SPINTRONIC TECHNOLOGY & ADVANCE RESEARCH

LECTURE NOTE ON

FLEXIBLE AC TRANSMISSION SYSTEM

SEMESTER-7^{TH}

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

By:Prof. Brahmananda Das

FLEXIBLE AC TRANSMISSION SYSTEM (3-0-0)

MODULE-I (12 Lectures) FACTS concept and General System Considerations: Transmission Interconnections, Flow of Power in an AC System, What limits the Loading Capability, Power Flow and Dynamic Stability Considerations of a Transmission Interconnection, Relative Importance of Controllable Parameters, Basic Types of FACTS Controllers, Basic Description and Definitions of FACTS Controllers. Static Shunt Compensation: Objectives of Shunt Compensation, Methods of Controllable VAR Generation, Static VAR Compensators, SVC and STATCOM. (Chapter-1: 1.1, 1.2, 1.3, 1.4, 1.5, 1.6 and 1.7) (Chapter-5: 5.1, 5.2 and 5.3)

MODULE-II (12 Lectures) Static Series Compensators: Objective of Series Compensation (GCSC, TSSC, TCSC), Variable Impedance Type Series Compensators, Switching Converter Type Series Compensators (SSSC) Static Voltage and Phase Angle Regulators: Objectives of Voltage and Phase Angle Regulators, Approaches to Thyristor-Controlled Voltage and Phase Angle Regulators (TCVRs and TCPARs). (Chapter-6: 6.1, 6.2 and 6.3) (Chapter-7: 7.1 and 7.2)

MODULE-III (10 Lectures)

Combined Compensators: Introduction, Unified Power Flow Controller (UPFC), The

Interline Power Flow Controller (IPFC), Generalized and Multifunctional FACTS

Controllers.

(Chapter-8: 8.1, 8.2, 8.3 and 8.4)

TEXT BOOK:

"Understanding FACTS: Concepts & Technology of Flexible AC Transmission

Systems" By N.G.Hingorani & L.Gyugyi, IEEE Press, Standard Publishers Distributors,

Delhi.

Reference Book:

1) Facts Controllers in Power Transmission & Distribution by K.R.Padiyan, New Age

Intermational.

2) Modelling & Simulation in Power Networks, Enrique Acha, Clandio Esquival &

H.A.Perez,CA Camcho, John Wiley & Sons.

FLEXIBLE AC TRANSMISSION SYSTEMS

CHAPTER 1

FACTS CONTROLLERS

1.1 INTRODUCTION

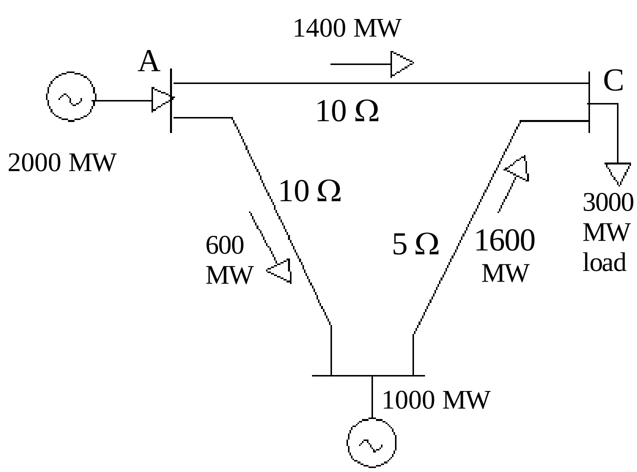
The electric power supply systems of whole world are interconnected, involving connections inside the utilities, own territories with external to inter-utility, internationals to inter regional and then international connections. This is done for economic reasons, to reduce the cost of electricity and to improve reliability of power supply. We need the interconnections to pool power plants and load centers in order to minimize the total power generation capacity and fuel cost. Transmission lines interconnections enable to supply, electricity to the loads at minimized cost with a required reliability. The FACTS Technology is adopted in the transmissions to enhance grid reliability and to overcome the practical difficulties which occur in mechanical devises used as controllers of the transmission network.

The FACTS Technology has opened a new opportunity to the transmission planner for controlling power and enhancing the useable capacity presently, also to upgrade the transmission lines. The current through the line can be controlled at a reasonable cost which enables a large potential of increasing the capacity of existing lines with large conductors and by the use of FACTS controllers the power flow through the lines is maintained stable. The FACTS controllers control the parameters governing the operation of transmission systems, such as series impedance, shunt impedance, current, voltage, phase angle and damping of oscillations at various frequencies below the rated frequency.

In an A.C power flow, the electrical generation and load must be balanced all the times. Since the electrical system is self-regulating, therefore, if one of the generators supplies less power than the load, the voltage and frequency drop, thereby load goes on decreasing to equalize the generated power by subtracting the transmission losses. How ever there is small margin of self regulating. If voltage is dropped due to reactive power, the load will go up and frequency goes on decreasing and the system will collapse ultimately. Also the system will collapse if there is a large reactive power available in it. In case of high power generation the active power flows from surplus generating area to the deficit area.

1.2 POWER FLOW

Consider a simple case of power flow in parallel paths. Here power flows from surplus generation area to the deficit generation area. Power flow is based on the inverse of line impedance. It is likely that lower impedance line become overloaded and limits the loading on both the paths, though the higher impedance area is not fully loaded. There would not be any chance to upgrade the current capacity of the overloaded path, because it would further decrease the impedance. The power flow with HVDC converters is controlled by high speed HVDC converters. The parallel A.C. transmission maintains the stability of power flow. The power flow control with FACTS controllers can be carried out by means of controlling impedance, phase angle and by injected voltage in series.



(a)

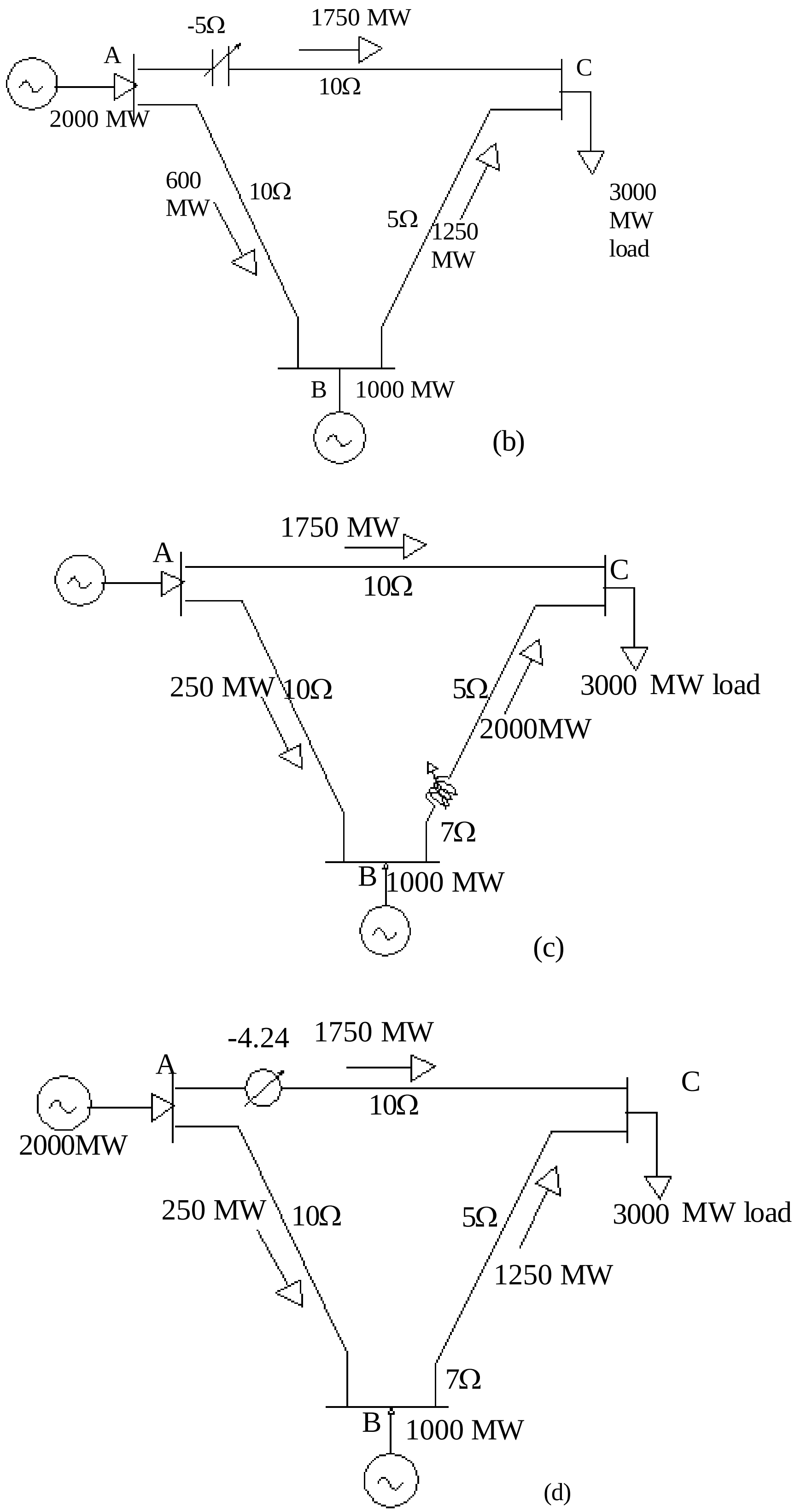


Fig 2.1 Power Flow in Meshed Paths

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For understanding free flow of power, consider a simplified case in which two generators are sending power to load center from different sites. The Mesh network has the lines AB, BC and AC having continuous rating of 1000 MW, 1250 MW respectively. If one of the generators is generating 2000 MW and the other 1000 MW, a total power of 3000 MW would be delivered to the load center. In Fig 2.1 (a) the three impedances 10Ω, 5Ω and 10Ω, carry the powers 600 MW, 1600 MW and 1400 MW respectively. Such a situation would overload line BC and therefore generation would have to be decreased at „B" and increased at „A" in order to meet the load without overloading the line BC.

If a capacitor of reactance (-5Ω) at the synchronous frequency is inserted in the line AC as in Fig 2.1 (b), it reduces the line impedance from 10Ω to 5Ω so that the power flow through the lines AB, BC and AC are 250 MW, 1250 MW and 1750 MW respectively. It is clear that if the series capacitor is adjusted the power flow level may be realized. The complication is if the series capacitor is mechanically controlled it may lead to sub synchronous resonance. This resonance occurs when one of the mechanical resonance frequencies of the shaft of a multiple-turbine generator unit coincides with normal frequency by subtracting the electrical resonance frequency of the capacitor with the inductive load impedance of the line. Then the shaft will be damaged.

If the series capacitor is thyristor controlled, it can be varied whenever required. It can be modulated to rapidly damped and sub synchronous conditions. Also can be modulated at damped low frequency oscillations. The transmission system to go from one steady-state condition to another without the risk of damaging the shaft, the system collapse. In other words thyristor controlled series capacitor can enhance the stability of network similarly as in Fig 2.1(c). The impedance of line BC is increased by inserting an inductor of reactance in series

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with the line AB, the series inductor which is controlled by thyristor could serve to adjust the steady-state power flow and damped unwanted oscillations.

Another option of thyristor controlled method is, phase angle regulator could be installed instead of series capacitor in the line as in Fig 2.1(d). The regulator is installed in line AC to reduce the total phase angle difference along the line from 8.5 degree to 4.26 degrees. Thus the combination of Mesh and thyristor control of the phase angle regulator may reduce the cost. The same result could be achieved by injecting a variable voltage in one of the lines. Balancing of power flow in the line is carried out by the use of FACTS controller in the line.

1.3 LOADING CAPABILITY LIMITS

For the best use of the transmission and to improve the loading capability of the system one has to over come the following three kinds of limitations:-

- Thermal Limitations
- Dielectric Limitations
- Limitations of Stability

1.3.1 Thermal Limitations

Thermal capability of an overhead lines is a function of the ambient temperature, wind conditions, conductors condition and ground clearance. It varies by a factor of 2 to 1 due to variable environment and the loading history. It needs to find out the nature of environment and other loading parameters. For this, off-line computer programs are made use to calculate a line loading capability based on available ambient environment and present loading history. The over load line monitoring devices are also used to know the on line loading capability of the line. The normal loading of the line is also decided on a loss evaluation basis which may vary for many reasons. The increase of the rating of transmission line involves the

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consideration of the real time rating of a transformer which is a function of ambient temperature, aging of transformer and present loading history of off-line and on-line monitoring. The loading capability of transformer is also used to obtain real time loading capability. Enhancement of cooling of transformer is also a factor of increase of load on transmission line. From the above discussion it is necessary of upgrading line loading capability which can be done by changing the conductor of higher current rating which requires the structural upgrading. The loading capability of line is also achieved by converting a single circuit to double circuit line. If the higher current capability is available then the question arises, how to control this high current in the line, also, the acceptance of sudden voltage drop with such high current etc. The FACTS technology helps in making an effective use of the above technique of upgrading the loading capability of line.

1.3.2 Dielectric Limitations

From insulation point of view, many transmission lines are designed very conservatively. For a normal voltage rating, it is rarely possible to increase normal operation by +10% voltages, e.g. 500 kV, - 550 kV or even higher. Care must be taken such that the dynamic and transient over voltages are within the limit. Modern type of gapless arresters, or line insulators with internal gapless arresters or powerful Thyristor-controlled over voltage suppressors at the sub-stations are used to increase the line and sub station voltage capability. The FACTS technology could be used to ensure acceptable over-voltage and power conditions.

2.3.3 Limitations of Stability

There are a number of stability issues that limit the transmission capability. They are:

- Transient Stability
- Dynamic Stability

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- Steady-state Stability
- Frequency Collapse
- Voltage Collapse
- Sub synchronous Resonance

1.4 IMPORTANCE OF CONTROLLABLE PARAMETERS

- Control of line impedance „X" with a Thyristor controlled series capacitor can provide a powerful means of current control.
- When the angle is not large in some cases the control of „X" or the angle provides the control of active power.
- Control of angle with a phase angle regulator controls the driving voltage, which provides the powerful means of controlling the current flow and hence active power flow when the angle is not large.
- Injecting a voltage in series with the line, which is perpendicular to the current flow can increase or decrease the magnitude of current flow. Since the current flow lags the driving voltage by 90º, this means injection of reactive power in series compensation can provide a powerful means of controlling the line current and hence the active power when the angle is not large.
- Injecting voltage in series with line with any phase angle with respect to the driving voltage can control the magnitude and the phase of the line current. This means that injecting a voltage phasor with variable phase angle can provide a powerful means of controlling the active and reactive power flow. This requires injection if both active and reactive power are in series.

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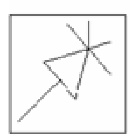
- ❖ When the angle is not-large, controlling the magnitude of one or the other line voltages with a Thyristor-controlled voltage regularly can very cost-effective means for the control of reactive power flow through the inter connection.
- ❖ Combination of the line impedance with a series controller and voltage regulation with shunt controller can also provide a cost effective means to control both the active and reactive power flow between the two systems.

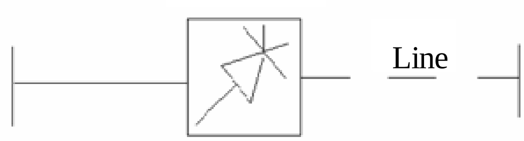
1.5 TYPES OF FACTS CONTROLLERS

In general FACTS controllers can be classified into four categories.

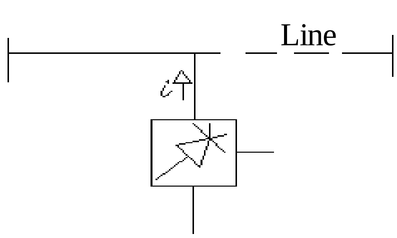
- ❖ Series controllers
- ❖ Shunt controllers
- ❖ Combined series-series controllers
- ❖ Combined series-shunt controllers



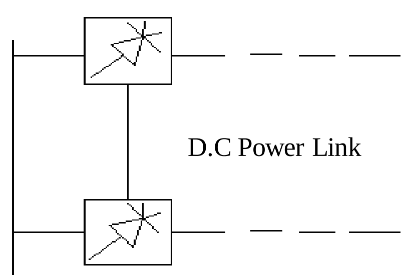
(a) General symbol of FACTS controller



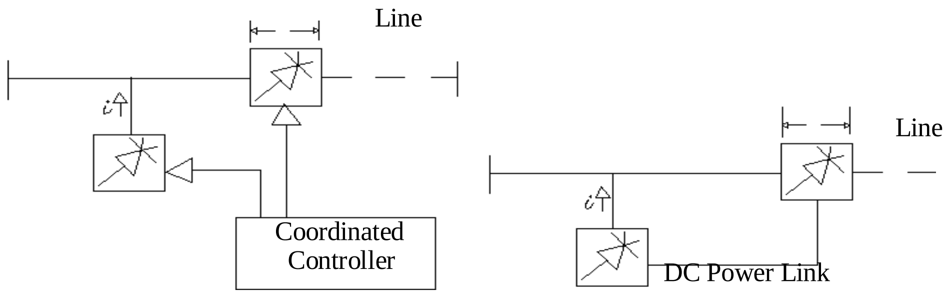
(b) Series controller



(c) Shunt controller



(d) Unified Series controller



(e)

(f) Unified Series shunt controller

Fig 2.2 Schematic diagrams of FACTS Controller

Fig 2.2 (a) shows the general symbol for FACTS controller; with a thyristor arrow inside a box. Fig 2.2 (b) shows the series controller could be variable impedance, such as capacitor, reactor etc. or it is a power electronics based variable source of main frequency sub-synchronous frequency and harmonics frequencies or combination of all to serve the desired need. The principle of series controller is to inject the voltage in series with the line. Even variable impedance multiplied by the current flow through it, represents an injected series voltage in the line. So long as the voltage is in phase quadrature with the line current, the series controller supplies or consumes variable reactive power. If any other phase relation involves it will handle the real power also.

