HVDC AND FACTS

(20A02604a)

LECTURE NOTES

III-B.TECH & II-SEM

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Course Code	HVDC AND FACTS	L	T	P	C
20A02303T		**3**	**0**	**0**	**3**
		Semester			**IV**

Course Objectives:

- High voltage DC transmission systems
- Flexible AC transmission systems
- Various configurations of the above, Principle of operation, Characteristics of various FACTS devices

Course Outcomes (CO): After completion of the course, the student can able to

CO-1 Understand the necessity of HVDC systems as emerging transmission networks

CO-2: Understand the necessity of reactive power compensation devices

CO-3: Design equivalent circuits of various HVDC system configurations

CO-4: Design and analysis of various FACTS devices

Unit – I:

INTRODUCTION

Electrical Transmission Networks, Conventional Control Mechanisms-Automatic Generation Control, Excitation Control, Transformer Tap-Changer Control, Phase-Shifting Transformers; Advances in Power-Electronic Switching Devices, Principles and Applications of Semiconductor Switches; Limitations of Conventional Transmission Systems, Emerging Transmission Networks, HVDC and FACTS

Unit – II:

HIGH VOLTAGE DC TRANSMISSION – I

Types of HVDC links - Monopolar, Homopolar, Bipolar and Back-to-Back, Advantages and disadvantages of HVDC Transmission, Analysis of Greatz circuit, Analysis of bridge circuit without overlap, Analysis of bridge with overlap less than 600, Rectifier and inverter characteristics, complete characteristics of rectifier and inverter, Equivalent circuit of HVDC Link.

Unit – III:

HIGH VOLTAGE DC TRANSMISSION – II

Desired features and means of control, control of the direct current transmission link, Constant current control, Constant ignition angle control, Constant extinction angle control, Converter firing-angle control-IPC and EPC, frequency control and Tap changer control, Starting, Stopping and Reversal of power flow in HVDC links.

Unit – IV:

FLEXIBLE AC TRANSMISSION SYSTEMS-I

Types of FACTS Controllers, brief description about various types of FACTS controllers, Operation of 6-pulse converter, Transformer Connections for 12-pulse, 24-pulse and 48-pulse operation, principle of operation of various types of Controllable shunt Var Generation, Principle of switching converter type shunt compensator, principles of operation of various types of Controllable Series Var Generation, Principle of Switching Converter type series compensator

Unit – V:

FLEXIBLE AC TRANSMISSION SYSTEMS-II

Unified Power Flow Controller (UPFC) – Principle of operation, Transmission Control Capabilities, Independent Real and Reactive Power Flow Control; Interline Power Flow Controller (IPFC) – Principle of operation and Characteristics, UPFC and IPFC control structures (only block diagram description), objectives and approaches of voltage and phase angle regulators

Textbooks:

1. Narain G. Hingorani and Laszlo Gyugyi, Understanding FACTS: Concepts and Technology of Flexible AC Transmission Systems, IEEE Press, Wiley-Interscience, New Jersey, 2000.
2. E.W. Kimbark, Direct current transmission, Vol. I, Wiley Interscience, New York, 1971

Reference Books:

1. K R Padiyar, FACTS Controllers in Power Transmission and Distribution, New Age International Publishers, New Delhi, 2007.
2. AnriqueAcha, Claudio R. Fuerte-Esquivel, Hugo Ambriz-Pérez and César Angeles-Camacho, FACTS: Modelling and Simulation in Power Networks, John Wiley & Sons, West Sussex, 2004.

HVDC Transmission Systems

UNIT-1

Introduction

Electric power transmission was originally developed with direct current. The availability of transformers and the development and improvement of induction motors at the beginning of the 20th century, led to the use of AC transmission.

DC Transmission now became practical when long distances were to be covered or where cables were required. Thyristors were applied to DC transmission and solid state valves became a reality.

With the fast development of converters (rectifiers and inverters) at higher voltages and larger currents, DC transmission has become a major factor in the planning of the power transmission. In the beginning all HVDC schemes used mercury arc valves, invariably single phase in construction, in contrast to the low voltage polyphase units used for industrial application. About 1960 control electrodes were added to silicon diodes, giving silicon-controlled-rectifiers (SCRs or Thyristors).

Today, the highest functional DC voltage for DC transmission is +/- 600kV. D.C transmission is now an integral part of the delivery of electricity in many countries throughout the world.

Comparison of AC and DC Transmission

The merits of two modes of transmission (AC & DC) should be compared based on the following factors.

1) Economics of transmission
2) Technical Performance
3) Reliability

Economics of Power Transmission:

In DC transmission, inductance and capacitance of the line has no effect on the power transfer capability of the line and the line drop. Also, there is no leakage or charging current of the line under steady conditions.

A DC line requires only 2 conductors whereas AC line requires 3 conductors in 3-phase AC systems. The cost of the terminal equipment is more in DC lines than in AC line. Break-even distance is one at which the cost of the two systems is the same. It is understood from the below figure that a DC line is economical for long distances which are greater than the break-even distance.

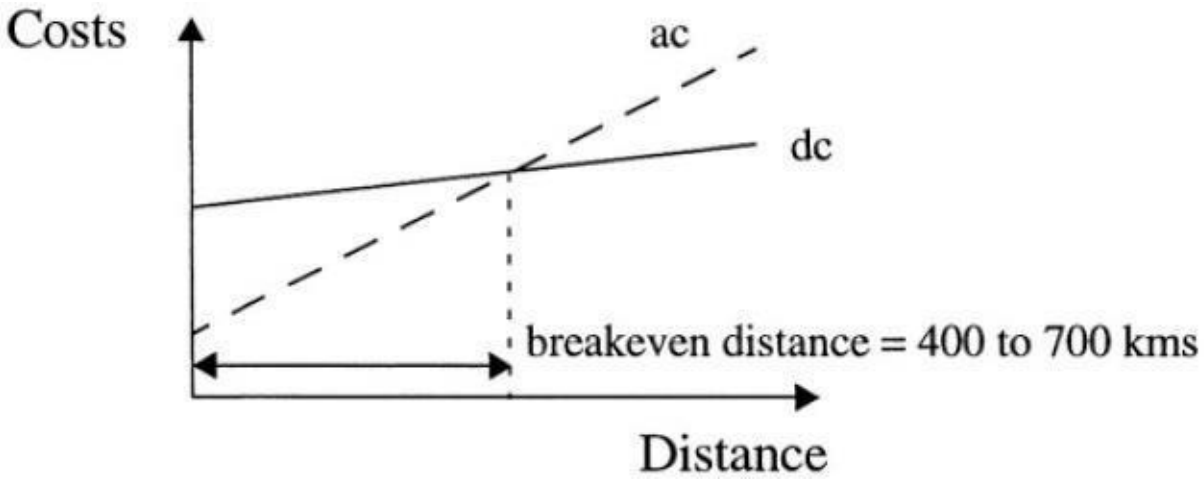


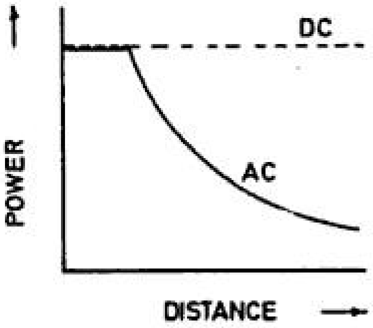
Figure: Relative costs of AC and DC transmission lines vs distance

<u>Technical Performance:</u>

Due to its fast controllability, a DC transmission has full control over transmitted power, an ability to enhance transient and dynamic stability in associated AC networks and can limit fault currents in the DC lines. Furthermore, DC transmission overcomes some of the following problems associated with AC transmission.

