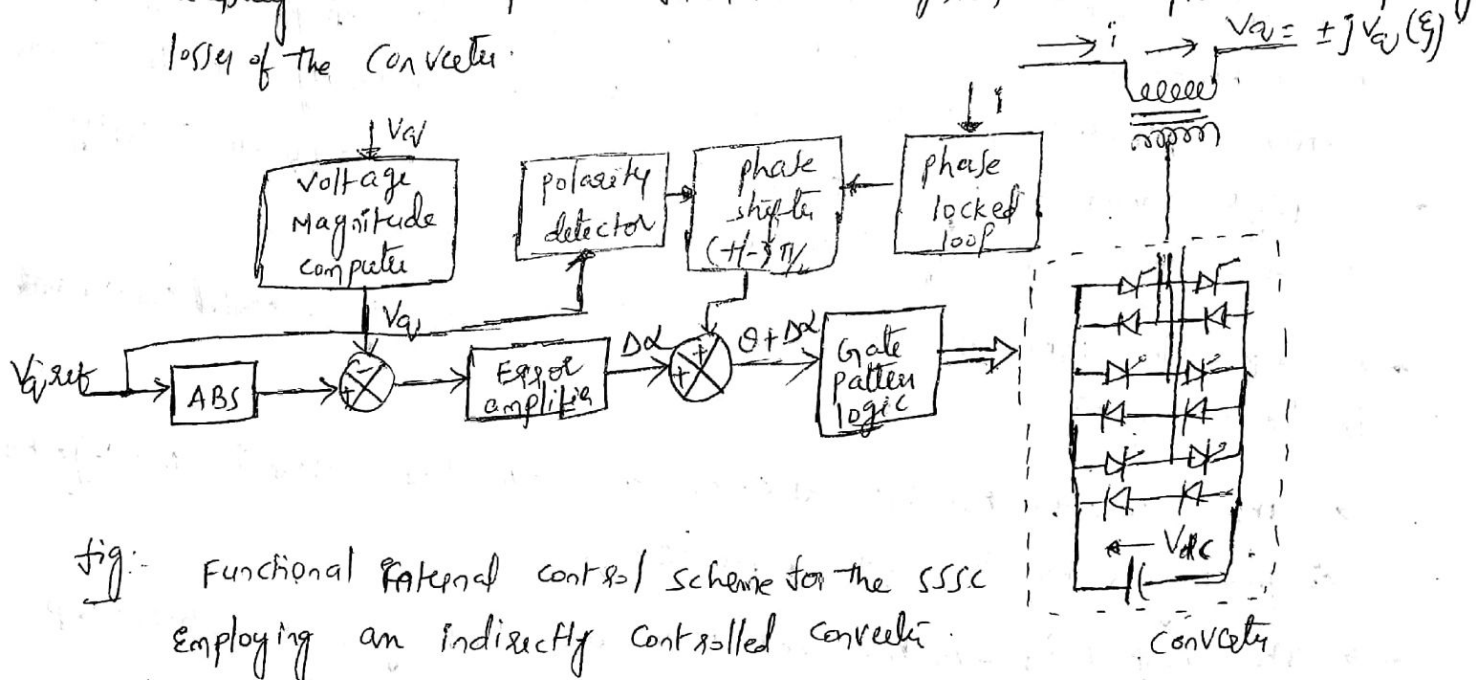
- ① Internal control scheme
- ② External control scheme.

1) Internal control scheme:-

From the stand point of output voltage control, Converters may be categorized as "directly & indirectly" controlled.

- For directly controlled converters both the angular position & the magnitude of the output voltage are controllable by appropriate value. (On & off gating).
- For indirectly controlled converter only the angular position of the output voltage is controllable by value gating: the magnitude remains proportional to the dc terminal voltage.
- The control method of maintaining a quadrature relationship b/w the instantaneous converter voltage & line current vector, to provide reactive series compensation, can be implemented with an indirectly controlled converter.
- High-power directly controlled converters are more difficult & costly to implement than indirectly controlled converters.
- A possible internal control scheme for the indirectly controlled SSSC converter is shown fig (a)
- The inputs to the internal control are: the line current i , the injected compensating voltage V_q , & the reference V_q .
- The control is synchronized to the line current by a phase locked loop which, after a $+\pi/2$ (or) $-\pi/2$ phase shift, provides the basic synchronizing signal θ .
- The phase shifter is operated from the output of a polarity detector which determines whether reference V_q is positive (capacitive) (or) negative (inductive).
- The compensating voltage V_q is controlled by a simple closed loop. the absolute value of reference V_q is compared to the measured magnitude of the injected voltage V_q & the amplitude difference is added, as a correction angle $\Delta\alpha$, to the synchronizing signal θ .