Fig 2.2 (c) shows the shunt controllers. As series controller, the shunt controller also has variable impedance, variable source, or a combination of all. The principle of shunt controller is to inject current into the system at the point of connection. Even variable shunt impedance connected to the line voltage causes a variable current flow and hence represents injection of current into the line. As long as the injected current is in phase quadrature with the line voltage. The shunt controller supplies or consumes variable reactive power. If any other phase relationship involves, it will also handle real power.

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Fig 2.2 (d) shows the combination of two separate series controllers, which are controlled in a coordinated manner, in a multi line transmission system. Other wise it could be unified controller. As shown in Fig 2.2 (d) the series controllers provide independent series reactive compensation for each line and also transfer the real power among the lines via the unified series-series controller, referred to as inter-line power flow controller, which makes it possible to balance both the real and reactive power flow in the lines and thereby maximizing the utilization of transmission system. Note that the term "unified" here means that the D.C terminals of all controller converters are connected together for real power transfer.

Fig 2.2 (e & f) shows the combined series-shunt controllers. This could be a combination of separate shunt and series controllers, which are controlled in coordinated manner in Fig 2.2 (e) or a unified power flow controller with series and shunt elements in Fig 2.2 (f). The principle of combined shunt and series controllers is, it injects current into the system with the shunt part of the controller and voltage through series part. However, when the shunt and series controllers are unified, there can be a real power exchange between the series and shunt controllers via the power link.

1.6 BENEFITS FROM FACTS CONTROLLER

- ❖ Control of power flow is in order, meet the utilities, own needs, ensure optimum power flow, and ride through emergency conditions or a combination of all.
- ❖ Increase the loading capability of lines to their thermal capabilities, including short term and seasonal, this can be done by overcoming other limitations and sharing of power among lines according to their capability.

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- Increase the system security through raising the transient stability limit, limiting short circuit currents and over loads, managing cascading black-outs and damping electro-mechanical oscillations of power systems and machines.
- Provide secure tie-line connections to neighboring utilities and regions thereby decreasing overall generation reserve requirements both sides.
- Provide greater flexibility in setting new generation.
- Provide upgrade of lines.
- Reduce the reactive power flow, thus allowing the lines to carry more active power.
- Reduce loop flows.
- Increase utilization of lowest cost generation.

UNIT - II

2.1 VOLTAGE SOURCE CONVERTERS

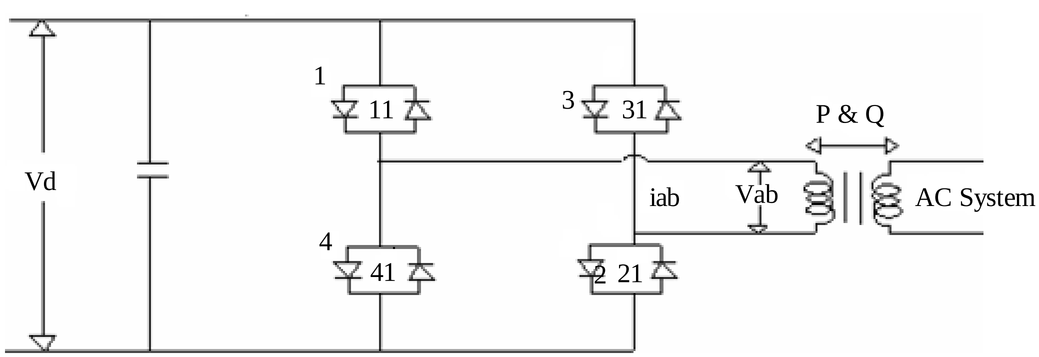
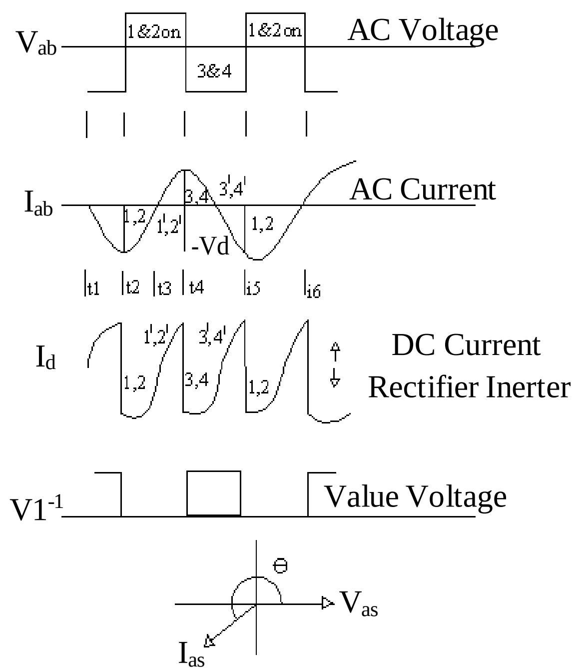


Fig 2.3 (a) Single Phase Full Wave Bridge Converters

2.1.1 Operation of Single Phase Bridge Converter

Fig 2.3 (a) shows a single phase bridge converter consisting of four valves i.e. valves (1-1') to (4 -4'), a capacitor to provide stiff D.C. Voltage and two A.C. connection points „a" and „b". The designated valve numbers represent their sequence of turn on and turn off operation. The

D.C. voltage is converted to A.C. voltage with the appropriate valve turn-off sequence, as explained below. As in the first wave form 2.3 (b) when devices 1and 2 are turned on voltage „V_{ab}‟ becomes „$+V_d$‟ for one half cycle and when devices 3 and 4 turned off „V_{ab}‟ becomes „$-V_b$‟ for the other half cycle. Suppose the current flow in Fig 2.3 (c) is A.C. wave form which is a sinusoidal wave form „I_{ab},‟ the angle „θ‟ leads with respect to the square-wave voltage wave form t_1 the operation is illustrated.



(b)

Fig 2.3(b) Single phase full wave bridge converter

1. From instant t_1 to t_2 when devices 1 and 2 are ON and 3 and 4 are OFF, „V_{ab}‟ is +ve and I_{ab} is -ve. The current flows through device 1 into A.C. phase „a‟ and then out of A.C. phase „b‟ through device „2‟ with power flow from D.C. to A.C. (inverter action).

2. From instant t_2 to t_3 the current reverses i.e. becomes +ve and flows through diodes 1' and 2' with power flow from A.C. to D.C. (rectifier action)

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3. From instant t_3 and t_4 device 1 and 2 are OFF and 3 and 4 are ON, V_{ab} becomes -ve and Iab is still +ve the current flow through devices 3 and 4 with power flow from D.C. to A.C. (inverter action).

4. From instant t_4 and t_5 devices 3 and 4 still ON and 1 and 2 OFF V_{ab} is -ve current I_{ab} reverses and flows through diodes 3' and 4' with power flow from A.C. to D.C. (rectifier operation).

Fig 2.3(d) shows D.C. current wave form and Fig 2.3(e) shows Voltage across valve (1-1') Fig 2.3(f) shows phasor of power flow from A.C. to D.C. with lagging power factor. Four operating modes in one cycle of a single phase converter are shown in table

Table 2.1 Operational mode of Single Phase Full Wave Bridge Converter

ORD	Devices	V_{ab}	I_{ab}	Conducting devices	conversion
1	1 & 2 ON 3 & 4 OFF	+ve	-ve	1 and 2	Inverter
2	1 & 2 ON 3 & 4 OFF	+ve	+ve	1' and 2'	Rectifier
3	1 & 2 OFF 3 & 4 ON	-ve	+ve	3 and 4	Inverter
4	1 & 2 OFF 3 & 4 ON	-ve	-ve	3' and 4'	Rectifier

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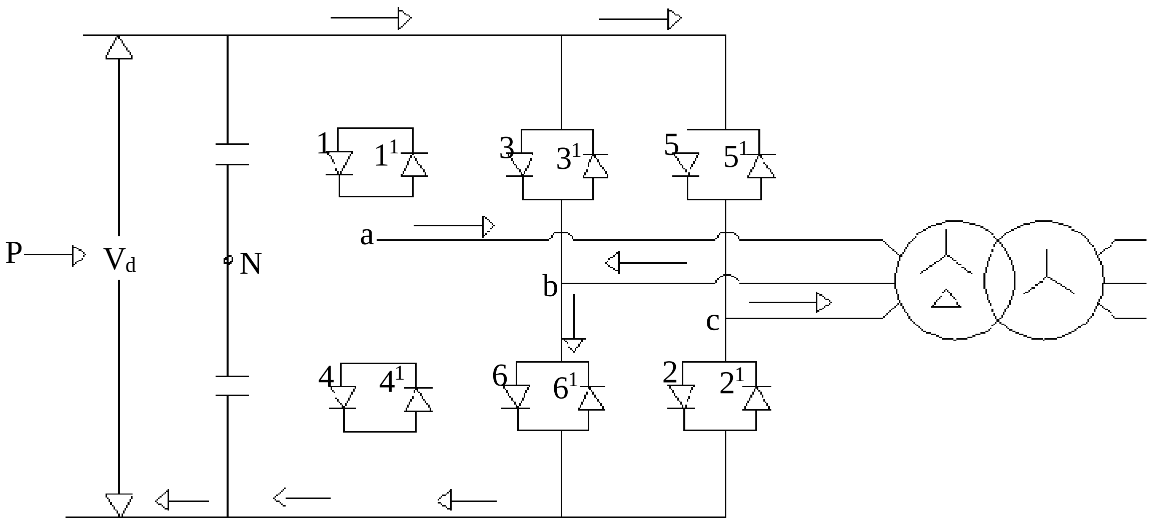
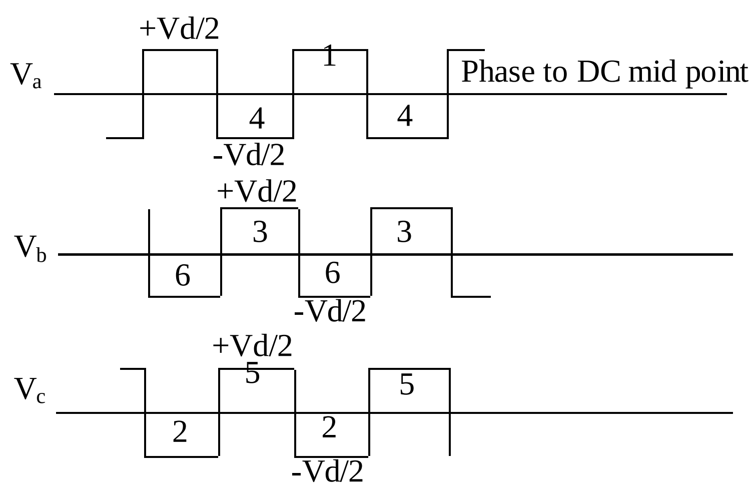


(a) Three Phase Full Wave Bridge Converters



(b) (b)

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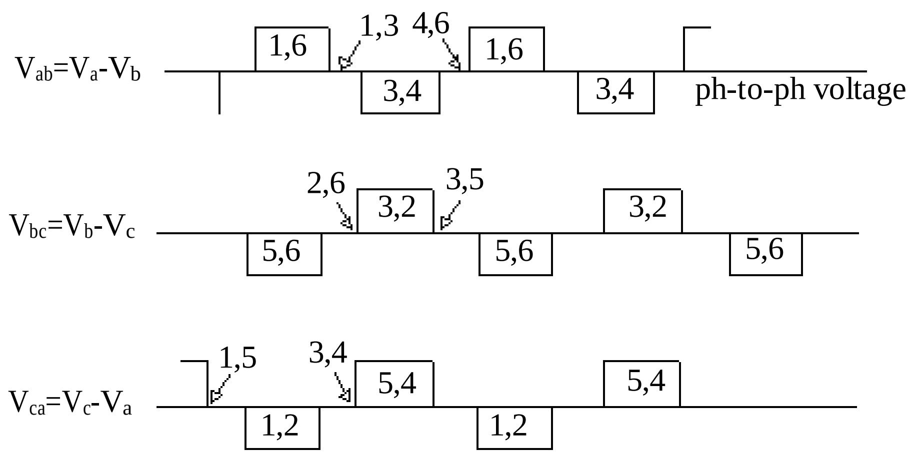
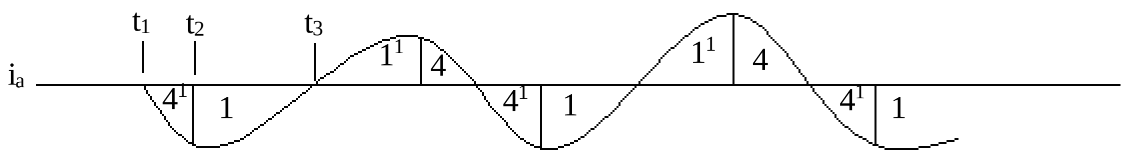
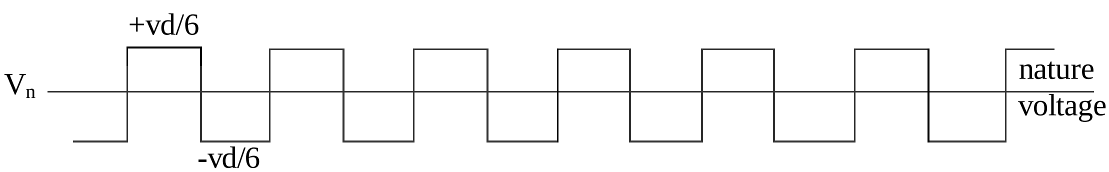

$V_{ab}=V_a-V_b$
1,6
1,3
4,6
1,6
3,4
3,4
ph-to-ph voltage
$V_{bc}=V_b-V_c$
2,6
3,2
3,5
3,2
5,6
5,6
5,6
$V_{ca}=V_c-V_a$
1,5
3,4
5,4
5,4
1,2
1,2

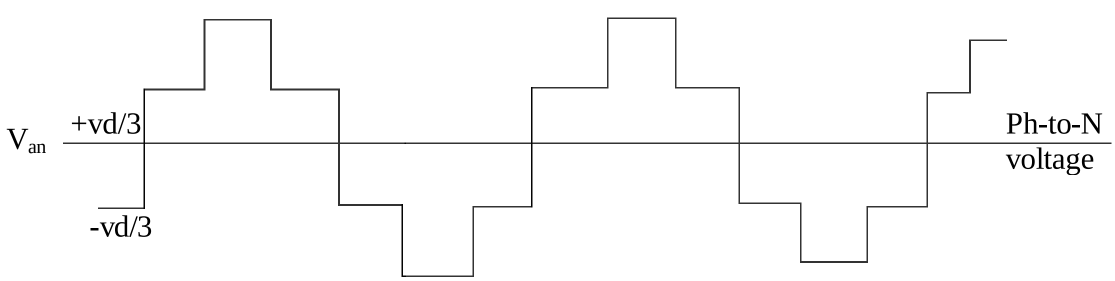
(c) (c)


t_1
t_2
t_3
i_a
4^1
1
1^1
4
4^1
1
1^1
4
4^1
1

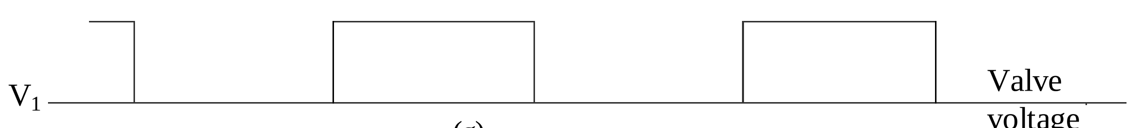
(d) (d)


+vd/6
V_n
-vd/6
nature
voltage

(e) (e)


V_{an}
+vd/3
-vd/3
Ph-to-N
voltage

(f) (f)


V_1
Valve
voltage

(g)

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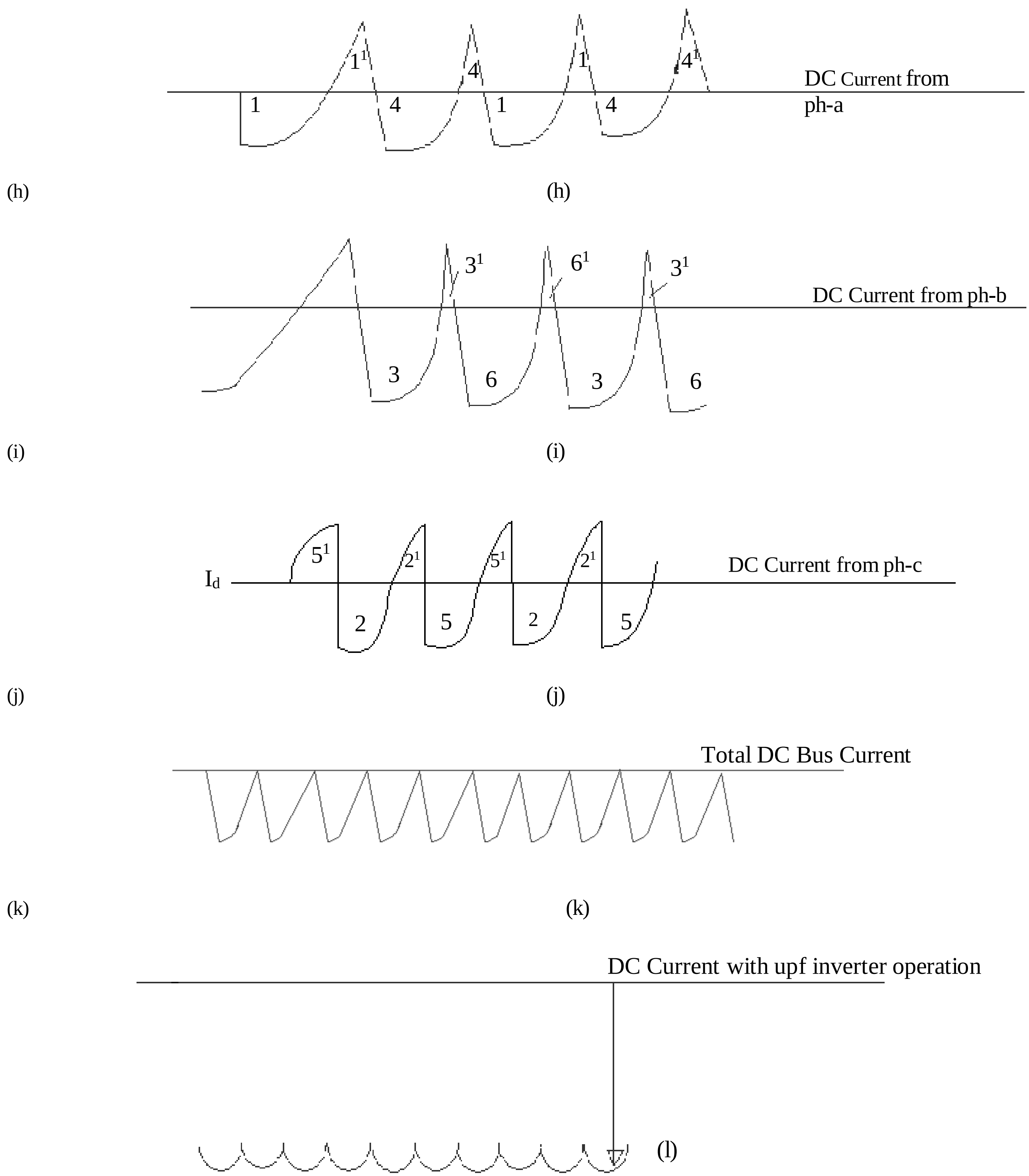

Fig 2.4 Three phase full wave bridge converter

Fig 2.4 (a) shows a three phase wave converter with six valves, i.e. (1-1') to (6-6') they are designated in the order. 1 to 6 represents the sequence of valve operation in time.It consists of three legs, 120º apart. The three legs operate in a square wave mode; each valve alternately closes for 180º as in the wave form of Fig 2.4 (b), V_a, V_b and V_C.