Stability Limits:

The power transfer in an AC line is dependent on the angle difference between the voltage phasors at the two line ends. For a given power transfer level, this angle increases with distance. The maximum power transfer is limited by the considerations of steady state and transient stability. The power carrying capability of an AC line is inversely proportional to transmission distance whereas the power carrying ability of DC lines is unaffected by the distance of transmission.



Power transfer capability vs. distance

Voltage Control:

Voltage control in ac lines is complicated by line charging and voltage drops. The voltage profile in an AC line is relatively flat only for a fixed level of power transfer corresponding to its Surge Impedance Loading (SIL). The voltage profile varies with the line loading. For constant voltage at the line ends, the midpoint voltage is reduced for line loadings higher than SIL and increased for loadings less than SIL.

The maintenance of constant voltage at the two ends requires reactive power control as the line loading is increased. The reactive power requirements increase with line length. Although DC converter stations require reactive power related to the power transmitted, the DC line itself does not require any reactive power. The steady-state charging currents in AC cables pose serious problems and make the break-even distance for cable transmission around 50kms.

Line Compensation:

Line compensation is necessary for long distance AC transmission to overcome the problems of line charging and stability limitations. The increase in power transfer and voltage control is possible through the use of shunt inductors, series capacitors, Static Var Compensators (SVCs) and, lately, the new generation Static Compensators (STATCOMs). In the case of DC lines, such compensation is not needed.

Problems of AC Interconnection:

The interconnection of two power systems through ac ties requires the automatic generation controllers of both systems to be coordinated using tie line power and frequency signals. Even with coordinated control of interconnected systems, the operation of AC ties can be problematic due to:

1. The presence of large power oscillations which can lead to frequent tripping,
2. Increase in fault level, and
3. Transmission of disturbances from one system to the other.

The fast controllability of power flow in DC lines eliminates all of the above problems. Furthermore, the asynchronous interconnection of two power systems can only be achieved with the use of DC links.

Ground Impedance:

In AC transmission, the existence of ground (zero sequence) current cannot be permitted in steady-state due to the high magnitude of ground impedance which will not only affect efficient power transfer, but also result in telephonic interference. The ground impedance is negligible for DC currents and a DC link can operate using one conductor with ground return (monopolar operation).

The ground return is objectionable only when buried metallic structures (such as pipes) are present and are subject to corrosion with DC current flow. While operating in the monopolar mode, the AC network feeding the DC converter station operates with balanced voltages and currents. Hence, single pole operation of dc transmission systems is possible for extended period, while in AC transmission, single phase operation (or any unbalanced operation) is not feasible for more than a second.

Disadvantages of DC Transmission:

The scope of application of DC transmission is limited by

1. High cost of conversion equipment.
2. Inability to use transformers to alter voltage levels.
3. Generation of harmonics.
4. Requirement of reactive power and
5. Complexity of controls.

Over the years, there have been significant advances in DC technology, which have tried to overcome the disadvantages listed above except for (2). These are

1. Increase in the ratings of a thyristor cell that makes up a valve.
2. Modular construction of thyristor valves.
3. Twelve-pulse (and higher) operation of converters.
4. Use of forced commutation.
5. Application of digital electronics and fiber optics in the control of converters.

Reliability:

The reliability of DC transmission systems is good and comparable to that of AC systems. The reliability of DC links has also been very good.

There are two measures of overall system reliability-energy availability and transient reliability.

Energy availability:

$$\text{Energy availability} = 100\left(1 - \frac{\text{equivalent outage time}}{\text{Actual time}}\right)\ \%$$

Where equivalent outage time is the product of the actual outage time and the fraction of system capacity lost due to outage.

Transient reliability:

This is a factor specifying the performance of HVDC systems during recordable faults on the associated AC systems.

$$\text{Transient reliability} = \frac{100 \text{ X No. of times HVDC systems performed as designed}}{\text{No. of recordable AC faults}}$$

Recordable AC system faults are those faults which cause one or more AC bus phase voltages to drop below 90% of the voltage prior to the fault.

Both energy availability and transient reliability of existing DC systems with thyristor valves is 95% or more.

Application of DC Transmission

Due to their costs and special nature, most applications of DC transmission generally fall into one of the following three categories.

Underground or underwater cables:

In the case of long cable connections over the breakeven distance of about 40-50 km, DC cable transmission system has a marked advantage over AC cable connections. Examples of this type of applications were the Gotland (1954) and Sardinia (1967) schemes. The recent development of Voltage Source Converters (VSC) and the use of rugged polymer DC cables, with the so-called “HVDC Light” option, are being increasingly considered. An example of this type of application is the 180 MW Direct link connection (2000) in Australia.

Long distance bulk power transmission:

Bulk power transmission over long distances is an application ideally suited for DC transmission and is more economical than ac transmission whenever the breakeven distance is exceeded. Examples of this type of application abound from the earlier Pacific Intertie to the recent links in China and India.

The breakeven distance is being effectively decreased with the reduced costs of new compact converter stations possible due to the recent advances in power electronics.

Stabilization of power flows in integrated power system:

In large interconnected systems, power flow in AC ties (particularly under disturbance conditions) can be uncontrolled and lead to overloads and stability problems thus endangering system security. Strategically placed DC lines can overcome this problem due to the fast controllability of DC power and provide much needed damping and timely overload capability. The planning of DC transmission in such applications requires detailed study to evaluate the benefits. Example is the Chandrapur-Padghe link in India.

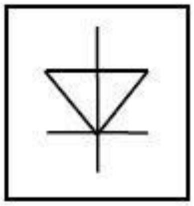
Presently the number of DC lines in a power grid is very small compared to the number of AC lines. This indicates that DC transmission is justified only for specific applications. Although advances in technology and introduction of Multi-Terminal DC (MTDC) systems are expected to increase the scope of application of DC transmission, it is not anticipated that the AC grid will be replaced by a DC power grid in the future. There are two major reasons for this:

First, the control and protection of MTDC systems is complex and the inability of voltage transformation in dc networks imposes economic penalties.