- Depending on the polarity of $\Delta\alpha$, angle θ , & consequently the converter gate drive signals, will be advanced (a) retarded & thereby, the compensating V_q will be shifted with respect to the prevailing line current from its original $+\pi/2$ (a) $-\pi/2$ phase position.
- The phase shift will cause the converter to absorb real power from the ac system for the dc capacitor (a) vice versa, supply that to the ac system from the dc capacitor.
- The voltage of the dc capacitor will increase (a) decrease, causing a corresponding change in the magnitude of compensating voltage.
- Once the desired magnitude of V_q is reached, the substantially quadrature relationship b/w the line current & compensating voltage gets reestablished with only a remaining small, steady angular difference necessary to absorb power from the ac system to replenish the operating losses of the converter.



SSR: that will arise in all fact applications. The basic reason that all high speed, high power controllers have potential of enhancing (a) degrading subsynchronous phenomenon.

- SSR may be avoided by series capacitor compensation & also high-speed reclosing of faulted lines with (a) without series capacitor compensation.

External control schemes:-

- variable impedance type & synchronous voltage source compensators have different operating principles and exhibit differing compensation & performance characteristics.
- The external control that defines the functional operation of the compensator & derives the reference input for it can basically be the same for all types of series compensator.
- The improvement of transient & dynamic stability, in some cases, for the damping of subsynchronous oscillation may be included in the external control of the series compensator.
- Transient stability enhancement may be applied in response to a major disturbance.
- power oscillations typically take place in the 0.2-2 Hz frequency range. For effective damping, the external control has to provide a variable reference that will modulate the output of the series compensator so as to increase the transmitted power over the line when the associated generators are accelerating and to decrease it when the generators are decelerating.
- A possible structure of the external control is illustrated shown in figure.
- The main power flow control is executed by a closed loop, which is operated from one of the selectable references $X_{q,ref}(\omega)$, $V_{q,ref}(\omega)$, $I_{ref}(\omega)$, P_{ref} .
- The corresponding network variable ($X_q(\omega)$, $V_q(\omega)$, $I(\omega, p)$) is derived by the voltage & current processor & compared to the selected reference.
- The amplified error at the output of the PI Controller provides the reference, $X_q(\omega)$, V_q for the internal control.
- The auxiliary control signals to improve transient & dynamic stability, & to damp subsynchronous oscillations, are derived from the relevant system variables.

→ when available (a) synthesized from locally measurable voltage & current, by the power oscillation damping, transient stability enhancement & subsynchronous oscillation Damping auxiliary control circuits & fed directly, as reference, to the internal control.

→ These auxiliary control circuits may be control (a) inhibit the operation of the main power flow regulation loop in order to avoid contradictory reference requirements & maintain an operational set point appropriate under the particular system contingency.