These three square-wave waveform are the voltages of A.C. buses a, b and c with respect to a D.C. capacitor mid point „N‟ with peak voltages of $+V_{d/2}$ and $-V_{d/2}$. The three phase legs have their timing 120º apart with respect to each other to a 6-phase converter operation phase leg (3-6) switches 120º after phase leg (1-4) and phase leg (5-2) switches 120º after phase (3-6), thus completing the cycle as shown by the valve close-open sequence.

Fig 2.4 (c) shows the three phase-to-phase voltages V_{ab}, V_{bc} and V_{ca}, where $V_{AB} = V_a - V_b$, $V_{bc} = V_b - V_c$ and $V_{ca} = V_c - V_a$. These phase-to-phase voltages have 120º pulse width with peak voltage magnitude of V_d. The periods of 60, º when the phase-to-phase voltages are zero, represents the condition when two valves on the same order of the D.C. bus.

For example the waveform for V_{ab} shows voltage V_d when device „1‟ connects A.C. bus „a‟ to the D.C. + $V_{d/2}$, and device 6 connects A.C. bus „b‟ to the D.C. bus $-V_{d/2}$, giving a total voltage $V_{ab} = V_a - V_b = V_d$. It is seen 120º later, when device „6‟ is turned OFF and device „3‟ is turned ON both A.C. buses „a‟ and „b‟ become connected to the same D.C. bus $+V_{d/2}$, giving zero voltage between buses „a‟ and „b‟. After another 60º later. When device 1 turns OFF and device „4‟ connects bus „a‟ to $-V_{d/2}$, V_{ab} becomes $-V_d$. Another 120º later, device „3‟ turns OFF and device „6‟, connects bus „b‟ to $-V_{d/2}$, giving $V_{ab} = 0$ the cycle is completed, after another 60º. device „4‟ turns OFF and device „1‟ turns ON, the other two voltages V_{ab} and V_{ca} have the same sequence 120º a part.

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The turn ON and turn OFF of the devices establish the wave forms of the A.C. bus voltages in relation to the D.C. voltage, the current flows itself, is the result of the interaction of the A.C. voltage with the D.C. system. Each converter phase-leg can handle resultant current flow in either direction. In fig 2.4 (d) A.C. current „I_a" in phase „a" with +ve current representing current from A.C. to D.C. side for simplicity, the current is assumed to have fundamental frequency only. From point t_1 to t_2. For example phase „a" current is -ve and has to flow through either valve (1-1') or valve (4-4'). It is seen, when comparing the phase „a" voltage with the form of the phase „a" current that when device 4 is ON and device „1" is OFF and the current is -ve, the current would actually flow through diode 4'. But later say from point t_2, t_3, when device „1" is ON, the -Ve current flows through device „1", i.e., the current is transferred from diode 4' to device „1" the current covering out of phase „b" flows through device „6" but then part of this current returns back through diode 4' into the D.C. bus. The D.C. current returns via device „5" into phase „e". At any time three valves are conducting in a three phase converter system. In fact only the active power part of A.C. current and part of the harmonics flow into the D.C. side, as shown in Fig 2.4(*l*). [19]

2.2 TRANSFORMER CONNECTION FOR 12-PULSE OPERATION

The harmonics content of the phase to phase voltage and phase to neutral voltage are 30º out of phase. If this phase shift is corrected, then the phase to neutral voltage (V_{an}) other then that of the harmonics order 12n±1 would be in phase opposition to those of the phase to phase voltage (V_{ab}) and with $1/\sqrt{3}$ times the amplitude.

In Fig 2.5 (a) if the phase to phase voltages of a second converter were connected to a delta-connected secondary of a second transformer, with √3 times the turns compared to the star connected secondary, and the pulse train of one converter was shifted by 30º with respect to the

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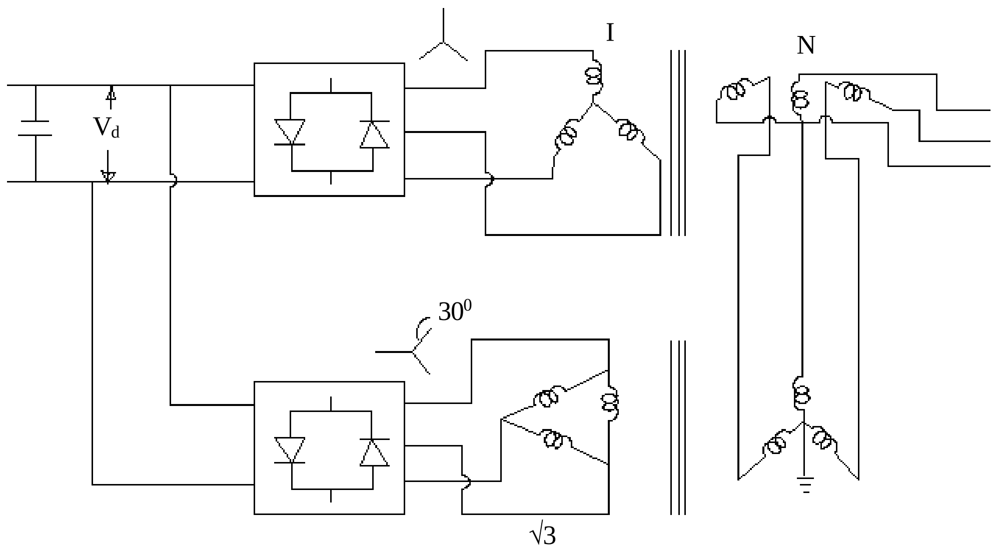
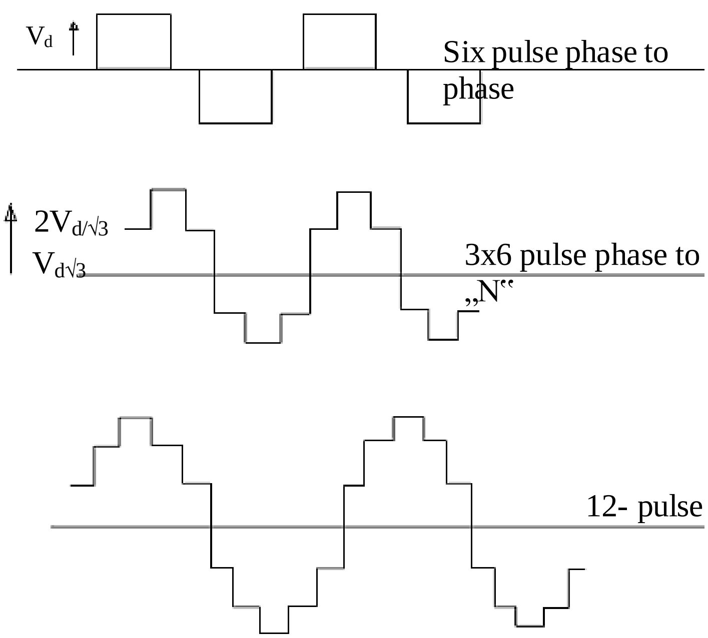
other “in order to bring „V_{ab}“ and „V_{an}“ to be in phase”, the combined out put voltage would have a 12-phase wave form, with harmonics of the order of 12n±1, i.e. 11^{th} , 13^{th} , 23^{rd} , 25^{th} …. And with amplitudes of $1/11^{th}$, $1/13^{th}$, $1/23^{rd}$ $1/25^{th.}$ respectively, compared to the fundamental.



(a)



(b)

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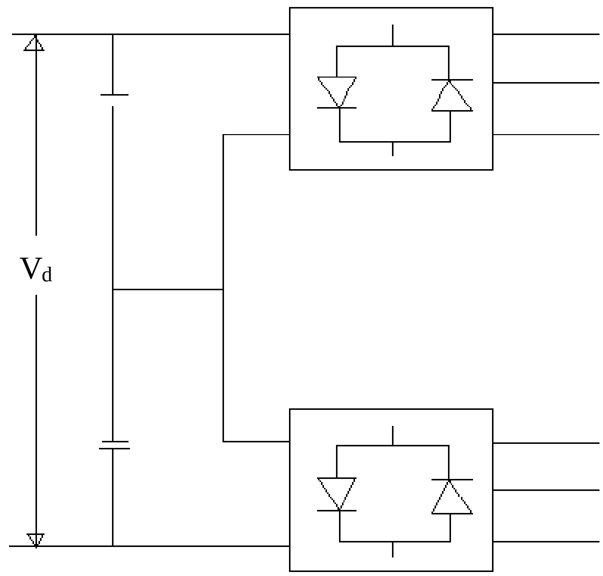

(c)

Fig 2.5 Transformer Connection for 12-Pulse Operation

Fig 2.5 (b): shows the two wave forms Van and Vab, adjusted for the transformer ratio and one of them phase displaced by 30º. These two wave forms are then added to give the third wave form, which is a 12-pulse wave form, closer to being a sine wave than each of the six-phase wave form.

In the arrangement of Fig 2.5 (a), the two six-pulse converters, involving a total of six-phase legs are connected in parallel on the same D.C. bus, and work together as a 12-pulse converter. It is necessary to have two separate transformers, otherwise phase shift in the non 12-pulse harmonics i.e. 5^{th}, 7^{th}, 17^{th}, 19^{th} …. In the secondaries it will result in a large circulating current due to common core flux. To the non 12-pulse voltage harmonics, common core flux will represent a near short circuit. Also for the same reason, the two primary side windings should not be directly connected in parallel to the same three phase A.C. bus bars on the primary side. Again this side becomes the non 12-pulse voltage harmonics i.e. 5^{th}, 7^{th}, 17^{th}, 19^{th} …. while they cancel out looking into the A.C. system would be in phase for the closed loop. At the

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same time harmonics will also flow in this loop, which is essentially the leakage inductance of the transformers.

The circulating current of each non 12-pulse harmonics is given by:

$I_n / I_1 = 100/ (X_T * n^2)$ Percent

Where I_1 is the nominal fundamental current, n is the relevant harmonic number, and X_T is the per unit transformer impedance of each transformer at the fundamental frequency. For example, if X_T is 0.15 per unit at fundamental frequency, then the circulating current for the fifth harmonic will be 26.6%, seventh, 14.9%, eleventh, 5.5%, thirteenth, 3.9%, of the rated fundamental current, and so on. Clearly this is not acceptable for practical voltage sourced converters. Therefore, it is necessary to connect the transformer primaries of two separate transformers in series and connect the combination to the A.C. bus as shown in Fig 2.5 (a), with the arrangement shown in Fig 2.5 (a), the 5^{th}, 7^{th}, 17^{th}, 19^{th}…. harmonics voltages cancel out, and the two fundamental voltages add up, as shown in Fig 2.5 (b), and the combined unit becomes a true 12-pulse converter.

2.3 TRANSFORMER CONNECTIONS FOR 24-PULSE AND 48-PULSE OPERATION

Two 12-pulse converters phase shifted by 15º from each other can provide a 24-pulse converter, with much lower harmonics on both A.C. and D.C. sides. It‟s A.C. out put voltage would have 24n±1 order of harmonics i.e. 23^{rd}, 25^{th}, 47^{th}, 49^{th} …. , with magnitudes of $1/23^{rd}$, $1/25^{th}$, $1/47^{th}$, $1/49^{th}$ …. respectively, of the fundamental A.C. voltage. The question now is, how to arrange this phase shift. One approach is to provide 15º phase shift windings on the two transformers of one of the two 12-pulse converters. Another approach is to provide phase shift windings for (+7.5º) phase shift on the two transformers of one 12-pulse converter and (-7.5º) on the two transformers of the other 12-pulse converter, as shown in Fig2.6 (a), the later

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is preferred because it requires transformer of the same design and leakage inductances. It is also necessary to shift the firing pulses of one 12-pulse converter by 15º with respect to the other. All four six-pulse converters can be connected on the D.C. side in parallel, i.e. 12-pulse legs in parallel. Alternately all four six-pulse converters can be connected in series for high voltage or two pair of 12-pulse series converters may then be connected will have a separate transformer, two with star connected secondaries, and the other two with delta-connected secondaries.

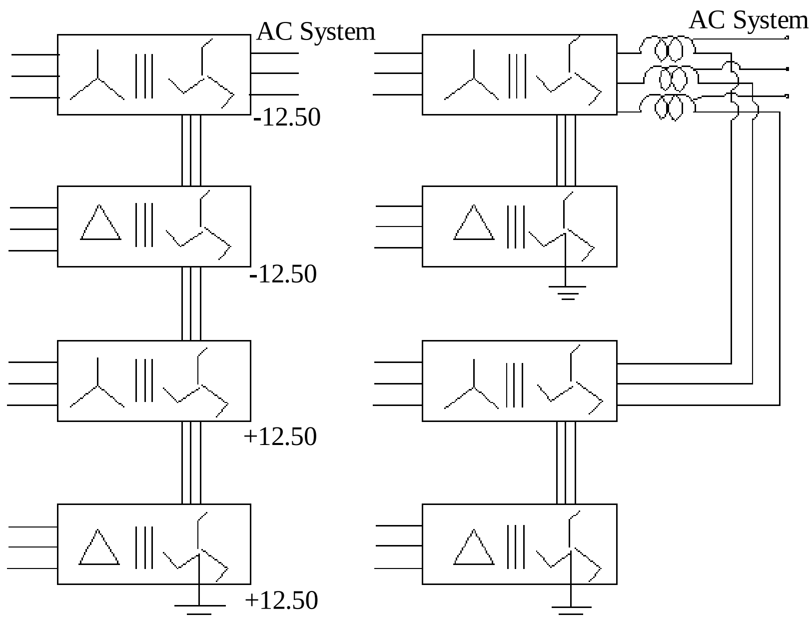


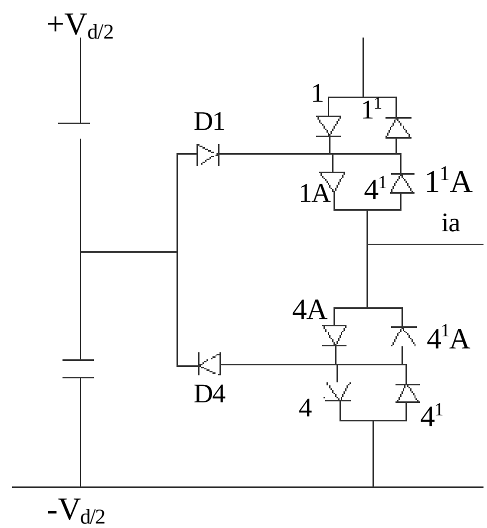
Fig 2.6 Transformer connections in series & parallel

Primaries of all four transformers can be connected in series as shown in Fig 2.6 (b) in order to avoid harmonic circulation current corresponding the 12-pulse order i.e. 11^{th}, 13^{th}, and 23rd, 24^{th}. It may be worth while to consider two 12-pulse converters connected in parallel on the A.C. system bus bars, with inter phase reactors as shown in Fig 2.6 (b) for a penalty of small harmonic circulation inside the converter loop. While this may be manageable from the point of view of converter rating. Care has to be taken in the design of converter controls, particularly during light load when the harmonic currents could become the significant part of the A.C. current flowing through the converter. As increase in the transformer impedance to say 0.2 per unit may be appropriate when connecting two 12-pulse transformers to the A.C. bus directly and less than that when connected through inter phase reactors. For high power FACTS Controllers, from the point of view of the A.C. system, even a 24-pulse converter with out A.C. filters could have voltage harmonics, which are higher then the acceptable level in this case, a single high pass filter turned to the 23rd - 25th harmonics located on the system side of the converter transformers should be adequate.