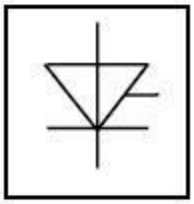
Second, the advances in power electronics technology have resulted in the improvement of the performance of AC transmissions using FACTS devices, for instance through introduction of static VAR systems, static phase shifters, etc.

Types of Valves

Based on the controllability and configuration valves are classified into four types as under.



Non-controllable bridge or valve group

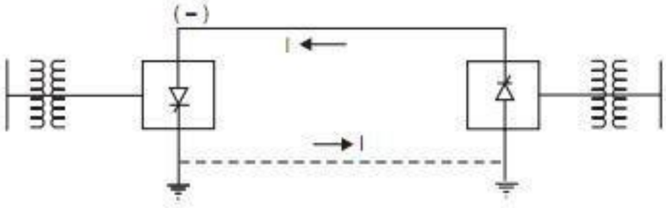


Controllable bridge or valve group

Types of HVDC Links

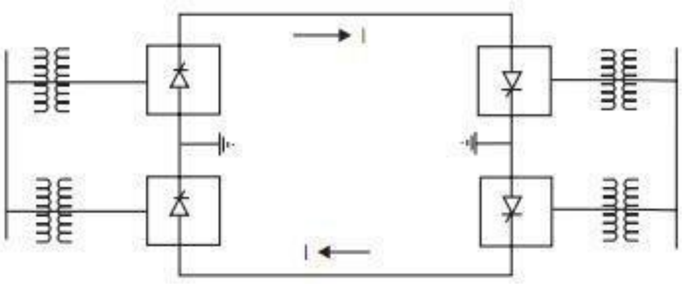
Three types of HVDC Links are considered in HVDC applications which are

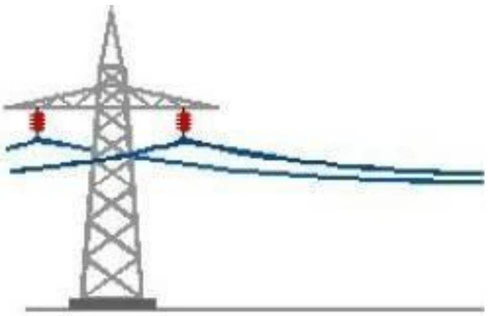
Monopolar Link:



A monopolar link as shown in the above figure has one conductor and uses either ground and/or sea return. A metallic return can also be used where concerns for harmonic interference and/or corrosion exist. In applications with DC cables (i.e., HVDC Light), a cable return is used. Since the corona effects in a DC line are substantially less with negative polarity of the conductor as compared to the positive polarity, a monopolar link is normally operated with negative polarity.

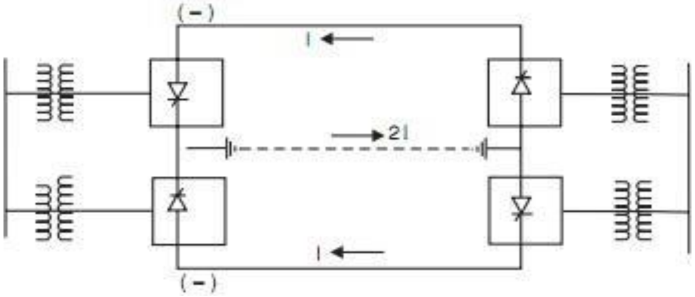
Bipolar Link:





A bipolar link as shown in the above figure has two conductors, one positive and the other negative. Each terminal has two sets of converters of equal rating, in series on the DC side. The junction between the two sets of converters is grounded at one or both ends by the use of a short electrode line. Since both poles operate with equal currents under normal operation, there is zero ground current flowing under these conditions. Monopolar operation can also be used in the first stages of the development of a bipolar link. Alternatively, under faulty converter conditions, one DC line may be temporarily used as a metallic return with the use of suitable switching.

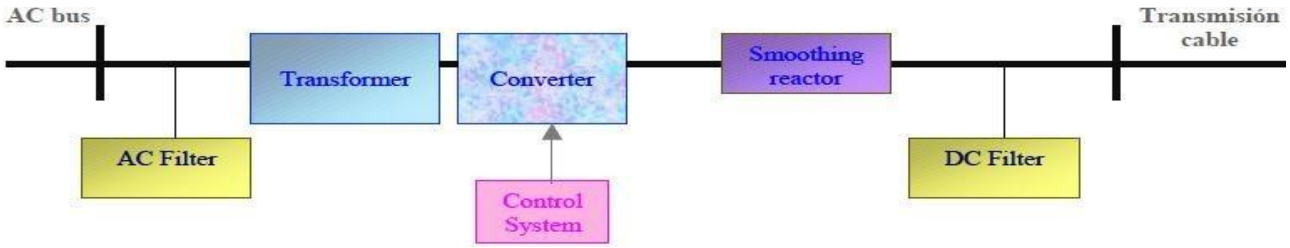
Homopolar Link:



In this type of link as shown in the above figure two conductors having the same polarity (usually negative) can be operated with ground or metallic return.

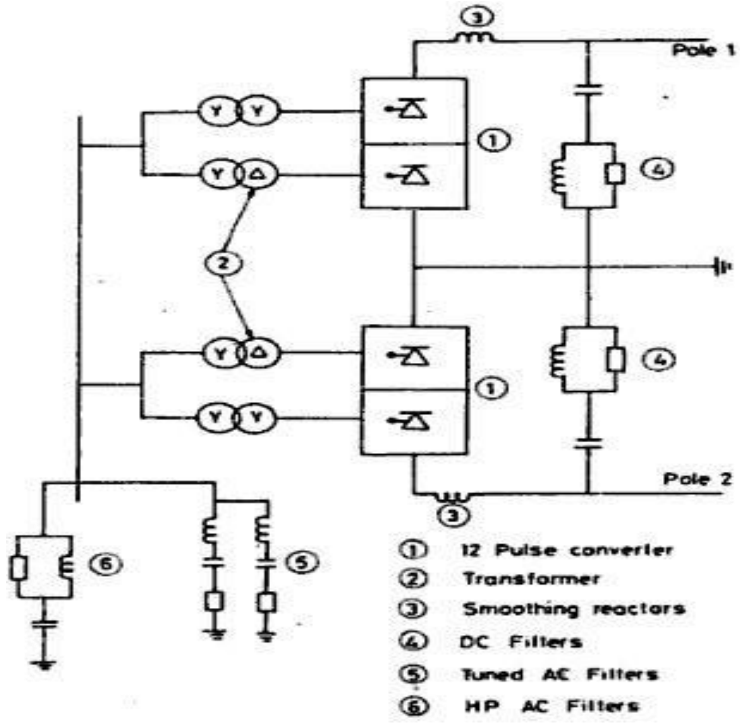
Due to the undesirability of operating a DC link with ground return, bipolar links are mostly used. A homopolar link has the advantage of reduced insulation costs, but the disadvantages of earth return outweigh the advantages.