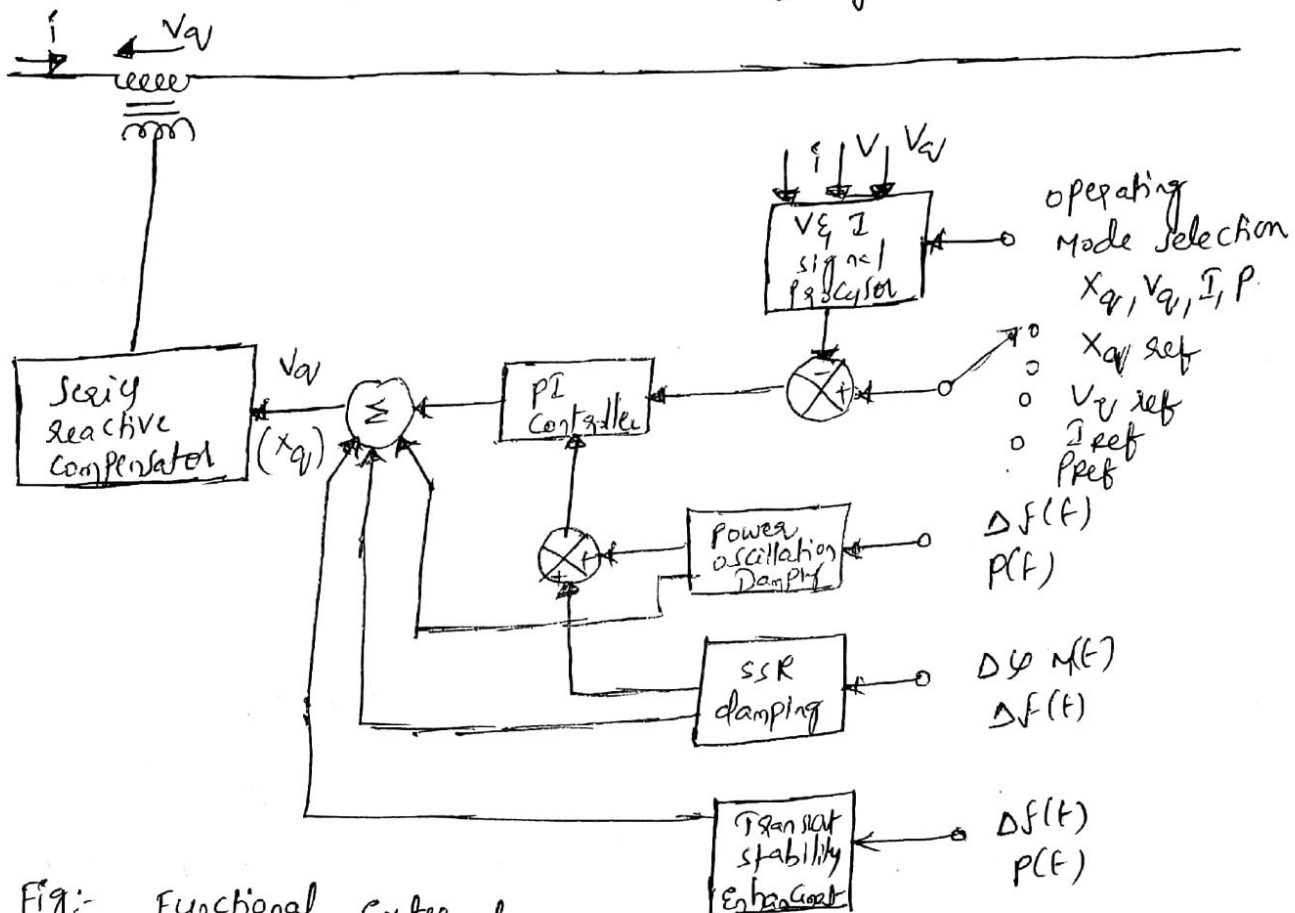


Fig:- Functional External Control scheme for the SSSC.

- Converter 2 provides the main function of the UPFC by injecting a ⁽²⁾ voltage V_{pv} with controllable magnitude V_{pv} & phase angle ϕ in series with the line via an insertion transformer.
- The line current flows through this voltage source resulting in reactive & real power exchange b/w it and the ac system.
- The reactive power exchanged at the ac terminal is generated internally by the converter.
- The real power exchanged at the ac terminal is converted into dc power which appears at the dc link as a positive or negative real power demand.
- The basic function of Converter 1 is to supply (or) absorb the real power demanded by converter 2 at the common dc link to support the real power exchange resulting from the series voltage injection.
- In addition to the real power need of Converter 2, Converter 1 can also generate (or) absorb controllable reactive power, & thus by provide shunt reactive compensation for the line.
- It is important to note that whereas there is a closed direct path for the real power negotiated by the action of series voltage injection through converters 1 & 2 back to the line,
- The converter 1 can be operated at a unity power factor (or) be controlled to have a reactive exchange with the line independent of the reactive power exchanged by converter 2.
- obviously, there can be no reactive power flow through the UPFC dc link.

Independent Real & Reactive power flow Control:-

In order to investigate the capability of the UPFC to control real & reactive power flow in the transmission line shown in fig (a)

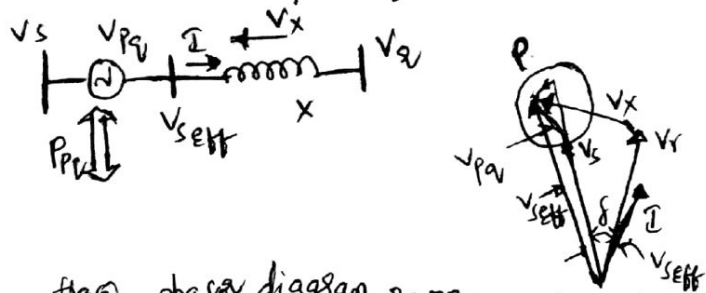


fig (a) phasor diagram representation of UPFC.