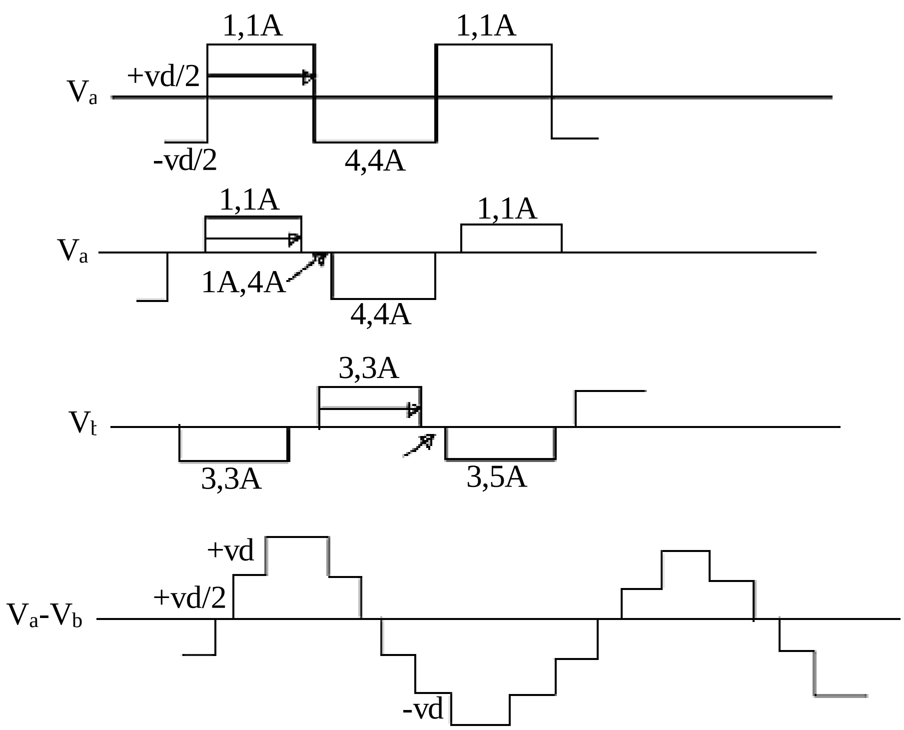
The alternative of course, is go to 48-pulse operation with eight six pulse groups, with one set of transformers of one 24-pulse converter phase shifted from the other by 7.5º, or one set shifted (+7.5º) and the other by (-3.7º). Logically, all eight transformer primaries may be connected in series, but because of the small phase shift (i.e. 7.5º) the primaries of the two 24-pulse converters each with four primaries in series may be connected in parallel, if the consequent circulating current is accepted. This should not be much of a problem, because the higher the order of a harmonic, the lower would be the circulating current. For 0.1 per unit transformer impedance and the 23rd harmonic, the circulating current can be further limited by higher transformer inductance or by inter phase reactor at the point of parallel connection of the two 24-pulse converters, with 48-pulse operation A.C. filters are not necessary.

2.4 THREE LEVEL VOLTAGE SOURCE CONVERTERS

The three level converters is one, which is used to vary the magnitude of A.C. out put voltage without having to change the magnitude of the D.C. voltage.



(a)



(b)

Fig 2.7 Voltage source converters

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One phase leg of a three level converter is shown in Fig 2.7 (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 mid point „N" of the D.C. capacitor. It is seen that each half of the phase leg is splitted into two series connected valves i.e. 1-1' is Sp' into 1-1' and 1_A-$1'_A$. The mid point of the splitted valve is connected by diodes D_1 and D_2 to the mid point „N" as shown on the phase of it; this may seen like doubling the number of valves from two to four per phase leg, in addition to providing two extra diode valves. However, doubling the number of valves with the same voltage rating would double the D.C. voltage and hence the power capacity of the converter. Thus only the addition of the diode clamping valves D_1 and D_4 per phase leg as in Fig 2.7 (a) adds to the converter cost. If the converter is a high voltage converter with devices in series, then the number of main devices would be about the same. A diode clamp at the mid point may also help to ensure a more voltage sharing between the two valve halves.

Fig 2.7 (b) shows out put voltage corresponding to one three level phase leg. The first wave form shows a full 180º square wave obtained by the closing of devices 1 and 1_A to give ($+V_{d/2}$**)** for 180º and the closing of valves 4 and 4_A for180º to give ($-V_{d/2}$) for 180º . Now consider second voltage wave form in Fig 2.7 (b) in which upper device 1 is OFF and device 4_A is ON an angle α earlier than they were due in the 180º square wave operation. This leaves only device 1_A and 4_A ON, which in combination with diodes D_1 and D_2, clamp the phase voltage V_a to zero with respect to the D.C. mid point „N" regardless of which way the current is flowing, this continues for a period 2α until device 1_A is turned OFF and device 4 is turned ON and the voltage jumps to ($-V_{d/2}$) with both the lower devices 4 and 4A turned ON and both the upper devices 1 and 1A turned OFF and so ON. The angle α is variable and the output voltage V_a is made up of σ = 180º - 2αº square waves. This variable period σ per half cycle allows the

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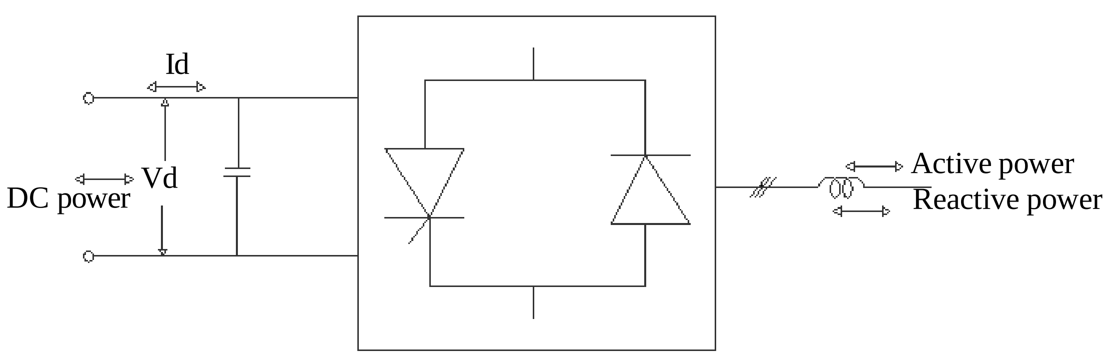
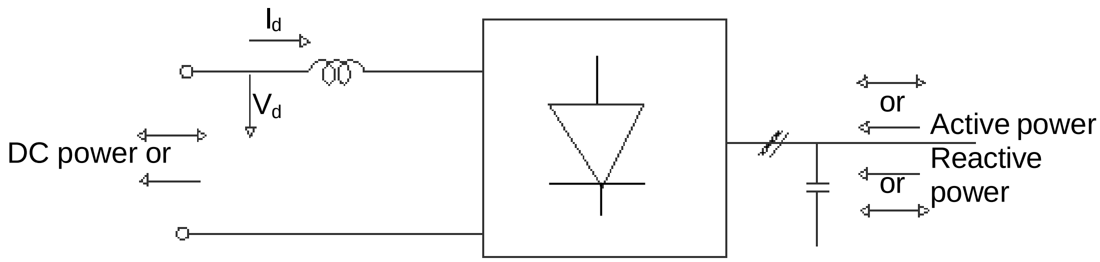
voltage V_a to be independently variable with a fast response. It is seen that devices 1_A and 4_A are turned ON for 180º during each cycle devices 1 and 4 are turned ON for σ = 180º - 2αº during each cycle, while diodes D_1 and D_4 conduct for 2αº = 180ºσ each cycle. The converter is referred to as three level because the D.C. voltage has three levels i.e. ($-V_{d/2}$) 0 and ($+V_{d/2}$).

2.5 CURRENT SOURCE CONVERTERS

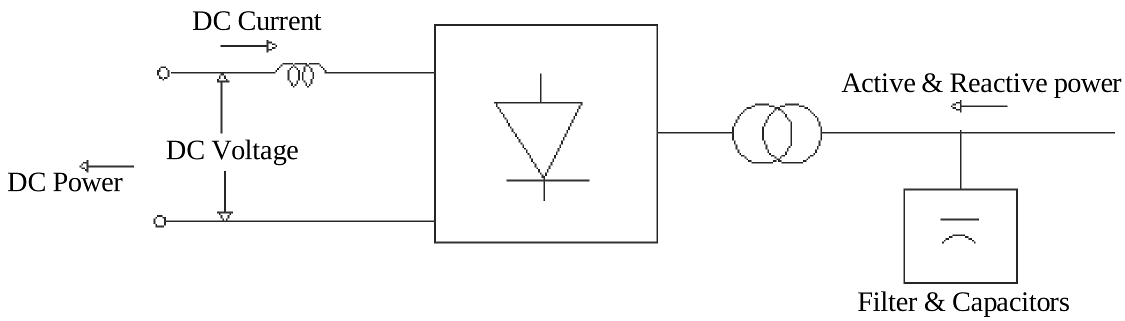
A current source converter is characterized by the fact that the D.C. current flow is always in one direction and the power flow reverses with the reversal of D.C. voltage shows in Fig 2.8 (b). Where as the voltage source converter in which the D.C. voltage always has one polarity and the power reversal of D.C. current is as shown in Fig 2.8 (a). In Fig2.8 (a) the converter box for the voltage source converter is a symbolically shown with a turn OFF device with a reverse diode. Where as the converter box in Fig 2.8 (b) for the current source converter is shown without a specific type of device. This is because the voltage source converter requires turn OFF devices with reverse diodes; where as the current source converter may be based on diodes conventional thyristor or the turn OFF devices. Thus, there are three principal types of current source converters as shown in Fig 2.8 (c), 2.8 (d), 2.8 (e).



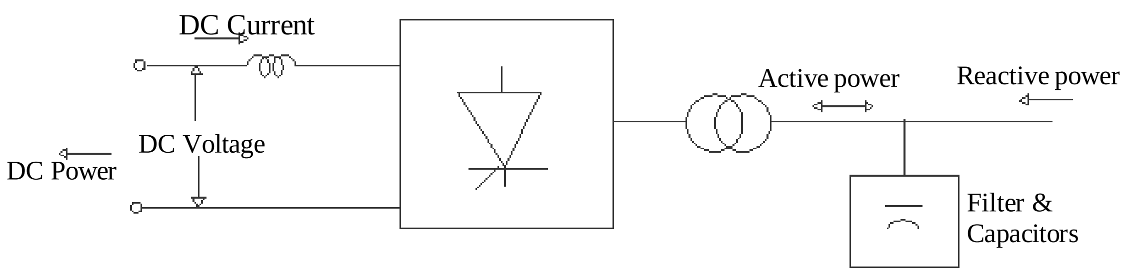
(a) Voltage source converter



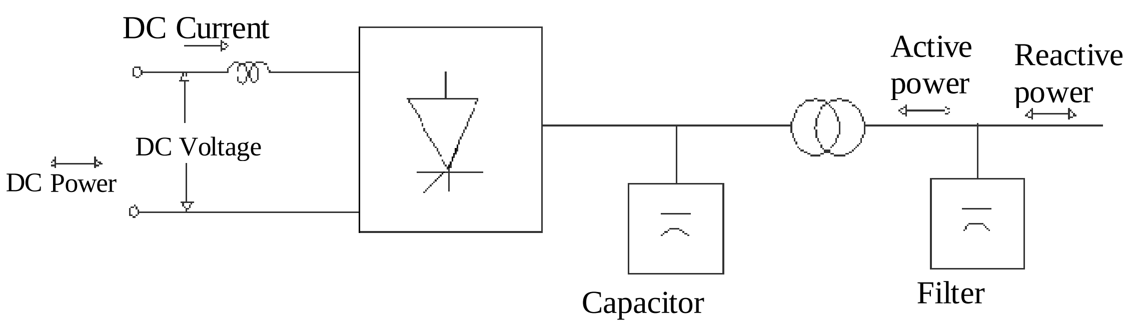
(b) Current source converter



(c) Diode Rectifier



(d) Thyristor line commutated converter



(e) Self commutated converters

Fig 2.8 Current source converters

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2.5.1 Diode Rectifier or Diode Converter

Fig 2.8 (c) represents the diode converter, which simply converts A.C. voltage to D.C. voltage and utilizes A.C. system voltage for commutating of D.C. current from one valve to another. Obviously the diode based line commutating converter just converts A.C. power to D.C. power without any control and also in doing so consumes some reactive power on the A.C. side.

2.5.2 Thyristor Line Commutated Converter

It is based on conventional thyristor with gate turn ON but without gate turn OFF capability as in Fig 2.8 (d): utilizes A.C. system voltage for commutation of current from one valve to another. This converter can convert and controls active power in either direction, but in doing so consumes reactive power on the A.C. side. It can not supply reactive power to the A.C. system.

2.5.3 Self Commutated Converter

It is based on turn OFF devices like (GTOs, MTOs, IGBTs, etc) in which commutation of current from valve to valve takes place with the device turn OFF action and provision of A.C. capacitors to facilitate transfer of current from valve to valve as in Fig 2.8 (e).Where as in a voltage source converter the commutation of current is supported by a stiff D.C. bus with D.C. capacitors provide a stiff A.C. bus for supplying the fact changing current pulses needed for the commutations. It also supplies or consumes the reactive power. [22]

Comparison between Current Source Converters and Voltage Source Converters

- Current source converters in which direct current always has one polarity and the power reversal takes place through reversal of D.C. voltage polarity. Where as voltage source converters in which the D.C. voltage always has one polarity, and the power reversal takes place through reversal of D.C. current polarity.

- Conventional Thyristor-based converters, being without turn OFF capability, can only be current source converters. Where as turn OFF device based converters can be of either type i.e. current source or voltage source converter.
- Diode based current source converters are the lowest cost converters, if control of active power by the converter is not required. Where as the same type of voltage source converters are expensive.
- If the leading reactive power is not required, then a conventional Thyristor based current source converter provides a low cost, converter with active power control. But for the same purpose Voltage source converter is costly.
- The current sourced converter does not have high short circuit current, where as the voltage source converter has high short circuit current.
- For current source converters, the rate of rise of fault current during external or internal faults is limited by the d.c reactor. For the voltage source converters the capacitor discharge current would rise very rapidly and can damage the valves.
- The six-pulse current source converter does not generate 3rd harmonic voltage, where as voltage source converter, it generates.
- The transformer primaries connected to current source converter of 12-pulse should not be connected in series, where as the voltage source converter for the same purpose may be connected in series for the cancellation of harmonics.
- In a current stiff converter, the valves are not subject to high dv/dt, due to the presence of A.c capacitor, where as in voltage source converter it can be available.

❖ A.C capacitors required for the current stiff converters can be quite large and expensive, where as voltage source converter used small size of capacitors which are cheap.

❖ Continuous losses in the d.c reactor of a current source converter are much higher than the losses in the d.c capacitor, where as in voltage source converter they are relaxable.[23]

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UNIT-III

STATIC SHUNT COMPENSATORS

Objectives of shunt compensation –methods of controllable VAR generation-static VAR compensators, SVC and STATCOM, comparison

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OBJECTIVES OF SHUNT COMPENSATION:

Shunt compensation is used to influence the natural characteristics of the transmission line to " steady-state transmittable power and to control voltage profile along the line" shunt connected fixed or mechanically switched reactors are used to minimize line over-voltage under light load conditions. Shunt connected fixed or mechanically switched capacitors are applied to maintain voltage levels under heavy load conditions.

Var compensation is used for voltage regulation.

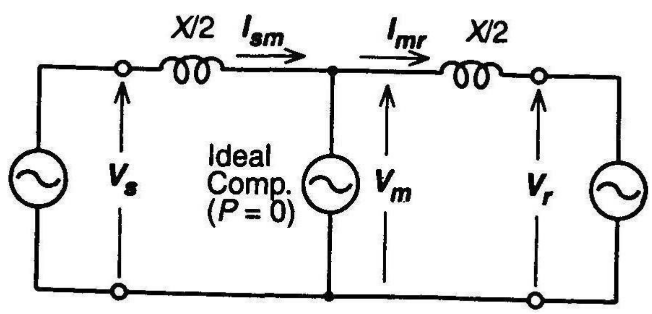
i. At the midpoint to segment the transmission line and
ii. At the end of the line

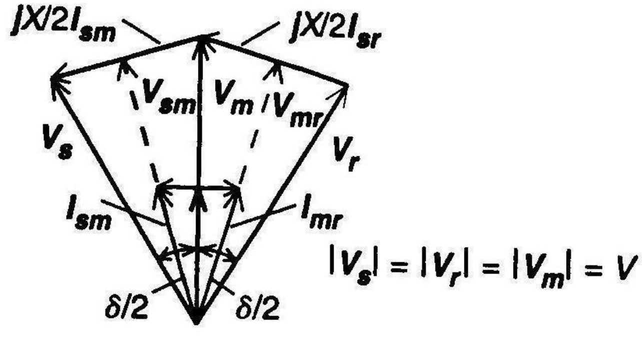
To prevent "voltage intangibility as well as for dynamic voltage control to increase transient stability and to damp out power oscillations".

MID-POINT VOLTAGE REGULATION FOR LINE SEGMENTATION:

Consider simple two-machine(two-bus)transmission model in which an ideal var compensator is shunt connected at the midpoint of the transmission line

FIG:





The line is represented by the series line inductance. The compensator is represented by a "sinusoidal ac voltage source". The mid-point compensator in effect segments the transmission line into two independent parts

1. The first segment, with an impedance of (f) carries power from the sending end to mid-point.
11. The second segment also with an impedance of G) carries power from midpoint to the receiving end

The relationship between voltages 11s,½- *and* V_m line currents/$_{sm}$ *and* I_{mr} is shown

For the loss-less system, the real power is same at each terminal (ie, sending and, midpoint and receiving end" of the line. From the vector diagram,

$$V_{sm} = V_{mr} = V\cos\left(\frac{\delta}{4}\right);$$

$$I_{sm} = I_{mr} = I = \frac{V}{\left(\frac{X}{4}\right)}\sin\left(\frac{\delta}{4}\right) = \frac{4V}{X}\sin\left(\frac{\delta}{4}\right)$$

The transmitted power is, $P = V_{sm}I_{sm} = V_{mr}I_{mr}$

$$P = \left[v_M.\cos\left(\frac{\delta}{4}\right)\right].I = VI\cos\left(\frac{\delta}{4}\right)$$

=v.[: *sin( )]* COS( )

=$\frac{2V^2}{X}$ 2sm $\left(\frac{0}{4}\right)$ cos $\left(\frac{0}{4}\right)$

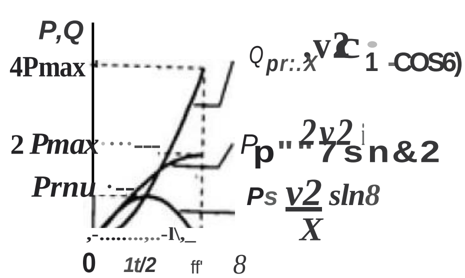
$$=\frac{2V^2}{X}\sin\left(2.\frac{\delta}{4}\right)$$

$$=\frac{2V^2}{X}\sin\left(\frac{\delta}{2}\right)$$

Active power, Q=VI *sin* (f)

$$=\frac{4V^2}{X}\left[1-\cos\left(\frac{\delta}{2}\right)\right]$$

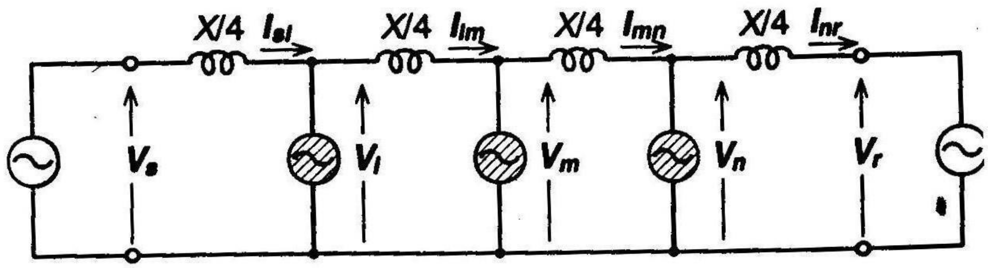
The relationship between real power (P), reactive power(Q) and 'o' for ideal shunt compensation is shown in fig



It can be observed that the midpoint shunt compensation can increase transmittable power significantly (doubling maximum value).