HVDC Converter Station

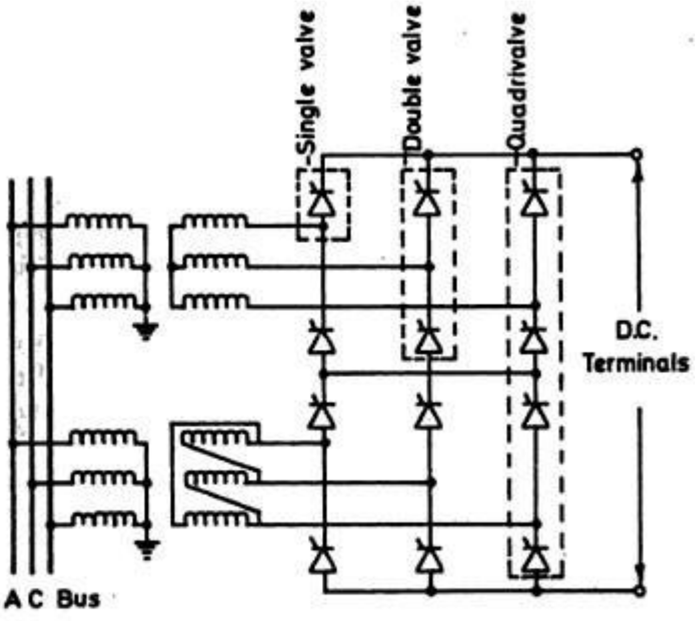


The major components of a HVDC transmission system are converter stations where conversions from AC to DC (Rectifier station) and from DC to AC (Inverter station) are performed. A point to point transmission requires two converter stations. The role of rectifier and inverter stations can be reversed (resulting in power reversals) by suitable converter control.

A typical converter station with two 12 pulse converter units per pole is shown in figure below. The block diagram of converter station is given above.



Converter Unit:



This usually consists of two three phase converter bridges connected in series to form a 12 pulse converter unit as shown in above figure. The total number of valves in such a unit is twelve. The valves can be packaged as single valve, double valve or quadrivalve arrangements. Each valve is used to switch in segment of an AC voltage waveform. The converter is fed by converter transformers connected in star/star and star/delta arrangements.

The valves are cooled by air, oil, water of freon. Liquid cooling using deionized water is more efficient and results in the reduction of station losses. The design of valves is based on the modular concept where each module contains a limited number of series connected thyristor levels.

Valve firing signals are generated in the converter control at ground potential and are transmitted to each thyristor in the valve through a fiber optic light guide system.

The valves are protected using snubber circuits, protective firing and gapless surge arrestors.

Converter Transformer:

The converter transformer has three different configurations-

(i) three phase, two winding,
(ii) single phase, three winding and
(iii)single phase, two winding

The valve side windings are connected in parallel with neutral grounded. The leakage reactance of the transformer is chosen to limit the short circuit currents through any valves.

The converter transformers are designed to withstand DC voltage stresses and increased eddy current losses due to harmonic currents. One problem that can arise is due to the DC magnetization of the core due to unsymmetrical firing of valves.

Filters:

There are three types of filters used which are

1. ***AC Filters:***

   These are passive circuits used to provide how impedance, shunt paths for AC harmonic currents. Both tuned and damped filter arrangements are used.

2. ***DC Filters:***

   These are similar to AC filters and are used for the filtering of DC harmonics.

3. ***High Frequency (RF/PLC) Filters:***

These are connected between the converter transformer and the station AC bus to suppress any high frequency currents. Sometimes such filters are provided on high-voltage DC bus connected between the DC filter and DC line and also on the neutral side.

Reactive power source:

Converter stations require reactive power supply that is dependent on the active power loading. But part of the reactive power requirement is provided by AC filters. In addition, shunt capacitors, synchronous condensors and static VAR systems are used depending on the speed of control desired.

Smoothing Reactor:

A sufficiently large series reactor is used on DC side to smooth DC current and also for protection. The reactor is designed as a linear reactor and is connected on the line side, neutral side or at intermediate location.

DC Switchgear:

It is modified AC equipment used to interrupt small DC currents. DC breakers or Metallic Return Transfer Breakers (MRTB) are used, if required for interruption of rated load currents.

In addition to the DC switchgear, AC switchgear and associated equipment for protection and measurement are also part of the converter station.

Modern Trends in DC Transmission

To overcome the losses and faults in AC transmission, HVDC transmission is preferred.

The trends which are being introduced are for the effective development to reduce the cost of the converters and to improve the performance of the transmission system.

Power semiconductors and valves:

The IGBTs or GTOs employed required huge amount of current to turn it ON which was a big problem. GTOs are available at 2500V and 2100A. As the disadvantage of GTOs is the large gate current needed to turn them OFF, so MCT which can be switched OFF by a small current is preferred as valves.

The power rating of thyristors is also increased by better cooling methods. Deionized water cooling has now become a standard and results in reduced losses in cooling.

Converter Control:

The development of micro-computer based converter control equipment has made possible to design systems with completely redundant converter control with automatic transfer between systems in the case of a problem.

The micro-computer based control also has the flexibility to implement adaptive control algorithms or even the use of expert systems for fault diagnosis and protection.

DC Breakers:

Parallel rather than series operation of converters is likely as it allows certain flexibility in the planned growth of a system. The DC breaker ratings are not likely to exceed the full load ratings as the control intervention is expected to limit the fault current.

Conversion of existing AC lines:

There are some operational problems due to electromagnetic induction from AC circuits where an experimental project of converting a single circuit of a double circuit is under process.