- Let it first be assumed that the injected compensating voltage, V_{pq} , is zero.
- Then the original elementary two machine system with sending end voltage V_s , receiving end voltage V_r , transmission angle δ , & line impedance X is restored.
- The normalized transmitted power, $P_o(\delta) = \left\{ \frac{V_s V_r}{X} \right\} \sin \delta = \sin \delta \rightarrow ①$
- The Normalized Reactive power, $Q_o(\delta) = \left\{ \frac{V_s V_r}{X} \right\} (1 - \cos \delta) = 1 - \cos \delta = Q_{os}(\delta) = -Q_{or}(\delta) \rightarrow ②$
- The Relationship b/w $P_o(\delta)$ & $Q_o(\delta)$ can be expressed as with $\frac{V_s V_r}{X} = 1$

$$Q_{or}(\delta) = -1 - \sqrt{1 - P_o(\delta)^2} \rightarrow ③$$

$$\{Q_{or}(\delta) + 1\}^2 + P_o(\delta)^2 = 1 \rightarrow ④$$

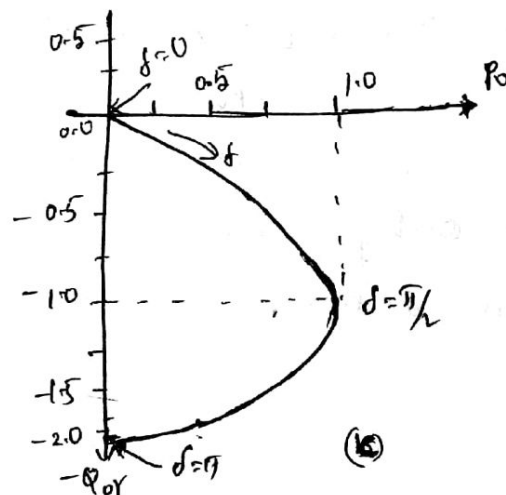
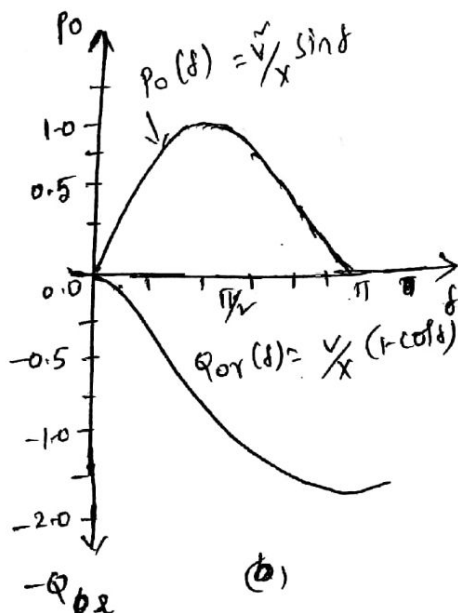


fig (b) Transmittable real power P_o & receiving end reactive power demand Q_{or} vs transmission angle δ of a two-machine system (a) and the corresponding Q_{or} vs P_o loci (b).

The Equation (4) describes a circle with a radius of 1.0 around the center defined by coordinates $p=0$ & $q_r=-1$ in a $\{q_r, p\}$ plane, as illustrated for positive values of P in fig (1) (b).

→ Ex:- at $\delta=0$, $P_0=0$ & $Q_{or}=0$; at $\delta=30^\circ$, $P_0=0.5$ & $Q_{or}=-0.134$; at $\delta=90^\circ$, $P_0=1.0$ & $Q_{or}=-1.0$ etc.

→ when $V_s=V_r=V$, The Boundary circle can be described by the following Equation

$$\{p(\delta, P) - P_0(\delta)\}^2 + \{q_r(\delta, P) - Q_{or}(\delta)\}^2 = \left\{ \frac{V V_{pmax}}{x} \right\}^2 \rightarrow (5)$$

→ The circular control regions defined by Eq (5) are shown in fig (2) (a) to (d).

for $V=1.0$, $V_{pmax}=0.5$, & $x=1.0$ (per unit) P.U. values).