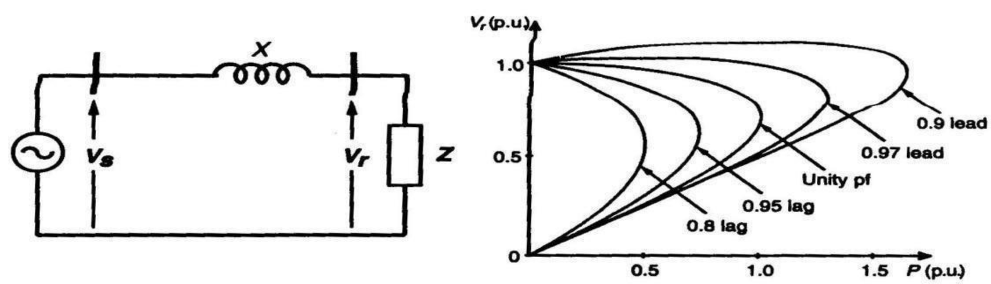
NOTE:

i. The midpoint of the transmission line is the best location for compensator because the voltage sage along the uncompensated transmission line is the longest at the midpoint
ii. The concept of transmission line segmentation can be expanded to use of multiple compensators, located at equal segments of the transmission line as shown in fig.



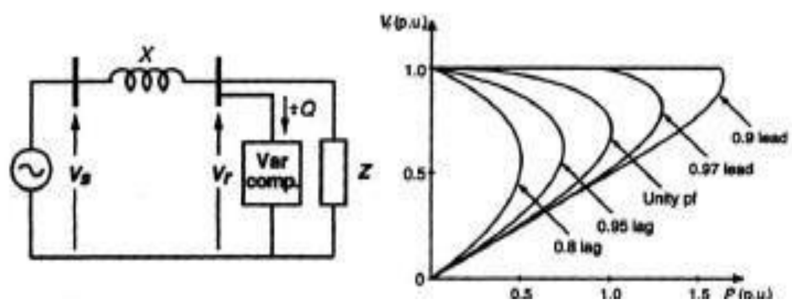
END OF LINE VOLTAGE TO SUPPORT TO PREVENT VOLTAGE INSTABILITY:

A simple radial system with feeder line reactance X and load impedance Z is shown.



The plot shows variation of normalized voltage(V_r) ,(V_s) power at different power factors ranging from 0.8 lag to 0.9 lo9ad. It should be that noted that voltage stability limit decreases with inductive loads and increases with capacitive loads.

i. The shunt compensation can effectively increase the voltage stability by supplying reactive load neglecting terminal voltage as shown in fig:



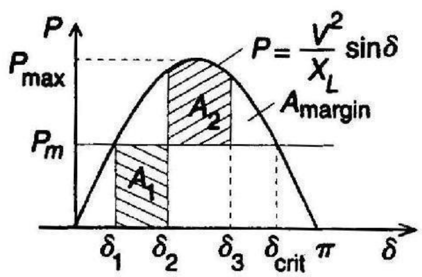
NOTE:

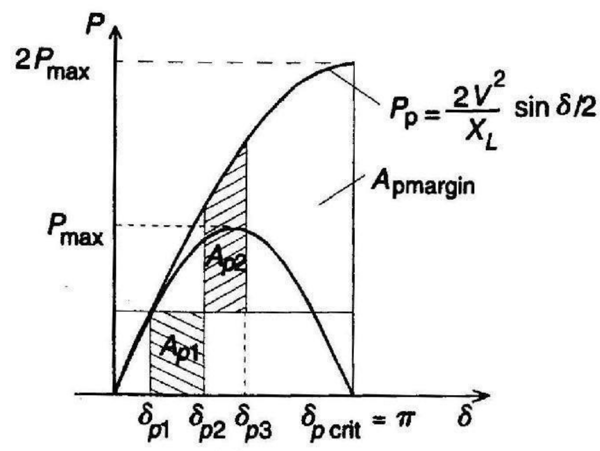
1. For a radial line , the end of the line, where the largest voltage variation is experienced, is the best location for the compensator.
2. Reactive shunt compensation is often used too regulate voltage support for the load when capacity of sending –end system becomes impaired.

IMPROVEMENT OF TRANSIENT STABILITY:

The shunt compensation will be able to change the power flow in the system during and following disturbances. So as to increase the transient stability limit. The potential effectiveness of shunt on transient stability improvement can be conveniently evaluated by "EQUAL AREA CRITERION".

Assume that both the uncompensated and compensated systems are subjected to the same fault for the same period of time. The dynamic behavior of these systems is illustrated in the following figures.





METHODS OF CONTROLLABLE VAR GENERATION:

Capacitors generate and inductors (reactors)absorb reactive power when connected to an ac power source. They have been used with mechanical switches for controlled var generation and absorption. Continuously variable var generation or absorption for dynamic system compensation as originally provided by

- over or under-excited rotating synchronous machines
- saturating reactors in conjunction with fixed capacitors

Using appropriate switch control, the var output can be controlled continuously from maximum capacitive to maximum inductive output at a given bus voltage.

More recently gate turn-off thyristors and other power semiconductors with internal turn off capacity have been use of ac capacitors or reactors.

\ a.1fable Impeda1rne T iPe S anr Var Generato,rs

ll•e peFjorm.mff'e a11d'opm-ati',ugd1amct:e1iistics of the iiupedance it,.pe J•a gei,e.i-ator m-edmieJ'miJied ,bl tJ1ei'i•major tii•iistor-s"'oo1;,n'i0lkd'ctmstih-1e11ts:·

(l)'Ihyristor Oonwllled Reac.mr(T ·R

(i:t)Tb:jristor S1,ritched Capacito!(TSC)

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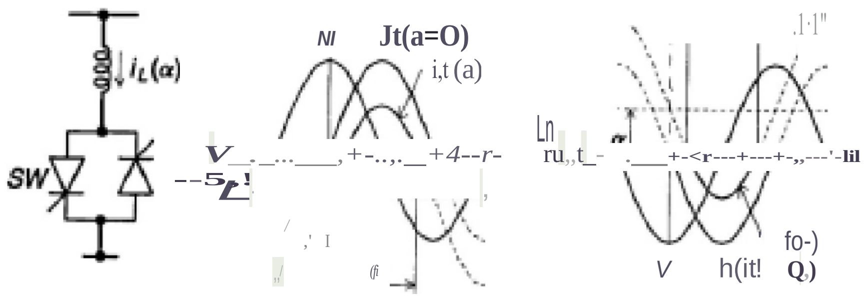
J\n eleme:maiy sm.gle-.pha:reihyristors-comroUed reactor• s_h, wn in fig..



It oowists of a fixed (i1.mi1aly air-oor,e) reactor of **indluct L, and a bidirectional thyristors valve(or switch).** Currently available large thyristors can hlock volfcage np to 4000 to 9000 voUs and. conduct cm:r,em:up to 000 to 6000 amperes..Tims, in:praotica] ma:nythyr.i.stors.are oonne,cited :in s,eries.to meet the :required bfock:ing .roUage 1eve . at ai gi.re:npowe:r rating.

A thy,r. ors.valve can.be brought into oondluction by sinrul.taneons applliclI•it on.of ai g,aite :pnllie to all thyristors of t:Ele srune polarity..The valve will. ll!utonmticalllyblock .immediately after the: ai..c C1I1,rrent z.ero, mtl lhe: gaite signail is. Je hed..

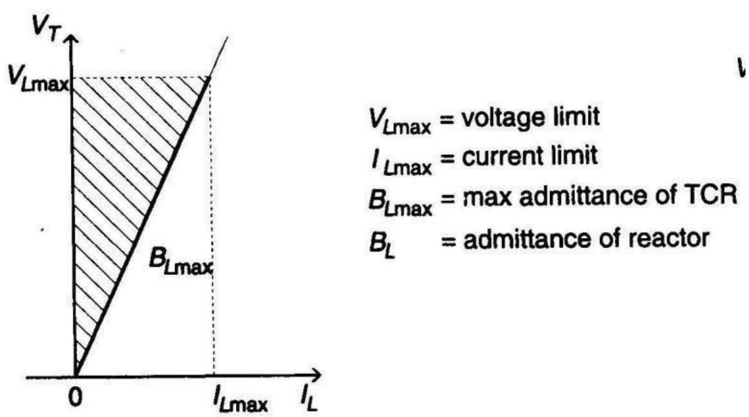
The: cmR-nt· ·the reactor cm.be comroUed.:fii:"o:w.maxi.w.nm.(t!hyristor\:r,d.re closed) ·teoro(thyri.s,to.rvah:reo.1>eu) by the mefllod.of firing delay angl\e control Unt is:, thedo·11.we ofthe t!hyru;tor . \:ralv.eis: del!ayed w.Li the peak of t:Ele applied.\:rollage .m.,ellJC!hh. alf cycl\e and t1ru,s ·the dmahon of the cuneut oondirtction :interva is: comro!lled. The: method. of cu:rrent oomrol is:.illnstr,3ited sep,anite1y ID£ tihe pooiti :e rum ne tn.:recurrent half cydes :in :fig..(b). where a.pplli.ed ,:rollage . anclthe reactor ou:rrem• ,ra) at zero dlelaiy angle rum at arbitr,11:y rm delaiyangle are sill, i.vu

- When ra=O ·the '1.:rahe closes at ·the crest ofthe:applied voli'age • ev.ident.1.y·the resulting cm:re in the Je.a.ctor v.'lll be the same ,as,that obtained in .ady state with a p t]ydosed witch.
- When t:Ele gating ofthe \:rail ·,e• delayed by an angle ro.(O:Srll'.S90) 'Wiffll.respect to the ere o:f th-eo:H:age, The cnrrent• ·the reacto1·c.m.be expressed with .(t)=\ oos.rot as fullows:

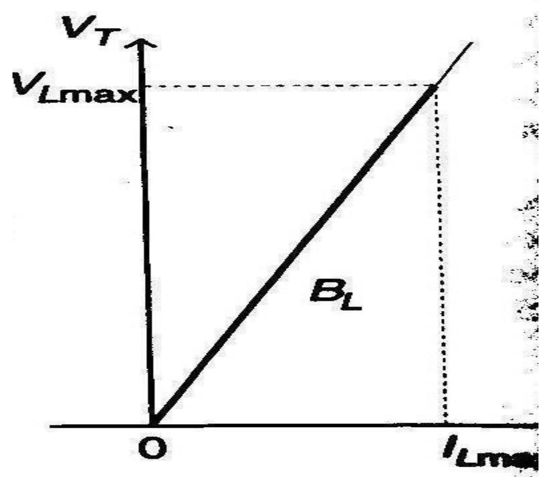
$$h.'t) = \frac{1}{l}\int_{a}^{wr} v(t)d't - \frac{V}{rul}(\sin rut - \sin a)$$

It is evident that the magnitude of current in the reactor can be varied continuously by the method of delay angle control from maximum (α=0) to zero (α=90).

In practice, the maximum magnitude of the applied voltage and that of the corresponding current will be limited by the ratings of the power components(reactor and thyristor valve)used. Thus, a practical TCR can be operated anywhere in a defined V-I area ,the boundaries of which are determined by its maximum attainable admittance, voltage and current ratings are shown in fig.



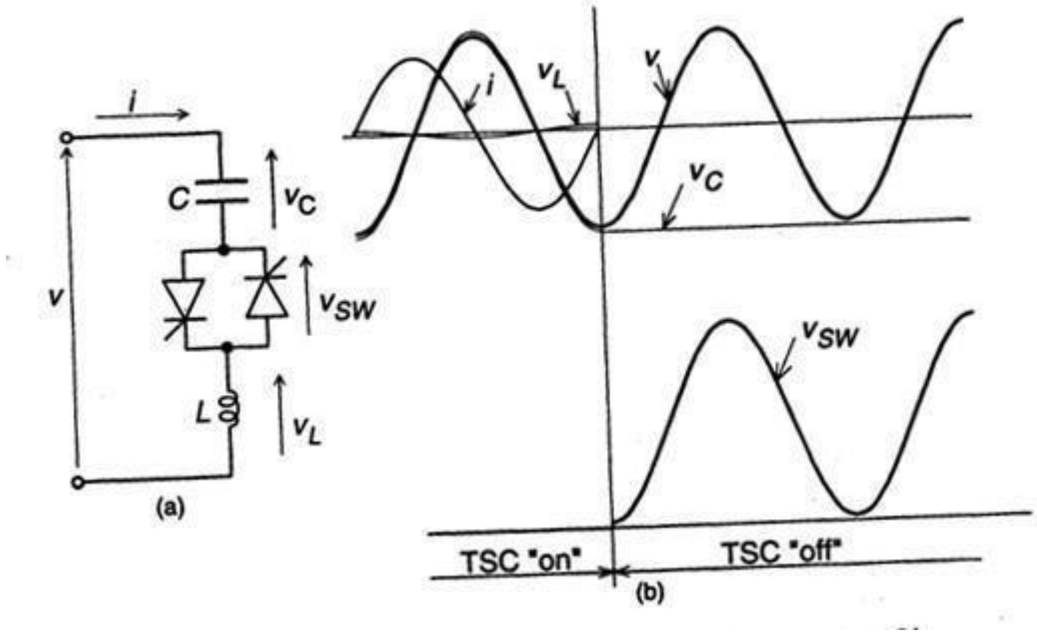
Note: If Thyristor Controlled Reactor(TCR) switching is restricted to a fixed delay angle, usually α=0, then it becomes a thyristors – switched reactor (TSR). The TSR provides a fixed inductive admittance. Thus, when connected to the a.c. system, the reactive current in it will be proportional to the applied voltage as shown in fig.



TSRs can provide at α=0, the resultant steady-state current will be sinusoidal.

THYRISTOR SWITCHED CAPACITOR(TSC):

A single-phase thyristors switched capacitor (TSC) is shown in fig.



It consists of a capacitor, a bi-directional thyristors valve, and a relatively small surge current limiting reactor. This reactor is needed primarily

To limit the surge current in the thyristors valve under abnormal operating conditions To avoid

resonances with the a.c. system impedance at particular frequencies

Under steady state conditions, when the thyristor valve is closed and the TSC branch is connected to a sinusoidal a.c. voltage source, υ=Vsin ωt, the current in the branch is given by

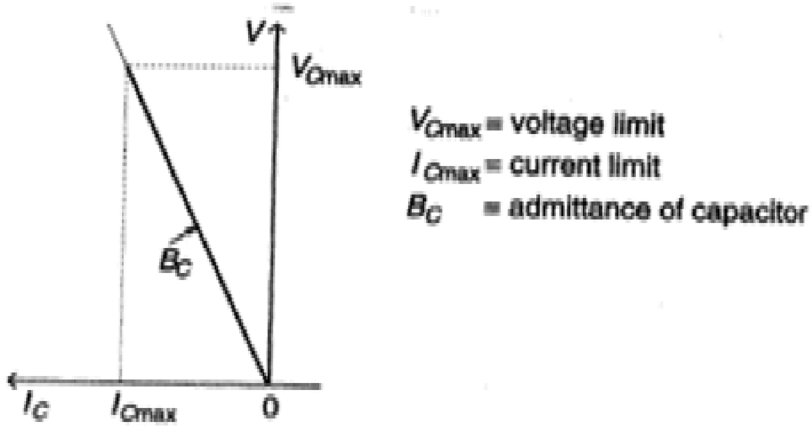
$$i(\omega t) = V\frac{n^2}{n^2-1}\ \omega C \cos\omega t$$

$$\text{where } n = \frac{1}{\sqrt{\omega^2 LC}} = \sqrt{\frac{X_c}{X_L}}$$

The amplitude of voltage across capacitor is given by $V_c = \frac{n^2}{n^2-1}V$

The TSC branch can be disconnected ("switched out") at any current zero by prior removal of the gate drive to the thyristor valve. At the current zero crossing, the capacitor voltage is at its peak valve. The disconnected capacitor stays charged to this voltage, and consequently the voltage across the non-conducting thyristors valve varied between zero and the peak-to-peak value of the applied a.c. voltage as shown in fig.(b).

The TSC branch represents a single capacitive admittance which is either connected to, or disconnected from the a.c. system. The current in the TSC branch varies linearly with the applied voltage according to the admittance of the capacitor as illustrated by the V-I plot in the following fig.



It is observed that , maximum applicable voltage and the corresponding current are limited by the ratings of the TSC components(capacitor and thyristor valve).To approximate continuous current variation, several TSC branches in parallel may be employed, which would increase in a step-like manner the capacitive admittance.

STATIC VAR COMPENSATOR:

The *static compensator term is used in a general sense to refer to an SVC as well as to a STATCOM.*

The static compensators are used in a power system to increase the power transmission capacity with a given network, from the generators to the loads. Since static compensators cannot generate or absorb real power, the power transmission of the system is affected indirectly by ***voltage control***. That is, the reactive output power (capacitive or inductive) of compensator is varied to control the voltage at given terminals of the transmission network so as to maintain the desired power flow under possible system disturbances and contingencies.