Operation with weak AC systems:

The strength of AC systems connected to the terminals of a DC link is measured in terms of Short Circuit Ratio (SCR) which is defined as

SCR = Short circuit level at the converter bus

Rated DC Power

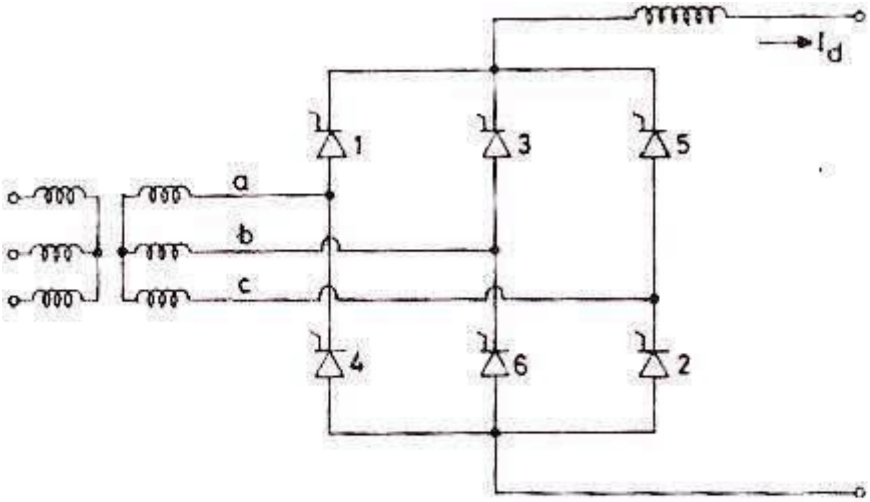
If SCR is less than 3, the AC system is said to be weak. The conventional constant extinction angle control may not be suitable for weak AC systems.

Constant reactive current control or AC voltage control may overcome some of the problems of weak AC systems.

The power modulation techniques used to improve dynamic stability of power systems will have to be modified in the presence of weak AC systems.

Six Pulse Converters

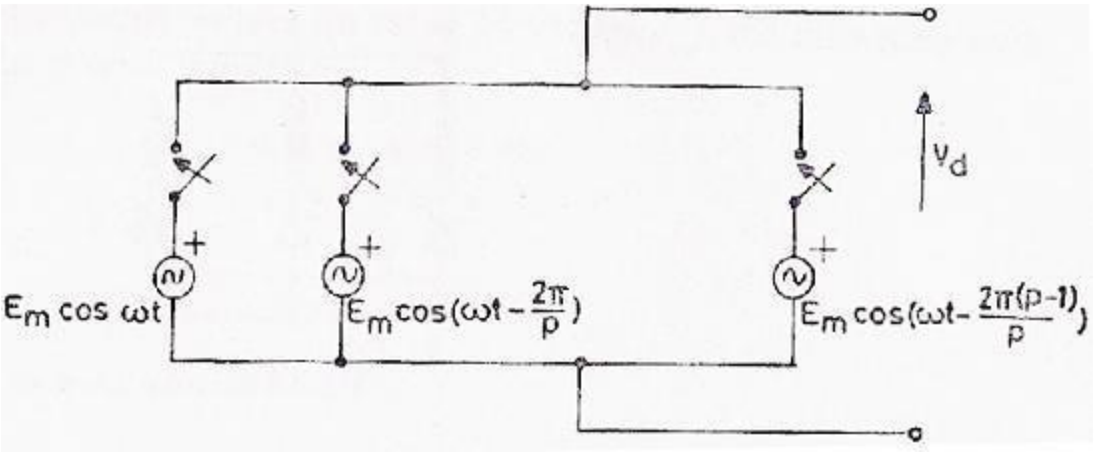
The conversion from AC to DC and vice-versa is done in HVDC converter stations by using three phase bridge converters. The configuration of the bridge (also called Graetz circuit) is a six pulse converter and the 12 pulse converter is composed of two bridges in series supplied from two different (three-phase) transformers with voltages differing in phase by 30° .



Pulse Number

The pulse number of a converter is defined as the number of pulsations (cycles of ripple) of direct voltage per cycle of alternating voltage.

The conversion from AC to DC involves switching sequentially different sinusoidal voltages onto the DC circuit.

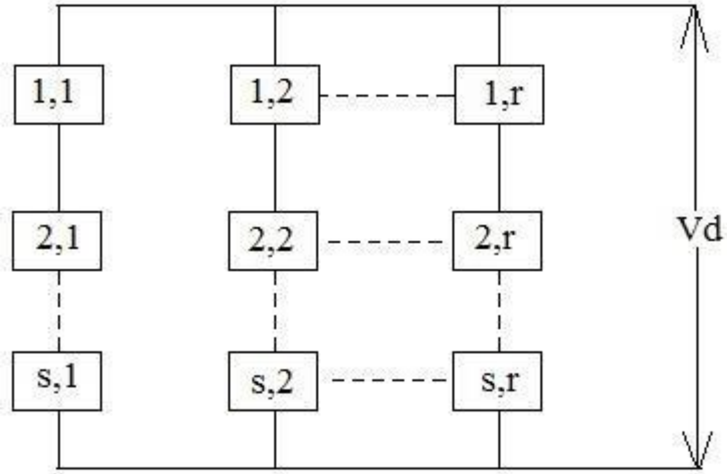


A valve can be treated as a controllable switch which can be turned ON at any instant, provided the voltage across it is positive.

The output voltage V_d of the converter consists of a DC component and a ripple whose frequency is determined by the pulse number

Choice of Converter Configuration

The configuration for a given pulse number is so chosen in such a way that the valve and transformer are used to the maximum.



A converter configuration can be defined by the basic commutation group and the number of such groups connected in series and parallel.

If there are ‘q’ valves in a basic commutation group and r of those are connected in parallel and s of them in series then,

p = q r s

Note:

A commutation group is defined as the group of valves in which only one (neglecting overlap) conducts at a time.

Valve Rating:

The valve rating is specified in terms of Peak Inverse Voltage (PIV). The ratio of PIV to average DC voltage is an index of valve utilization.

So, average maximum DC voltage across the converter is given by,

$$V_{do} = s\frac{q}{2\pi}\int_{-\pi/q}^{\pi/q} E_m \cos\omega t\, d(\omega t)$$

$$= s\frac{q}{2\pi}E_m(\sin\omega t)_{-\pi/q}^{\pi/q} = \frac{sq}{2\pi}E_m\left[\sin\left(\frac{\pi}{q}\right)-\sin\left(-\frac{\pi}{q}\right)\right] = \frac{sq}{2\pi}E_m .2\sin\frac{\pi}{q}$$

$$V_{do} = \frac{sq}{\pi}E_m \sin\frac{\pi}{q} \quad \text{----- (1)}$$

If ‘q’ is even, then maximum inverse voltage occurs when the valve with a phase displacement of 180° is conducting and is given by,

PIV = $2E_m$

If ‘q’ is odd, then maximum inverse voltage occurs when the valve with a phase shift of π±(π/q) is conducting and is given by,