→ The Transmission Angle $\delta=0^\circ, 30^\circ, 60^\circ$ & 90° . In other words, The center of the control regions are defined by the corresponding $P_0(\delta)$, $Q_{or}(\delta)$ coordinates at angles $\delta=0, 30^\circ, 60^\circ$ & 90° in the $\{q_r, p\}$ plane.

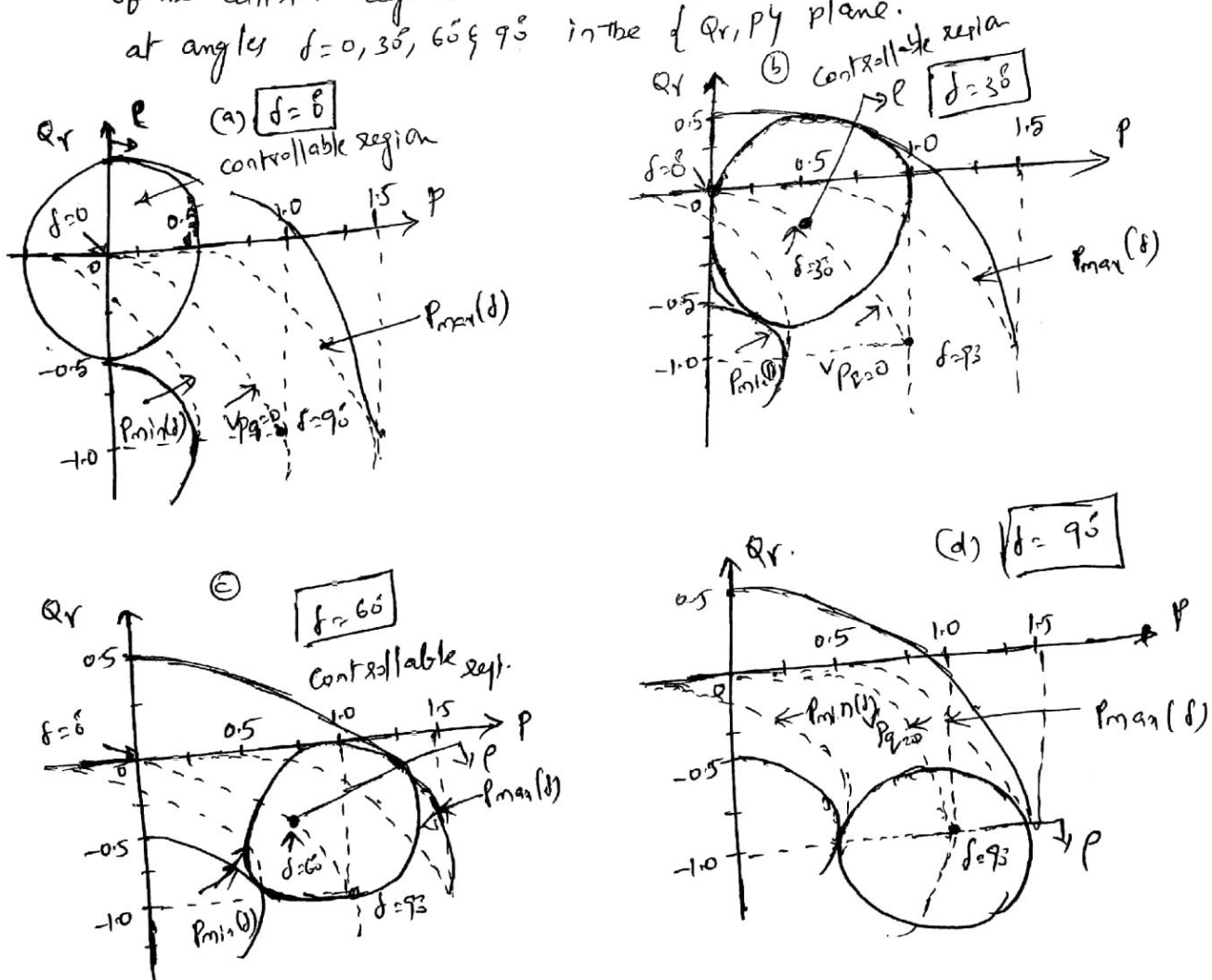


fig (2):- Control region of the attainable real power P & receiving end reactive power demand q_r with UPFC-controlled transmission line at $\delta=0$ (a) $\delta=30^\circ$ (b) $\delta=60^\circ$ (c) $\delta=90^\circ$ (d).