Static Var Compensator(SVC) and Static Synchronous Compensator(STATCOM) are var generators, whose output is varied so as to maintain to control specific parameters of the electric power system.

The basic compensation needs fall into one of the following two main categories

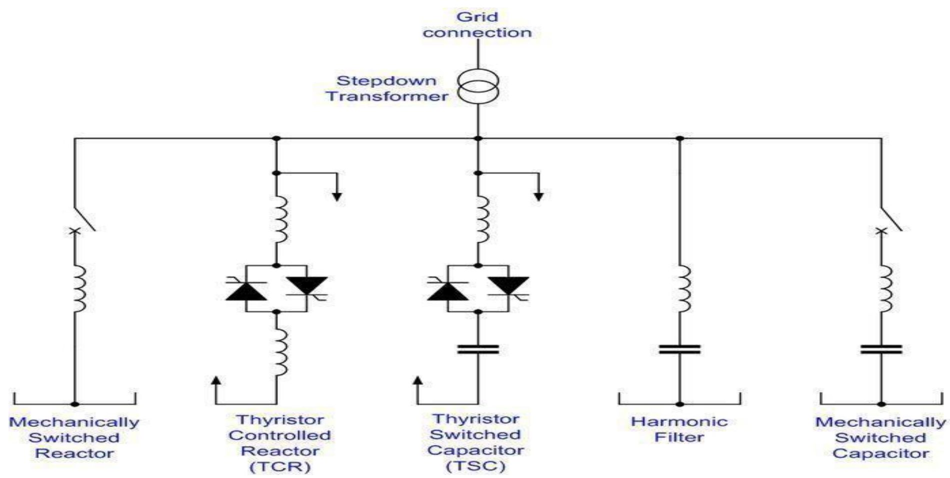
Direct voltage support to maintain sufficient line voltage for facilitating increased power flow under heavy loads and for preventing voltage instability.

Transient and dynamic stability improvements to improve the first swing stability margin and provide power oscillation damping.

SVC:

SVCs are part of the Flexible AC transmission system device family, regulating voltage and stabilizing the system. Unlike a synchronous condenser which is a rotating electrical machine, a "static" VAR compensator has no significant moving parts (other than internal switchgear). Prior to the invention of the SVC, power factor compensation was the preserve of large rotating machines such as synchronous condensers or switched capacitor banks.

Fig.shows Static Var Compensator(SVC).



An SVC comprises one or more banks of fixed or switched shunt capacitors or reactors, of which at least one bank is switched by thyristors. Elements which may be used to make an SVC typically include:

Thyristor controlled reactor (TCR), where the reactor may be air- or iron-cored Thyristor switched capacitor (TSC)

Harmonic filter(s)

Mechanically switched capacitors or reactors (switched by a circuit breaker)

The SVC is an automated impedance matching device, designed to bring the system closer to unity power factor. SVCs are used in two main situations:

Connected to the power system, to regulate the transmission voltage ("Transmission SVC") Connected near large industrial loads, to improve power quality ("Industrial SVC")

Fig.shows V-I Characteristics of SVC.

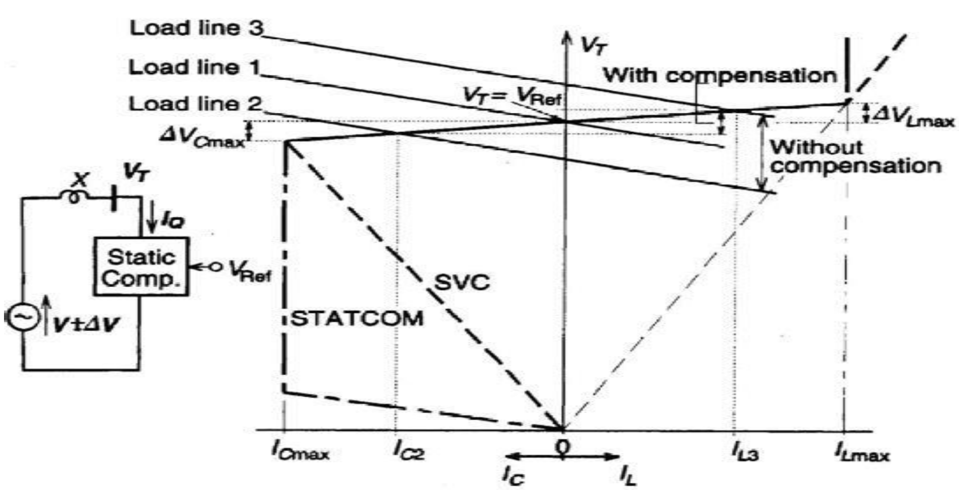
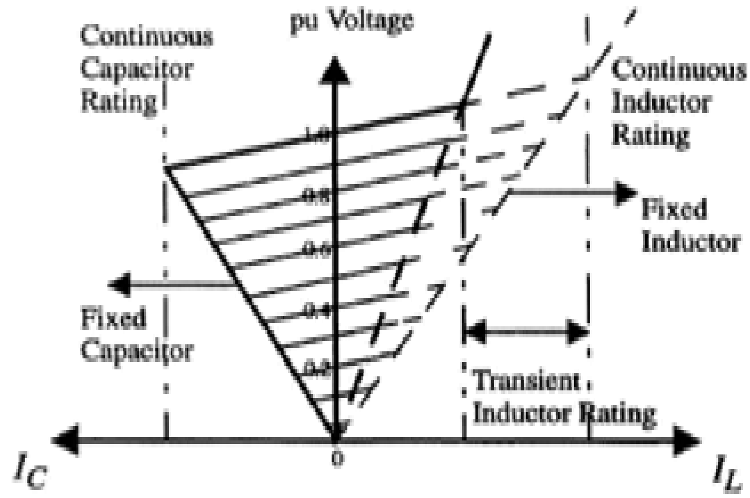


Figure 5.45 V-I characteristic of the SVC and the STATCOM.



(b)

In transmission applications, the SVC is used to regulate the grid voltage. If the power system's reactive load is capacitive (leading), the SVC will use thyristor controlled reactors to consume vars from the system, lowering the system voltage. Under inductive (lagging) conditions, the capacitor banks are automatically switched in, thus providing a higher system voltage. By connecting the thyristor-controlled reactor, which is continuously variable, along with a capacitor bank step, the net result is continuously-variable leading or lagging power.

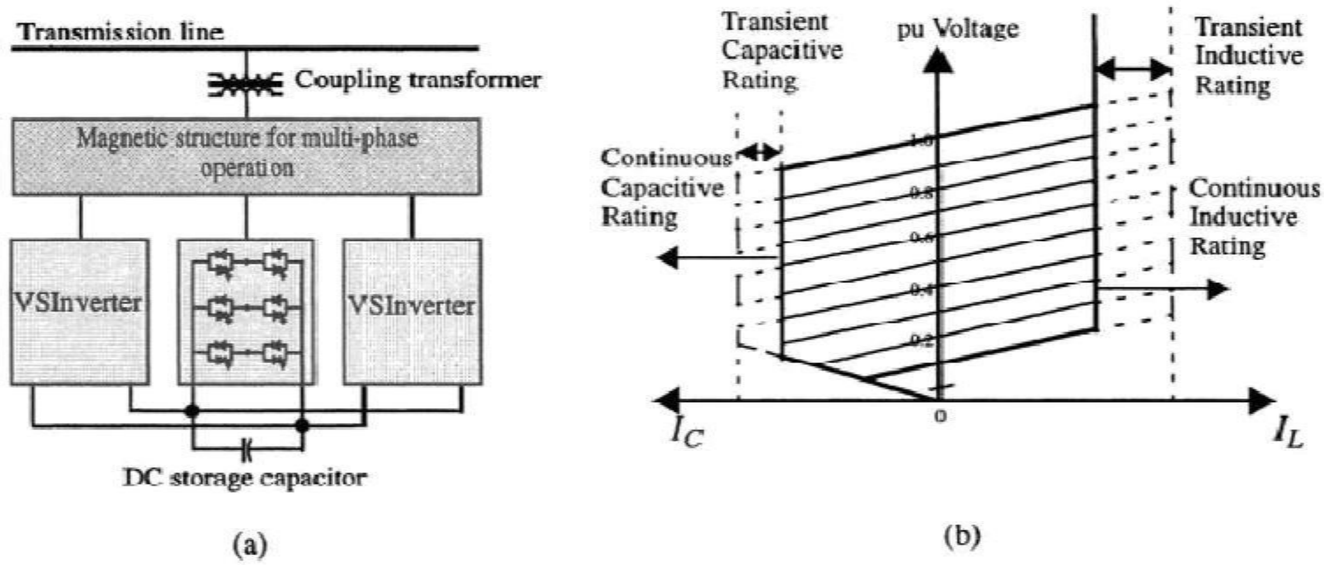
In industrial applications, SVCs are typically placed near high and rapidly varying loads, such as arc furnaces, where they can smooth flicker voltage.

STATCOM:

A **static synchronous compensator** (**STATCOM**), also known as a "static synchronous condenser" ("STATCON"), is a regulating device used on alternating current electricity transmission networks. It is based on a power electronics voltage-source converter and can act as either a source or sink of reactive AC power to an electricity network. If connected to a source of power it can also provide active AC power. It is a member of the FACTS family of devices.

The STATCOM generates a 3-phase voltage source with controllable amplitude and phase angle behind reactance. When the a.c. output voltage from the inverter is higher(lower) than the bus voltage, current flow is caused to lead(lag) and the difference in the voltage amplitudes determines how much current flows. This allows the control of reactive power.

Fig. shows block diagram representation of STATCOM and V-I characteristics.



The STATCOM is implemented by a 6-pulse Voltage Source Inverter(VSI) comprising GTO thyristors fed from a d.c.storage capacitor.The STATCOM is able to control its output current over the rated maximum capacitive or inductive range independently of a.c. system voltage, in contrast to the SVC that varies with the ac system voltage. Thus STATCOM is more effective than the SVC in providing voltage support and stability improvements. The STATCOM can continue to produce capacitive current independent of voltage.The amount and duration of the overload capability is dependent upon the thermal capacity of the GTO.

Note : Multi-pulse circuit configurations are employed to reduce the harmonic generation and to produce practically sinusoidal current.

Comparison between STATCOM and SVC:

S.No.	STATCOM	SVC
1	Acts as a voltage source behind a reactance	Acts as a variable susceptance
2	Insensitive to transmission system harmonic resonance	Sensitive to transmission system harmonic resonance
3	Has a larger dynamic range .	Has a smaller dynamic voltage
4	Lower generation of harmonics .	Higher generation of harmonics
5	Faster response and better performance during transients	Somewhat slower response
6	Both inductive and capacitive regions of operation is possible	Mostly capacitive region of operation
7	Can maintain a stable voltage even with a very weak a.c. system	Has difficulty operating with a very weak a.c. system

STATIC SYNCHRONOUS SERIES COMPENSATOR

3.1 INTRODUCTION

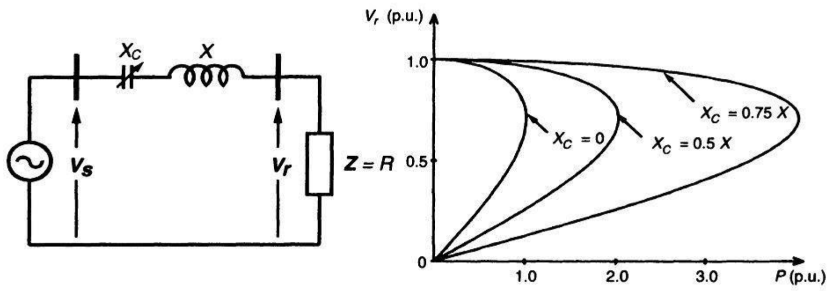
Series compensation is a means of controlling the power transmitted across transmission lines by altering or changing the characteristic impedance of the line. The power flow problem may be related to the length of the transmission line. The transmission line may be compensated by a fixed capacitor or inductor to meet the requirements of the transmission system. When the structure of the transmission network is considered, power flow imbalance problems arise. Inadvertent interchange occurs when the power system tie line becomes corrupted. This is because of unexpected change in load on a distribution feeder due to which the demand for power on that feeder increases or decreases. The generators are to be turned on or off to compensate for this change in load. If the generators are not activated very quickly, voltage sags or surges can occur. In such cases, controlled series compensation helps effectively.

3.2 SERIES COMPENSATOR

Series compensation, if properly controlled, provides voltage stability and transient stability improvements significantly for post-fault systems. It is also very effective in damping out power oscillations and mitigation of sub-synchronous resonance (Hingorani 2000).

3.2.1 Voltage Stability

Series capacitive compensation reduces the series reactive impedance to minimize the receiving end voltage variation and the possibility of voltage collapse. Figure 3.1 (a) shows a simple radial system with feeder line reactance X, series compensating reactance X_c and load impedance Z. The corresponding normalized terminal voltage V_r versus power P plots, with unity power factor load and 0, 50, and 75% series capacitive compensation, are shown in Figure 3.1(b). The "nose point" at each plot for a specific compensation level represents the corresponding voltage instability. So by cancelling a portion of the line reactance, a "stiff" voltage source for the load is given by the compensator.



(a) (b)

Figure 3.1 Transmittable power and voltage stability limit of a radial transmission line as a function of series capacitive compensation

3.2.2 Transient Stability Enhancement

The transient stability limit is increased with series compensation. The equal area criterion is used to investigate the capability of the ideal series compensator to improve the transient stability.

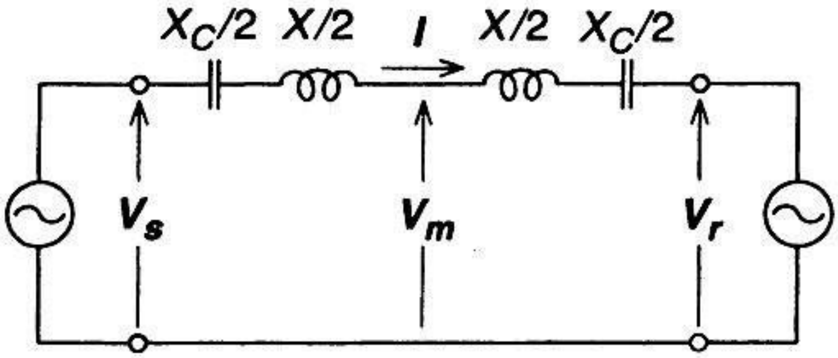


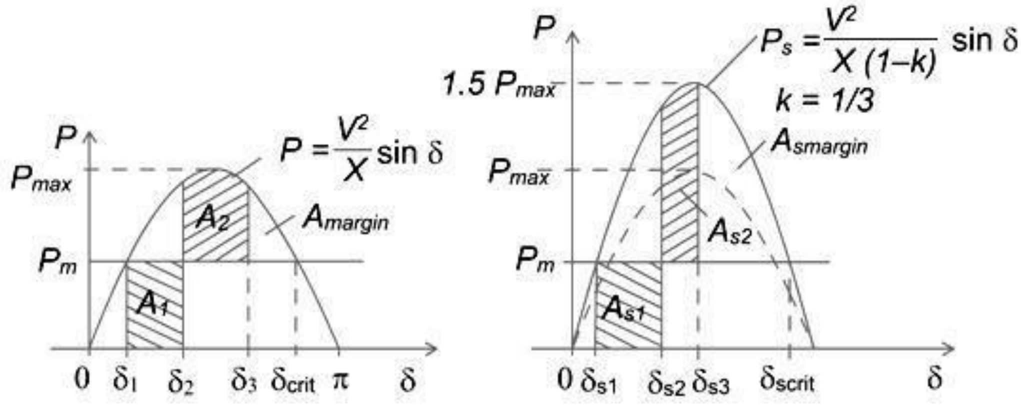
Figure 3.2 Two machine system with series capacitive compensation

Figure 3.2 shows the simple system with the series compensated line. Assumptions that are made here are as follows:

- The pre-fault and post-fault systems remain the same for the series compensated system.
- The system, with and without series capacitive compensation, transmits the same power P_m.
- Both the uncompensated and the series compensated systems are subjected to the same fault for the same period of time.

Figures 3.3 (a) and (b) show the equal area criterion for a simple two machine system without and with series compensator for a three phase to ground fault in the transmission line. From the figures, the dynamic behaviour of these systems are discussed.

Prior to the fault, both of them transmit power P_m at angles 6_1 and 6_{s1} respectively. During the fault, the transmitted electric power becomes zero, while the mechanical input power to the generators remains constant (P_m). Hence, the sending end generator accelerates from the steady-state angles 6_1 and 6_{s1} to 6_2 and 6_{s2} respectively, when the fault clears. In the figures, the accelerating energies are represented by areas A_1 and A_{s1}. After fault clearing, the transmitted electric power exceeds the mechanical input power and therefore the sending end machine decelerates. However, the accumulated kinetic energy further increases until a balance between the accelerating and decelerating energies, represented by the areas A_1, A_{s1} and A_2, A_{s2}, respectively, are reached at the maximum angular swings, 6_3 and 6_{s3} respectively. The areas between the P versus 6 curve and the constant P_m line over the intervals defined by angles 6_3 and 6_{crit}, and 6_{s1} and 6_{scrit}, respectively, determine the margin of transient stability represented by areas A_{margin} and $A_{smargin}$ for the system without and with compensation.



(a) (b)

Figure 3.3 Equal area criterion to illustrate the transient stability margin for a simple two-machine system (a) without compensation and (b) with a series capacitor

Comparing figures 3.3(a) and (b), it is clear that there is an increase in the transient stability margin with the series capacitive compensation by partial cancellation of the series impedance of the transmission line. The increase of transient stability margin is proportional to the degree of series compensation.

3.2.3 Power Oscillation Damping

Power oscillations are damped out effectively with controlled series compensation. The degree of compensation is varied to counteract the accelerating and decelerating swings of the disturbed machine(s) for damping out power oscillations. When the rotationally oscillating generator accelerates and angle 6 increases (d6/dt > 0), the electric power transmitted must be increased to compensate for the excess mechanical input power and conversely, when the generator decelerates and angle 6 decreases (d6/dt < 0), the electric power must be decreased to balance the insufficient mechanical input power.