PIV = $2E_m \cos(\pi/2q)$

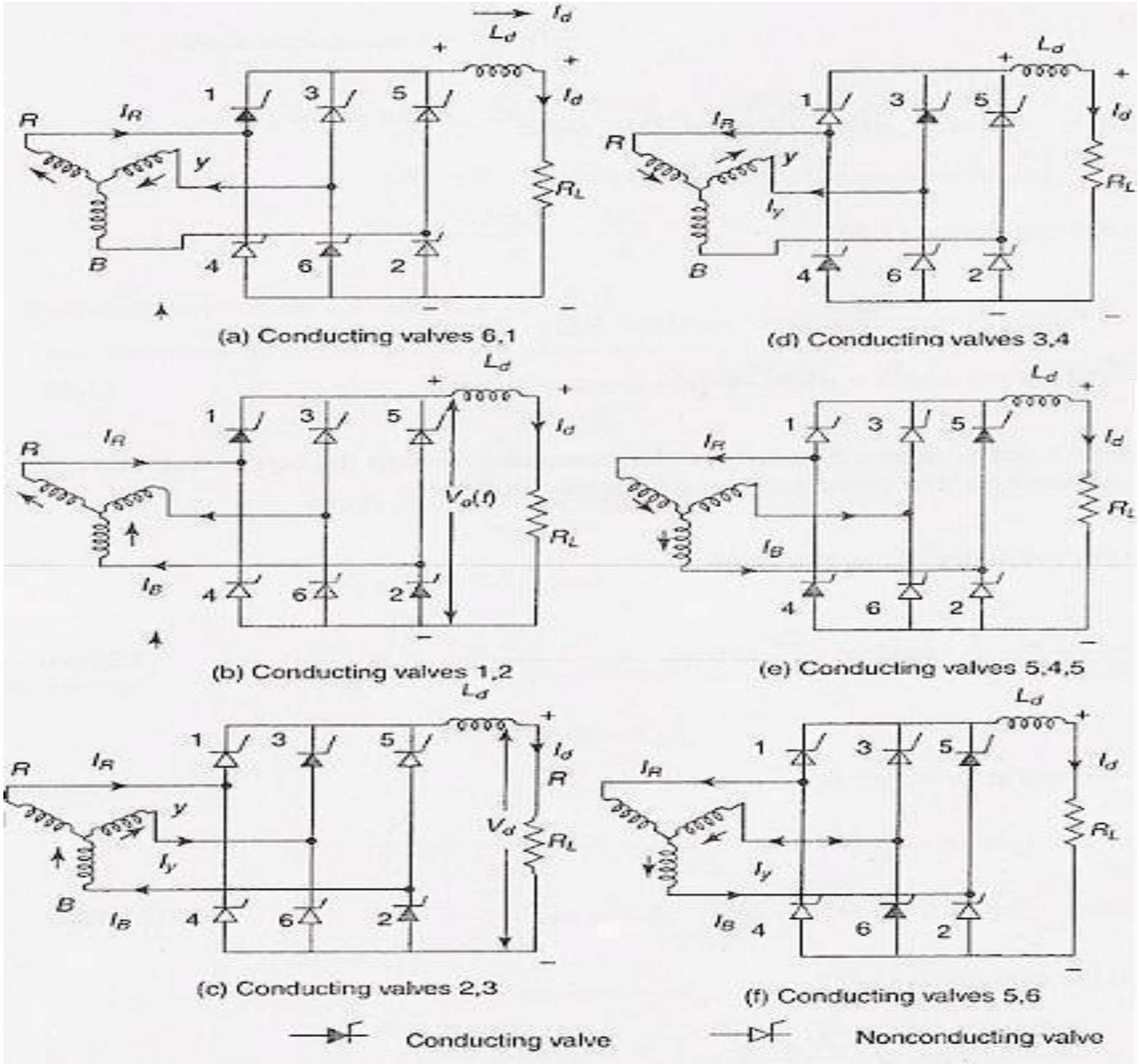
The valve utilization factor is given by

$$\text{For q even,}\quad \frac{PIV}{V_{do}} = \frac{2E_m}{\frac{sq}{\pi}E_m\sin\frac{\pi}{q}} = \frac{2\pi}{s.q.\sin\frac{\pi}{q}}$$

$$\text{For q odd,}\quad \frac{PIV}{V_{do}} = \frac{2E_m\cos\frac{\pi}{2q}}{\frac{sq}{\pi}E_m\sin\frac{\pi}{q}} = \frac{2\pi.\cos\frac{\pi}{2q}}{sq.\sin\frac{\pi}{q}} = \frac{2\pi.\cos\frac{\pi}{2q}}{sq.2\cos\frac{\pi}{2q}.\sin\frac{\pi}{2q}}$$

(Since sin2θ=2sinθcosθ and $2\cos\frac{\theta}{2}\sin\frac{\theta}{2} = \sin\frac{2\theta}{2} = \sin\theta$)

$$\frac{PIV}{V_{do}} = \frac{\square}{sq.\sin \frac{\square}{2q}} \quad \text{(For q odd)}$$



(a) Conducting valves 6,1

(d) Conducting valves 3,4

(b) Conducting valves 1,2

(e) Conducting valves 5,4,5

(c) Conducting valves 2,3

(f) Conducting valves 5,6

Sequence of conduction of valve of 3-phase fully controlled 6-pulse bridge converter (Graetz's circuit)

Transformer Rating:

The current rating of a valve is given by,

$$I_v = \frac{I_d}{r\sqrt{q}} \text{---------(2)}$$

where, I_d is the DC current which is assumed to be constant.

The transformer rating on the valve side (in VA) is given by,

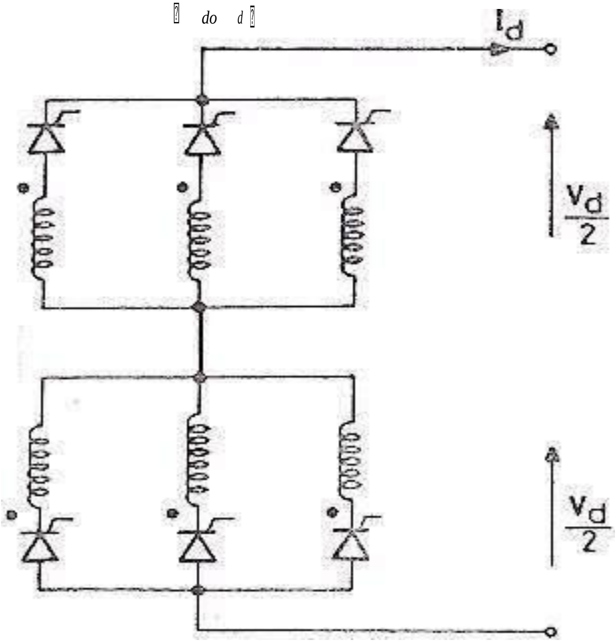
$$S_{tv} = p \frac{E_m}{\sqrt{2}} I_v$$

From equations (1), (2) & p=qrs, we have

$$S_{tv} = p\,\frac{V_{do}.\pi}{\sqrt{2}.sq.\sin\frac{\pi}{q}}.\frac{I_d}{r\sqrt{q}}$$

$$S_{tv} = \frac{\pi}{\sqrt{2}}\,\frac{V_{do}I_d}{\sqrt{q}.\sin\frac{\pi}{q}}$$

Transformer utilization factor $\left(\frac{S_{tv}}{V_{do}I_d}\right)$ is a function of q.