- fig 2 illustrates the case when the transmission angle ($\delta = 0$) with V_p , P , Q_r & (δ & Q_s) are all zero, i.e. the system is at standstill at the origin of the Q_r, P co-ordinates.
- The voltage rotates a full revolution ($0 \leq \rho \leq 360^\circ$) with its max magnitude V_{pmax} .
- Similar control characteristics for real power P & the reactive power Q_r can be observed at angles $\delta = 30^\circ, 60^\circ$ & 90° is shown in fig 2 (b), (c) & (d).
- The reactive power can actually be controlled with respect to the voltage selected at any point of the line.
- fig 2 (a) to (d) clearly demonstrates that the UPFC, with its unique capability to control independently the real & reactive power flow at any transmission angle..

Control structure:-

The UPFC Control system may be divided functionally into internal control & Functional operation control.

- The internal control operate the two converters so as to produce the command series injected voltage & draw the desired shunt reactive current.
- The internal controls provide gating signals to the converter valves so that the converter output voltages will properly respond to the internal reference variables, i_{pref} , i_{qref} & $\tilde{V}_{pqref}$, in advance the basic control structure shown in fig ①.
- As can be observed, the series converter responds directly & independently to the demand for series voltage vector injection.
- changes in series voltage vector, $\tilde{V}_{pq}$, can therefore be affected virtually instantaneously.
- The shunt converter operates under a closed loop current control structure whereby shunt real & reactive power components are independently controlled.
- The shunt reactive power responds directly to an input demand.
- The shunt real power dictated by another control loop that acts to maintain a preset voltage level on the dc link.

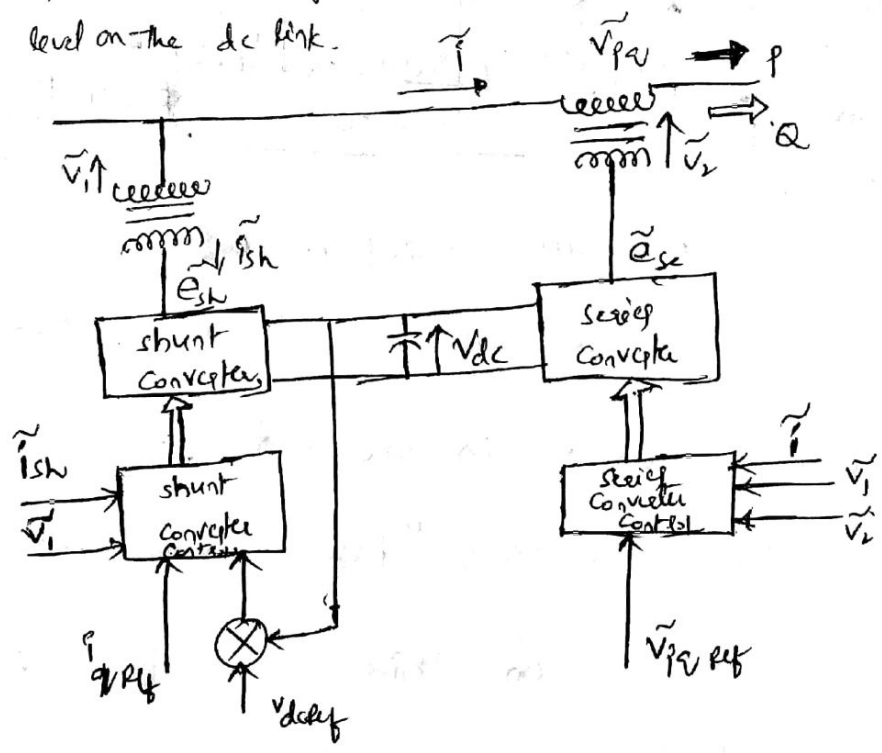


fig ① Basic UPFC control scheme.

- The External & Functional operation Control defines the functional operating mode of UPFC & is responsible for generating the internal references, $\bar{V}_{pcref}$ & $\bar{V}_{scref}$ for series & shunt compensation to meet the demands of the Tx system.
- Fig 2 shows that the capability of unrestricted series voltage injection together with independently controllable reactive power exchange offered by the circuit structure of two back-to-back converters, several operating & control modes for the UPFC.