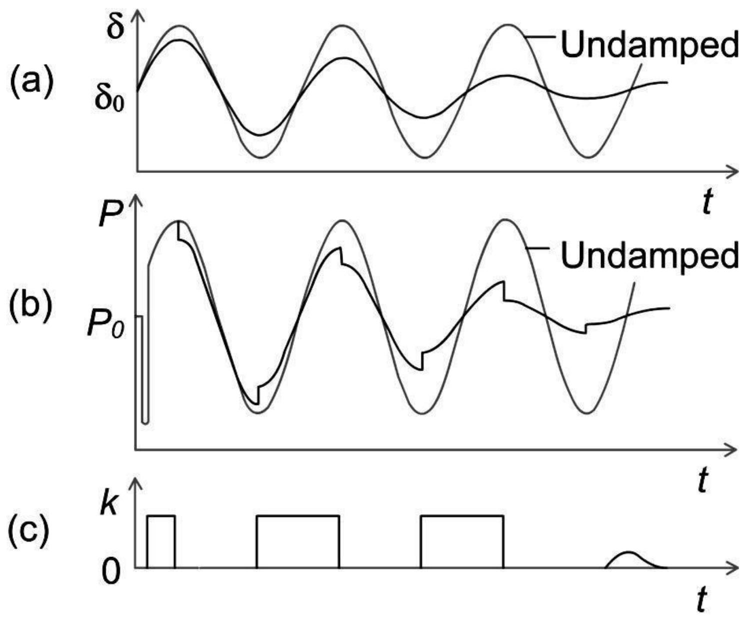


Figure 3.4 Waveforms illustrating power oscillation damping by controllable series compensation (a) generator angle (b) transmitted power and (c) degree of series compensation

Figure 3.4 shows the waveforms describing the power oscillation damping by controllable series compensation. Waveforms in figure 3.4(a) show the undamped and damped oscillations of angle 6 around the steady state value 6_0. The corresponding undamped and damped oscillations of the electric power P around the steady state value P_0, following an assumed fault (sudden drop in P) that initiated the oscillation are shown by the waveforms in figure 3.4(b). Waveform 3.4 (c) shows the applied variation of the degree of series compensation, k applied. ‘k’ is maximum when $d6/dt > 0$, and it is zero when $d6/dt < 0$.

3.2.4 Immunity to Sub-synchronous Resonance

The sub-synchronous resonance is known as an electric power system condition where the electric network exchanges energy with a turbine generator at one or more of the natural frequencies of the combined system below the synchronous frequency of the system. With controlled series compensation, the resonance zone is prohibited for operation and the control system is designed in such a way that the compensator does not enter that area. Also, an SSSC is an ac voltage source operating only at the fundamental output frequency and its output impedance at any other frequency should be zero. The SSSC is unable to form a series resonant circuit with the inductive line impedance to initiate sub-synchronous system oscillations.

3.2.5 Types of Series Compensators

Series compensation is accomplished either using a variable impedance type series compensators or a switching converter type series compensator.

3.2.5.1 Variable impedance type series compensators

The thyristor controlled series compensators are the variable type of compensators. The type of thyristor used for the variable type series compensators has an impact on their performance. The types of thyristors used in FACTS devices are Silicon Controller Rectifier (SCR), Gate Turn-Off Thyristor (GTO), MOS Turn-Off Thyristor (MTO), Integrated Gate Commutated Thyristor (GCT or IGCT), MOS Controlled Thyristor (MCT) and Emitter Turn-Off Thyristor (ETO). Each of these types of thyristors has several important device parameters that are needed for the design of FACT devices. These parameters are di/dt capability, dv/dt capability, turn-on time and turn-off time, Safe Operating Area (SOA), forward drop voltage, switching speed, switching losses, and gate drive power.

The variable impedance type series compensators are GTO thyristor controlled series compensator (GCSC), Thyristor Switched Series Capacitor (TSSC) and Thyristor Controlled Series Capacitor (TCSC).

GTO Thyristor Controlled Series Capacitor (GCSC)

A GCSC consists of a fixed capacitor in parallel with a GTO Thyristor as in figure 3.5which has the ability to be turned on or off. The GCSC controls the voltage across the capacitor (V_c) for a given line current. In other words, when the GTO is closed the voltage across the capacitor is zero and when the GTO is open the voltage across the capacitor is at its maximum value. The magnitude of the capacitor voltage can be varied continuously by the method of delayed angle control (max y = 0, zero y = n/2). For practical applications, the GCSC compensates either the voltage or reactance.

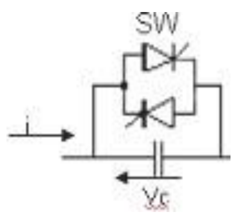


Figure 3.5 GTO Controlled Series Capacitor

Thyristor Switched Series Capacitor (TSSC)

Thyristor Switched Series Capacitor (TSSC) is another type of variable impedance type series compensators shown in Figure 3.6. The TSSC consists of several capacitors shunted by a reverse connected thyristor bypass switch.

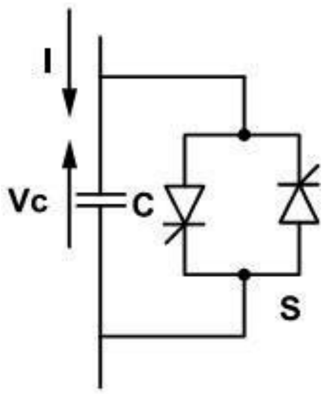


Figure 3.6 Thyristor Switched Series Capacitor

In TSSC, the amount of series compensation is controlled in a step-like manner by increasing or decreasing the number of series capacitors inserted into the line. The thyristor turns off when the line current crosses the zero point. As a result, capacitors can only be inserted or deleted from the string at the zero crossing. Due to this, a dc offset voltage arises which is equal to the amplitude of the ac capacitor voltage. In order to keep the initial surge current at a minimum, the thyristor is turned on when the capacitor voltage is zero.

The TSSC controls the degree of compensating voltage by either inserting or bypassing series capacitors. There are several limitations to the TSSC. A high degree of TSSC compensation can cause sub-synchronous resonance in the transmission line just like a traditional series capacitor. The TSSC is most commonly used for power flow control and for damping power flow oscillations where the response time required is moderate. There are two modes of operation for the TSSC-voltage compensating mode and impedance compensating mode.

Thyristor Controlled Series Capacitor (TCSC)

Figure 3.7 shows the basic Thyristor Controlled Series Capacitor (TCSC) scheme. The TCSC is composed of a series-compensating capacitor in parallel with a thyristor-controlled reactor. The TCSC provides a continuously variable capacitive or inductive reactance by means of thyristor firing angle control. The parallel LC circuit determines the steady-state impedance of the TCSC.

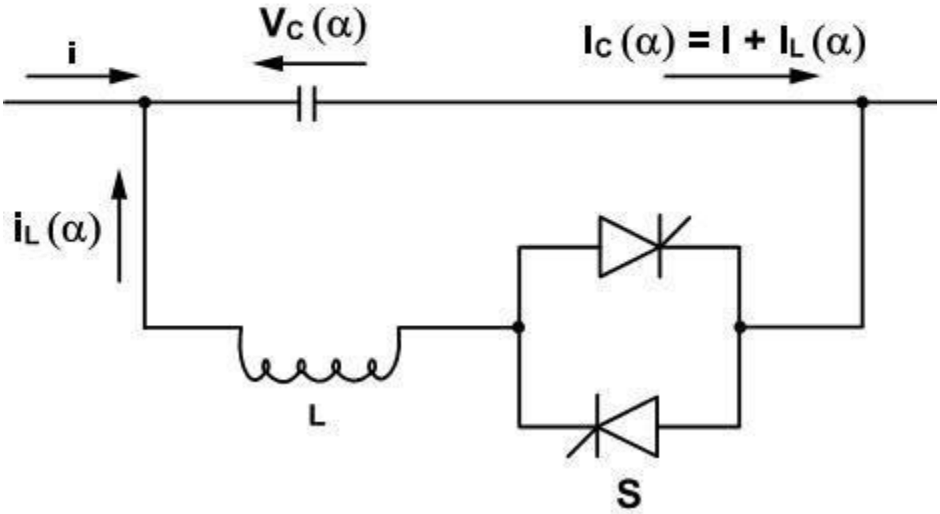


Figure 3.7 Thyristor Controlled Series Capacitor

The impedance of the controllable reactor is varied from its maximum (infinity) to its minimum (mL). The TCSC has two operating ranges; one is when $a_{Clim} \leq a \leq n/2$, where the TCSC is in capacitive mode. The other range of operation is $0 \leq a \leq a_{Llim}$, where the TCSC is in inductive mode. TCSC can be operated in impedance compensation mode or voltage compensation mode.

3.2.5.2 Switching converter type compensator

With the high power forced-commutated valves such as the GTO and ETO, the converter-based FACTS controllers have become true. The advantages of converter-based FACTS controllers are continuous and precise power control, cost reduction of the associated relative components and a reduction in size and weight of the overall system.

An SSSC is an example of a FACTS device that has its primary function to change the characteristic impedance of the transmission line and thus change the power flow. The impedance of the transmission line is changed by injecting a voltage which leads or lags the transmission line current by 90°.

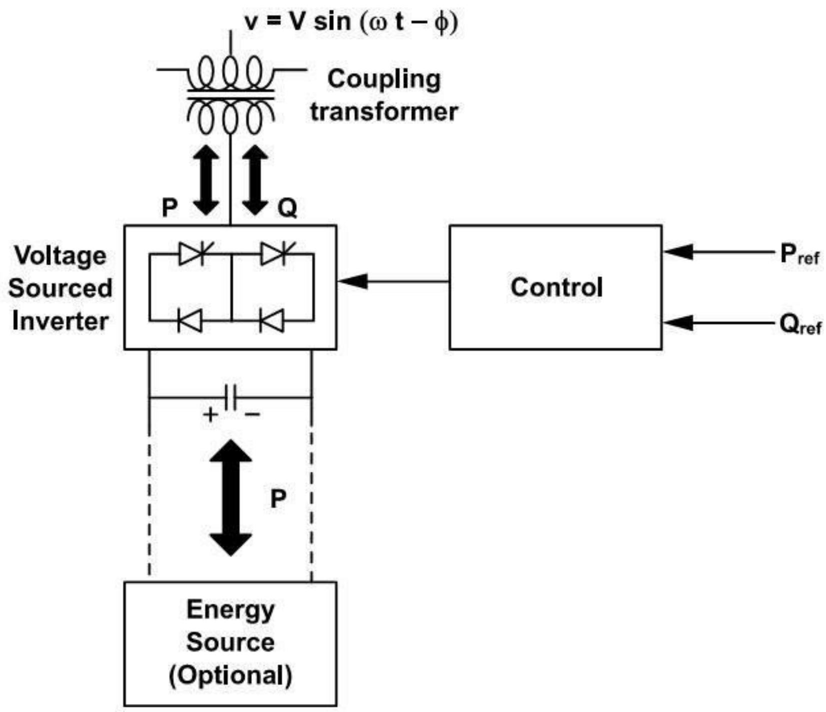


Figure 3.8 Schematic diagram of SSSC

If the SSSC is equipped with an energy storage system, the SSSC gets an added advantage of real and reactive power compensation in the power system. By controlling the angular position of the injected voltage with respect to the line current, the real power is provided by the SSSC with energy storage element. Figure 3.8 shows a schematic diagram of SSSC with energy storage system for real and reactive power exchange.

The applications for an SSSC are the same as for traditional controllable series capacitors. The SSSC is used for power flow control, voltage stability and phase angle stability. The benefit of the SSSC over the conventional controllable series capacitor is that the SSSC induces both capacitive and inductive series compensating voltages on a line. Hence, the SSSC has a wider range of operation compared with the traditional series capacitors.

The primary objective of this thesis is to examine the possible uses of the SSSC with energy storage system with state-of-the-art power semiconductor devices in order to provide a more cost effective solution.

3.2.5.3 Comparison of Series Compensator Types

Figure 3.9 shows a comparison of VI and loss characteristics of variable type series compensators and the converter based series compensator.

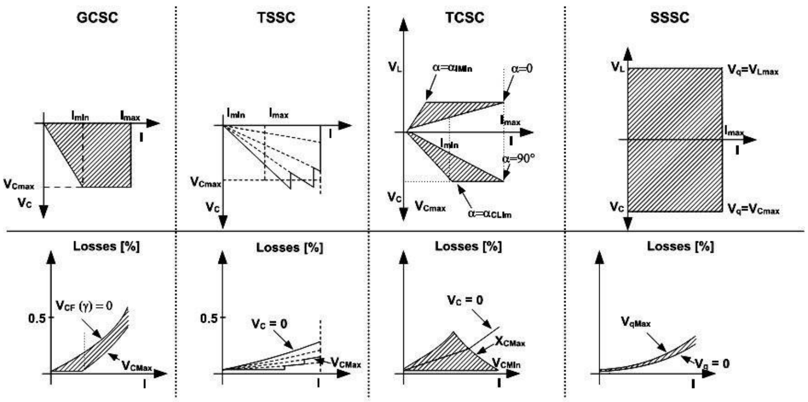


Figure 3.9 Comparison of Variable Type Series Compensators to Converter Type Series Compensator

From the figure the following conclusions can be made.

- The SSSC is capable of internally generating a controllable compensating voltage over any capacitive or inductive range independent of the magnitude of the line current. The GCSC and the TSSC generate a compensating voltage that is proportional to the line current. The TCSC maintains the maximum compensating voltage with decreasing line current but the control range of the compensating voltage is determined by the current boosting capability of the thyristor controlled reactor.
- The SSSC has the ability to be interfaced with an external dc power supply. The external dc power supply is used to provide compensation for the line resistance. This is accomplished by the injection of real power as well as for the line reactance by the injection of reactive power. The variable impedance type series compensators cannot inject real power into the transmission line. They can only provide reactive power compensation.
- The SSSC with energy storage can increase the effectiveness of the power oscillation damping by modulating the amount of series compensation in order to increase or decrease the transmitted power. The SSSC increases or decreases the amount of transmitted power by injecting positive and negative real impedances into the transmission line. The variable-type series compensators can damp the power oscillations by modulating the reactive compensation.

3.3 STATIC SYNCHRONOUS SERIES COMPENSATOR (SSSC)

The Voltage Sourced Converter (VSC) based series compensators - Static Synchronous Series Compensator (SSSC) was proposed by Gyugyi in 1989. The single line diagram of a two machine system with SSSC is shown in Figure 3.10. The SSSC injects a compensating voltage in series with the line irrespective of the line current. From the phasor diagram, it can be stated that at a given line current, the voltage injected by the SSSC forces the opposite polarity voltage across the series line reactance. It works by increasing the voltage across the transmission line and thus increases the corresponding line current and transmitted power.

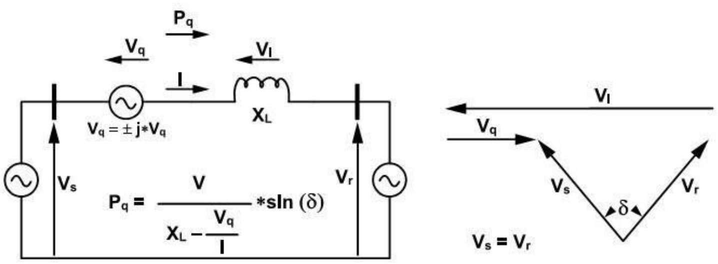


Figure 3.10 Simplified diagram of series compensation with the phasor diagram.

The compensating reactance is defined to be negative when the SSSC is operated in an inductive mode and positive when operated in capacitive mode. The voltage source converter can be controlled in such a way that the output voltage can either lead or lag the line current by 90^o. During normal capacitive compensation, the output voltage lags the line current by 90^o. The SSSC can increase or decrease the power flow to the same degree in either direction simply by changing the polarity of the injected ac voltage. The reversed (180^o) phase shifted voltage adds directly to the reactive voltage drop of the line. The reactive line impedance appears as if it were increased. If the amplitude of the reversed polarity voltage is large enough, the power flow will be reversed. The transmitted power verses transmitted phase angle relationship is shown in Equation (3.1) and the transmitted power verses transmitted angle as a function of the degree of series compensation is shown in Figure 3.11.

$$P = \frac{V^2}{X}\sin ð + \frac{V}{X} V_q \cos\frac{ð}{2} \qquad (3.1)$$

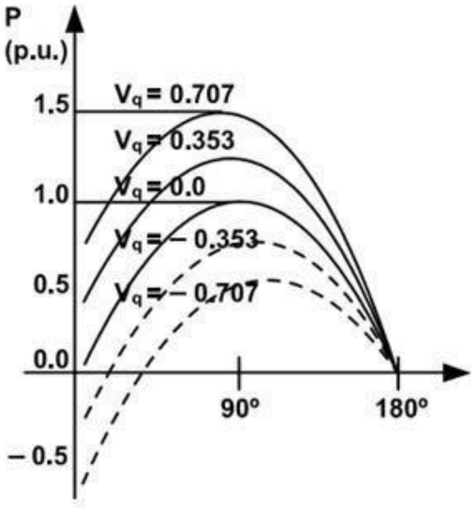


Figure 3.11 Transmitted power verses transmitted angle as a function of series compensation

3.4 CONVERTERS

3.4.1 Basic Concept

The conventional thyristor device has only the turn on control and its turn off depends on the natural current zero. Devices such as the Gate Turn Off Thyristor (GTO), Integrated Gate Bipolar Transistor (IGBT), MOS Turn Off Thyristor (MTO) and Integrated Gate Commutated Thyristor (IGCT) and similar devices have turn on and turn off capability. These devices are more expensive and have higher losses than the thyristors without turn off capability; however, turn off devices enable converter concepts that can have significant overall system cost and performance advantages. These advantages in principle result from the converter, which are self commutating as against the line commutating converters. The line commutating converter consumes reactive power and suffers from occasional commutation failures in the inverter mode of operation. Hence, the converters applicable for FACTS controllers are of self commutating type (Hingorani and Gyugyi, 2000). There are two basic categories of self commutating converters:

UNIT-V

POWER FLOW CONTROLLERS

THE UNIFIED POWER FLOW CONTROLLER

The Unified Power Flow Controller (UPFC) concept was proposed by Gyugyi in 1991. The UPFC was devised for the real-time control and dynamic compensation of ac transmission systems, providing multifunctional flexibility required to solve many of the problems facing the power delivery industry. Within the framework of traditional power transmission concepts, the UPFC is able to control, simultaneously or selectively, all the parameters affecting power flow in the transmission line (i.e., voltage, impedance, and phase angle), and this unique capability is signified by the adjective "unified"
in its name. Alternatively, it can independently control both the real and .reactive power flow in the line. The reader should recall that, for all the Controllers discussed in the previous chapters, the control of real power is associated with similar change in reactive power, i.e., increased real power flow also resulted in increased reactive line power.