As AC supply is three phase so, commutation group of three valves can be easily arranged. So, for q = 3,

$$\frac{S_{tv}}{V_{do}I_d} = \frac{\pi}{\sqrt{(2\,X\,3)}\,\sin\frac{\pi}{3}}$$

$$\frac{S_{tv}}{V_{do}I_d} = \frac{\pi}{\sqrt{6}\sin 60^o}$$

$$\frac{S_{tv}}{V_{do}I_d} = 1.48$$

Transformer utilization can be improved if two valve groups can share single transformer winding. In this case, the current rating of the winding can be increased by a factor of √2 while decreasing the number of windings by a factor of 2.

It is a 6-pulse converter consisting of two winding transformer where the transformer utilization factor is increased when compared to three winding transformer.

The series conduction of converter groups has been preferred because of controlling and protection as well as the requirements for high voltage ratings. So, a 12 pulse converter is obtained by series connection of two bridges.

The 30^o phase displacement between two sets of source voltages is achieved by transformer connections Y-Y for one bridge and Y-Δ for the other bridge.

The use of a 12 pulse converter is preferable over the 6 pulse converter because of the reduced filtering requirements.

Analysis of Graetz Circuit without overlap:

At any instant, two valves are conducting in the bridge, one from the upper commutation group and the second from the lower commutation group. The firing of the next valve in a particular group results in the turning OFF of the valve that is already conducting. The valves are numbered in the sequence in which they are fired. Each valve conducts for 120^o and the interval between consecutive firing pulse is 60^o in steady state.

The following assumptions are made to simplify the analysis

a. The DC current is constant.
b. The valves are modeled as ideal switches with zero impedance when ON and with infinite impedance when OFF.
c. The AC voltages at the converter bus are sinusoidal and remain constant.

One period of the AC supply voltage can be divided into 6 intervals – each corresponding to the conduction of a pair of valves. The DC voltage waveform repeats for each interval.

Assuming the firing of valve 3 is delayed by an angle α , the instantaneous DC voltage V_d during the interval is given by

$V_d = e_b - e_c = e_{bc}$ for $\alpha \le \omega t \le \alpha + 60^o$

Let $e_{ba} = \sqrt{2}\; E_{LL} \sin \omega t$

then $e_{bc} = \sqrt{2}E_{LL} \sin(\omega t + 60^o)$

Average DC Voltage = $V_d = \frac{3}{\pi}\int_{\alpha}^{\alpha+60^o} \sqrt{2}E_{LL} \sin(\omega t + 60^o)\, d\omega t$

$$= \frac{3}{\pi}\sqrt{2}E_{LL}\,[\cos(\alpha + 60^o) - \cos(\alpha + 120^o)]$$

$$V_d = \frac{3\sqrt{2}}{\pi} E_{LL} \cos\alpha = 1.35 E_{LL} \cos\alpha$$

$$V_d = V_{do} \cos\alpha \text{ -------------} (1)$$

The above equation indicates that for different values of α , V_d is variable.

The range of α is 180° and correspondingly V_d can vary from V_{do} to $-V_{do}$. Thus, the same converter can act as a rectifier or inverter depending upon whether the DC voltage is positive or negative.

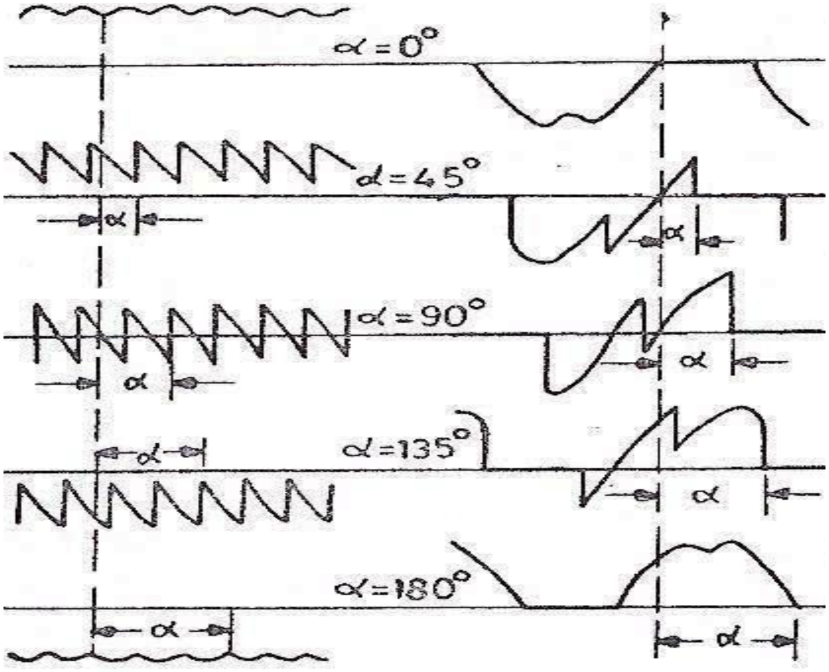
DC Voltage Waveform:

The DC voltage waveform contains a ripple whose fundamental frequency is six times the supply frequency. This can analyzed in Fourier series and contains harmonics of the order h = np
where, p is the pulse number and n is an integer.

The rms value of the h^{th} order harmonic in DC voltage is given by

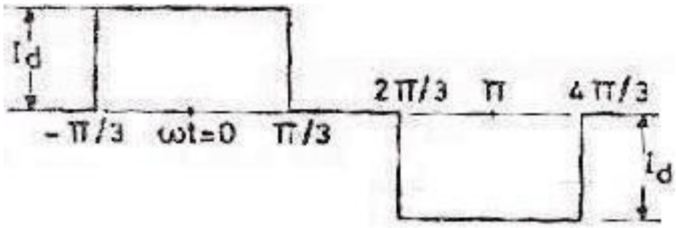
$$V_h = V_{do} \frac{\sqrt{2}}{h^2 - 1} [1 + (h^2 + 1) \sin^2 \alpha]^{1/2}$$

The waveforms of the direct voltage and calve voltage are shown for different values of α.



AC Current Waveform:

It is assumed that direct current has no ripple (or harmonics). The AC currents flowing through the valve (secondary) and primary windings of the converter transformer contain harmonics.



The waveform of the current in a valve winding is shown. The rms value of the fundamental component of current is given by

$$I_1 = \frac{1}{\sqrt{2}} \cdot \frac{2}{\pi} \int_{-\pi/3}^{\pi/3} I_d \cos\theta . d\theta = \frac{\sqrt{6}}{\pi} I_d \qquad \text{---- (2)}$$

where as the rms value of the current is

$$I = \sqrt{\frac{2}{3}} . I_d$$

The harmonics contained in the current waveform are of the order given by

$h = np \pm 1$

Where n is an integer, p is the pulse number. For a six pulse converter, the order of AC harmonics is 5, 7, 11, 13 and higher order. These are filtered out by using tuned filters for each one of the first four harmonics and a high pass filter for the remaining.