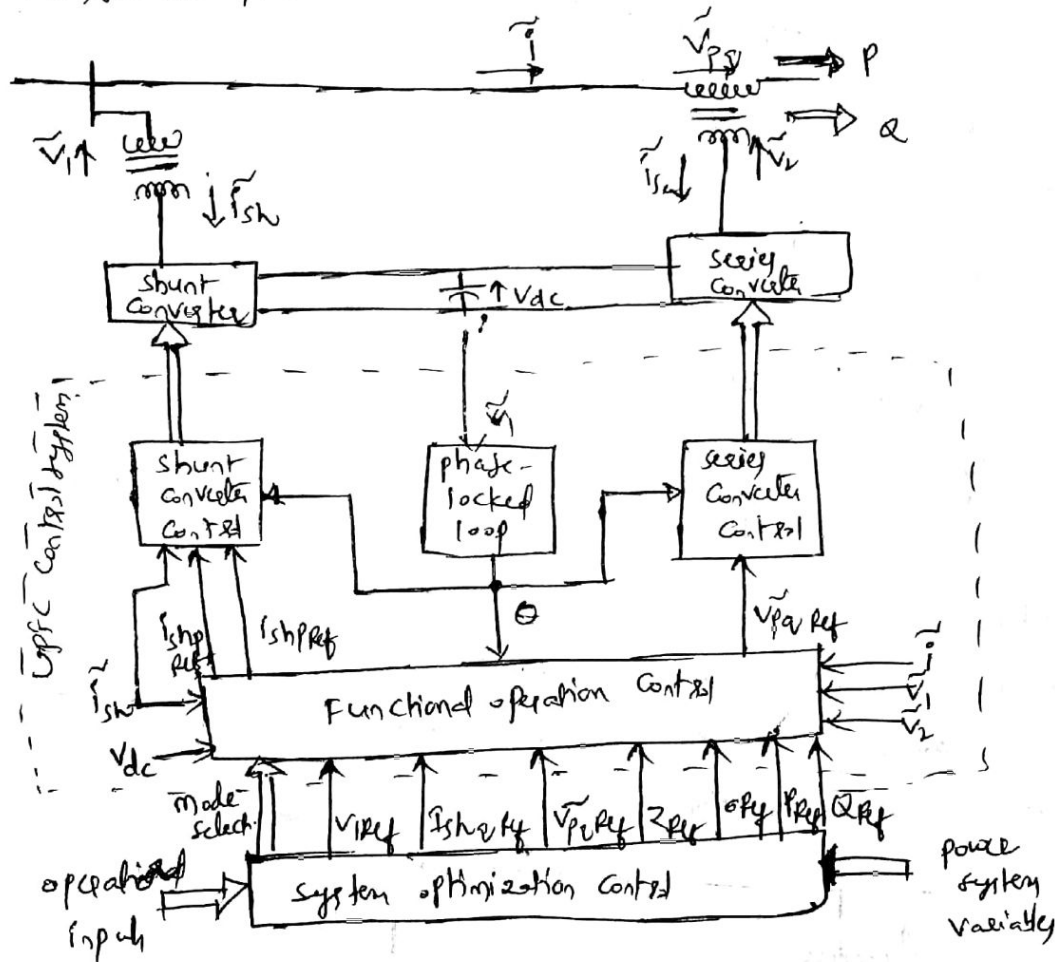


Fig 2 overall upfc control structure.

Function control of the shunt converter:-

- ⇒ The shunt converter is operated so as to draw a controlled current " I_{sh} " from the line.
- ⇒ One component of this current is " I_{shp} " is automatically determined by the requirement to balance the real power of the series converter.

5
The other current component " i_{shq} " is reactive and can be set to any desired reference level inductive (or) capacitive within the capability of the converter.

i) Reactive power control mode

ii) Automatic voltage control

Functional control of the series converter:-

$\Rightarrow$ It controls the magnitude angle of the voltage vector $\overline{V_{pq}}$ injected with the line.

$\Rightarrow$ This voltage injection is directly (or) indirectly always intended to influence the flow of the power on the line. However " V_{pq} " dependent on the following operating mode.

i) Direct voltage control mode

ii) Bus voltage regulation & control mode

iii) Linear impedance compensation mode

iv) phase angle regulation mode

v) Automatic power flow control mode