Basic Operating Principles of UPFC

From the conceptual viewpoint, the UPFC is a generalized synchronous voltage source (SVS), represented at the fundamental (power system) frequency by voltage phasor $\boldsymbol{V}_{pq}$ with controllable magnitude V_{pq} ($0 \leq V_{pq} \leq V_{pq\max}$) and angle ρ ($0 \leq \rho \leq 2\pi$), in series with the transmission line, as illustrated for the usual elementary two-machine system (or for two independent systems with a transmission link intertie) in Figure 8.3. In this functionally unrestricted operation, which clearly includes voltage and angle regulation, the SVS generally exchanges both reactive and real power with the transmission system. Since, as established previously, an SVS is able to generate only the reactive power exchanged, the real power must be supplied to it, or absorbed from it, by a suitable power supply or sink. In the UPFC arrangement the real power exchanged is provided by one of the end buses (e.g., the sending-end bus), as indicated in Figure 8.3.

In the presently used practical implementation, the UPFC consists of two voltage-sourced converters, as illustrated in Figure 8.4. These back-to-back converters, labeled "Converter 1" and "Converter 2" in the figure, are operated from a common dc link provided by a dc storage capacitor. As indicated before, this arrangement functions as an ideal ac-to-ac power converter in which the real power can freely flow in either direction between the ac terminals of the two converters, and each converter can independently generate (or absorb) reactive power at its own ac output terminal.

Converter 2 provides the main function of the UPFC by injecting a voltage $\boldsymbol{V}_{pq}$ with controllable magnitude V_{pq} and phase angle ρ in series with the line via an insertion transformer. This injected voltage acts essentially as a synchronous ac voltage

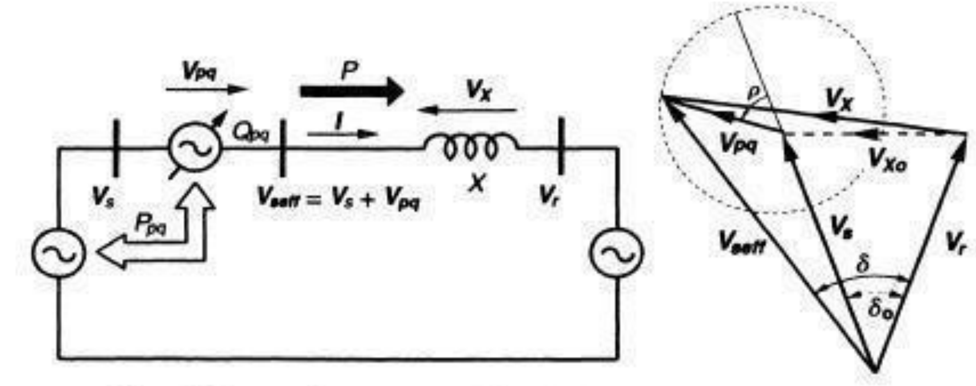


Figure 8.3 Conceptual representation of the UPFC in a two-machine power system.

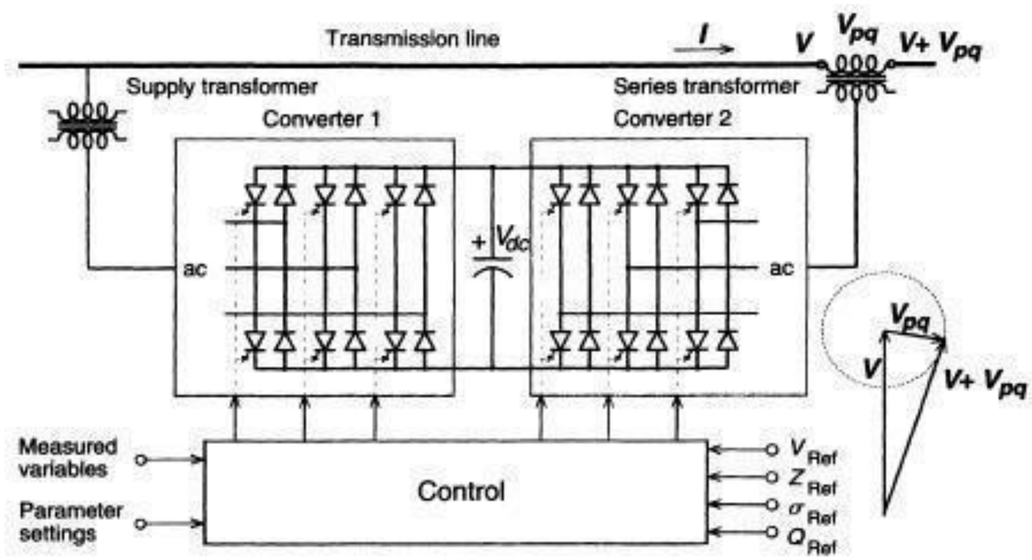


Figure 8.4 Implementation of the UPFC by two back-to-back voltage-sourced converters.

source. The transmission line current flows through this voltage source resulting in reactive and real power exchange between it and the ac system. The reactive power exchanged at the ac terminal (Le., at the terminal of the series insertion transformer) is generated internally by the converter. The real power exchanged at the ac terminal is converted into de power which appears at the de 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 de link to support the real power exchange resulting from the series voltage injection. This de link power demand of Converter 2 is converted back to ac by Converter 1 and coupled to the transmission line bus via a shuntconnected transformer. In addition to the real power need of Converter 2, Converter 1 can also generate or absorb controllable reactive power, if it is desired, and thereby provide independent 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 and 2 back to the line, the corresponding reactive power exchanged is supplied or absorbed locally by Converter 2 and therefore does not have to be transmitted by the line. Thus, Converter 1 can be operated at a unity power factor or be controlled to have a reactive power exchange with the line independent of the reactive power exchanged by Converter 2. Obviously, there can be no reactive power flow through the UPFC de link.

INDEPENDENT REAL AND REACTIVE POWER FLOW CONTROL:

In order to investigate the capability of the UPFC to control reat and reactive power flow in the tra.nsmission line. refer to Figure 8.7(a). Let it first be assum.ed that the injected compensating vohage. ***V***''' is zero. Th.en the original elementary two-machine (or two-bus ac intertie) system with sending-end voltage ***V*.,** receiving-end voltage *V*,., transmission angle *li.* and Jine impedance *X* is restored. **With** t.hese. the normalized transmitted power, $P_0(6)$ = {V^2/X} sin *S* = sin *li,* and the normalized reactive power, *Q0(8)* = *Q&:(6)* = -Q_0,(B) = {V^2/XH1-cos 8} = 1-cos *8,* supplied at the ends of the line. are shown plotted against angle (8) in Figure 8.8(a). The relationship between real power P_0(SJ and reactive power Qo,.(6) can readily be expressed with V^2IX = l in the following form:

$$Q_{0r}(\delta) = -1 - \sqrt{1 - \{P_0(\delta)\}^2} \tag{8.13}$$

or

$$\{Q_{0r}(\delta) + 1\}^2 + \{P_0(\delta)\}^2 = 1 \tag{8.14}$$

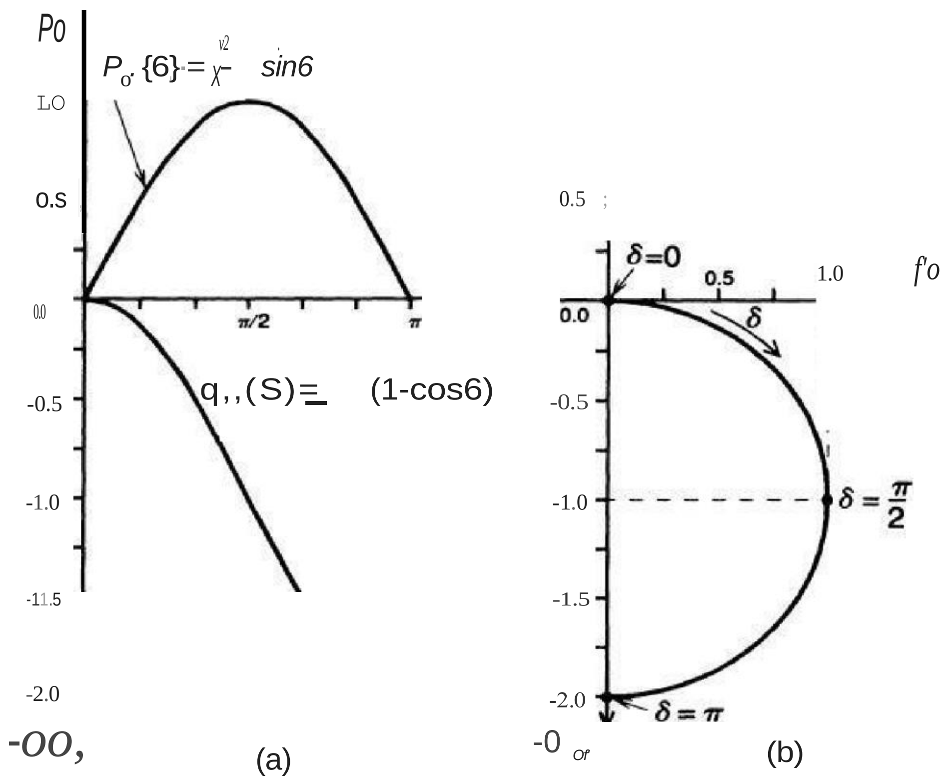


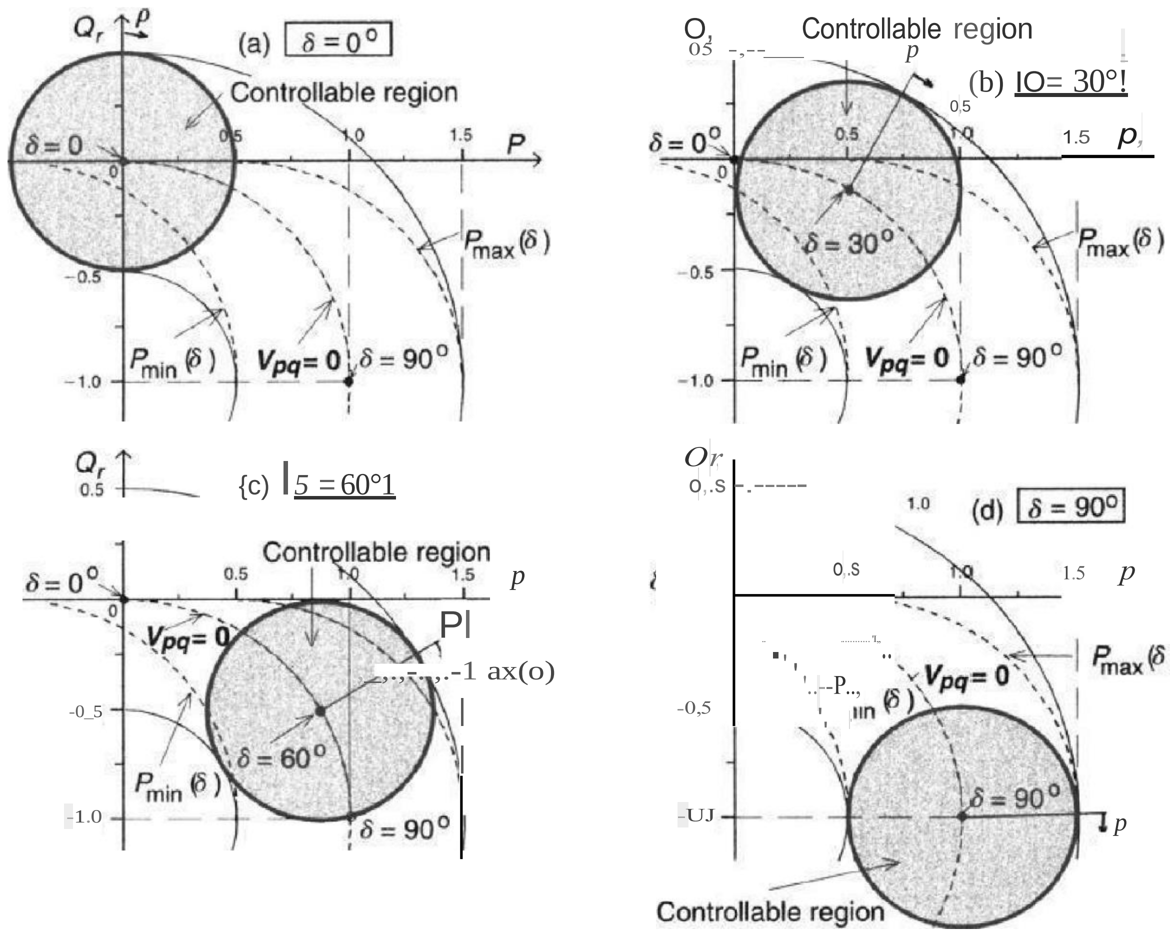
Figure 8.8 Transmiuable real power P_0 and receiving-end reactive power demand Q•• vs. transmission angle 8 of a two-machine system (a) and the corresponding Q., vs. Po loci (b).

Equation (8.14) describes a circle with a radius of 1.0 around the center defined by coordinates P =' 0 and Q, -1 in a {Q,, P} plane.. as illustrated for positive va]ues of P in Figure 8.8(b). Each point of this circle gives the corresponding Po and Q0r values of the uncompensated system at a specific transmission angle 8. For example, at 8 = 0, Prt = 0 and Qo, O; at 8 = 30°,P_0 = 0.5 and Qo, = -0.134; at B = 90°, P_0 = 1.0 and Qo, = -1.0; etc.

Refer again to Figure 8.7(a) and assume now that V_{pq} •,e,0. It follows from (8.3), or (8.7) and (8.8), and fr.om Figure 8.7(b), that the real and reactive power change from their uncompensated values. $P_0(6)$ and $Q_{0,}(8)$, as functions of the magnitude V_{pq} and angle p of the injected voltage phasor V_{pq}• Since ang1e p is an unrestricted variable (0 $\leq p \leq$ 211), the boundary of the attainable control region for $P(8$, p) and $Q,(B$, p) is obtained from a complete rotation of pbasor V,., with its maximum magnitude $VP'IffID$. It follows from the above equations that this control region is a circle with a center defined by coordinates Po(oJ and Qo,-(6) and a radius of $V,VpqlX$ **With** V., = V, = V, the boundary circle can be described by the following equation:

$$\{P(8, p) - Po(8)\}^2 + \{Q,\{8, p) - Qo,\{8)\}^2 = \{W...\}^2 \qquad (8.15)$$

The circular control regions defined by (8.15) are shown in Figures 8..9(a) through (d) for V = 1.0, $V_{pqm■11}$ = 0.5, and X = LO (per unit or p.u. values) with their centers on the circular arc characterizing the uncompensated system (8..14) at transmission angles 8;, 0°,.30°, 60°, and 90°. In other words, the centers of the control regions are defined



F11ure 8.9 Control region of the attainable real power P and receiving-end reactive power demand Q. with a UPFC-controlled transmission line at lJ """ O" (a), O = 30" (b), lJ = 60° (c), and lJ = 90" (d).

by the correspondingP0{S), Qo,(8) coordinates at angles li::;:: 0, 3QI", 60°, and 90° in the {Q,, P} plane.

Consider first Figme 8.9(a), which illustrates the case when the transmission angle is zero (8 = 0). With V_{pq} = 0, P, Q., (and Q,) are all zero. i.e., the system is at standstill at the origin of the Q,, P coordinates. The circle around the origin of the {Q., P} plane is the loci of the corresponding Q, and P values, obtained as the voltage phasor V_{pq} is rotated a ful] revolution (0 s p - 3600) with its maximum magnitude V_{pqnm}. The a rea within this circle defines aJl P and Q. values obtainable by controlling the magnitude V_{PT} and angle p of phasor V,,.,. In other words, the circle in the {Q., P} plane defines an P and Qr values attainable with the UPFC of a given rating. It can be observed, for exam.pie, that the UPFC with the stipulated voltage rating of 0.5 p.u. is able to establish 0.5 p.u. power flow, in either direction, without imposing any reacti ve power demand on either the sending-end or the receiving-end generator. (This statement tacitly assumes that the sending-end and receiving-end voltages are provided by independent power systems which are able to supply and absorb real power without any internal angular change.) Of course, the UPFC, as illustrated, can force the system at one end to supply reactive power for, or absorb that from, the system at the other end. Similar control characteristics for real power P and the reactive power Q_r can be observed at angles $\delta = 30°$, 60°, and 90° in Figures 8.9(b), (c), and (d).

In general, at any given transmission angle δ, the transmitted real power P, as well as the reactive power demand at the receiving end Q_r, can be controlled freely by the UPFC within the boundary circle obtained in the $\{Q_r, P\}$ plane by rotating the injected voltage phasor V_{pq} with its maximum magnitude a full revolution. Furthermore, it should be noted that, although the above presentation focuses on the receiving-end reactive power, Q_r, the reactive component of the line current, and the corresponding reactive power can actually be controlled with respect to the voltage selected at any point of the line.

Figures 8.9(a) through (d) dearly demonstrate that the UPFC, with its unique capability to control independently the real and reactive power flow at any transmission angle, provides a powerful, hitherto unattainable, new tool for transmission system control.