The rms value of hth harmonic is given by $I_h = \frac{I_1}{h}$

Power Factor:

The AC power supplied to the converter is given by

$P_{AC} = \sqrt{3} E_{LL} I_1 \cos\phi$

Where $\cos\phi$ is the power factor.

The DC power must match the AC power ignoring the losses in the converter. Thus,

$P_{AC} = P_{DC} = V_{do} I_d = \sqrt{3} E_{LL} I_1 \cos\phi$

Substituting for V_{do} and I_1 from equations (1) and (2) in the above equation, we get $\cos\phi$

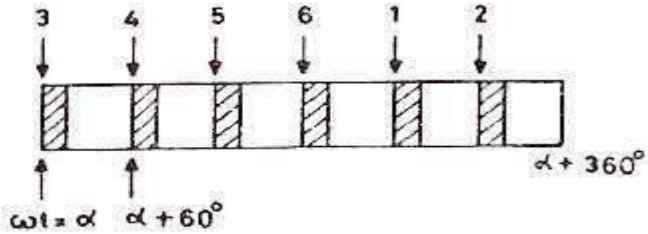
$= \cos\alpha$

The reactive power requirements are increased as α is increased from zero (or reduced from 180°).

Analysis of Graetz Circuit with overlap

Due to the leakage inductance of the converter transformers and the impedance in the supply network, the current in a valve cannot change suddenly and this commutation from one valve to the next cannot be instantaneous. This is called overlap and its duration is measured by the overlap (commutation) angle ‘μ’.

Each interval of the period of supply can be divided into two subintervals as shown in the below timing diagram. In the first subinterval, three valves are conducting and in the second subinterval, two valves are conducting which is based on the assumption that the overlap angle is less than 60°.



There are three modes of the converter which are

1. i) Mode 1 – Two and three valve conduction ($\mu<60^\circ$)
2. ii) Mode 2 – Three valve conduction ($\mu=60^\circ$)
3. iii) Mode 3 – Three and four valve conduction ($\mu>60^\circ$)

i) Analysis of Two and Three Valve Conduction Mode:

The equivalent circuit for three valve conduction is shown below.

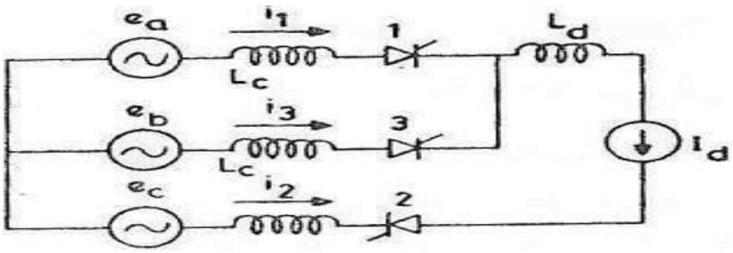
For this circuit,

$$e_b - e_a = L_c\left(\frac{di_3}{dt} - \frac{di_1}{dt}\right)$$

The LHS in the above equation is called the commutating emf whose value is given by

$$e_b - e_a = \sqrt{2}E_{LL}\sin\omega t$$

Which is the voltage across valve 3 just before it starts conducting.



Since, $i_1 = I_d - i_3$

We get,

$$\sqrt{2}E_{LL}\sin\omega t = 2L_c\frac{di_3}{dt}$$

Solving the above equation, we get

$$i_3(t) = I_s(\cos\alpha - \cos\omega t), \quad \alpha \le \omega t \le \alpha + \mu$$

Where,

$$I_s = \frac{\sqrt{2}E_{LL}}{2\omega L_c}$$

At ωt=α+μ , $i_s = I_d$. This gives $I_d = I_s[\cos\alpha - \cos(\alpha+\mu)]$The average direct voltage can be obtained as

$$V_d = \frac{3}{\pi}\left[\int_{\alpha}^{\alpha+\mu} -\frac{3}{2}e_c\,d(\omega t) + \int_{\alpha+\mu}^{\alpha+60}(e_b - e_c)\,d(\omega t)\right]$$

$$= V_{do}\cos\alpha - \frac{3}{2\pi}\sqrt{2}E_{LL}[\cos\alpha - \cos(\alpha+\mu)]$$

Since, $\frac{3\sqrt{2}}{\pi}E_{LL} = V_{do}$, we get

$$V_d = \frac{V_{do}}{2}[\cos\alpha + \cos(\alpha+\mu)]$$

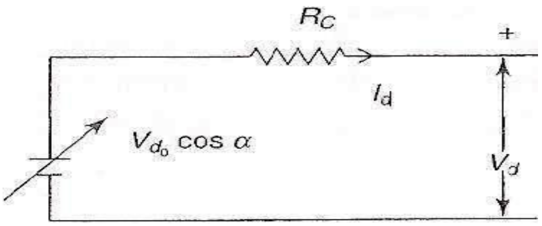
The value of $[\cos\alpha - \cos(\alpha+\mu)]$ can be substituted to get,

$$V_d = V_{do}\left[\cos\alpha - \frac{I_d}{2I_s}\right] = V_{do}\cos\alpha - R_c I_d$$

Where,

$$R_c = \frac{3}{\pi}\omega L_c = \frac{3}{\pi}X_c$$

R_c is called equivalent commutation resistance and the equivalent circuit for a bridge converter is shown below.



Inverter Equations:

For an inverter, advance angle β is given by

β=π-α

and use opposite polarity for the DC voltage with voltage rise opposite to the direction of current. Thus,

$$V_{di} = \frac{-V_{doi}}{2}[\cos\alpha + \cos(\alpha+\mu)]$$

$$= \frac{-V_{doi}}{2}[\cos(\pi-\beta) + \cos(\pi-\gamma)]$$

$$V_{di} = \frac{V_{doi}}{2}[\cos\beta + \cos\gamma]$$

Where, the extinction angle γ is defined as

γ = β-μ = π-α-μ

Similarly, it can be shown that

$$V_{di} = V_{doi}\cos\gamma + R_{ci} I_d$$

$$= V_{doi}\cos\beta - R_{ci} I_d$$

The subscript "i" refers to the inverter.

ii) Analysis of Three and Four Valve Conduction Mode:

The equivalent circuit for three and four valve conduction is shown below.

For, $\alpha \le \omega t \le \alpha+\mu-60^o$

$i_1 = I_s \sin(\omega t+60^o) + A$

$i_6 = I_d - i_2 = I_d - I_s \sin\omega t + C$

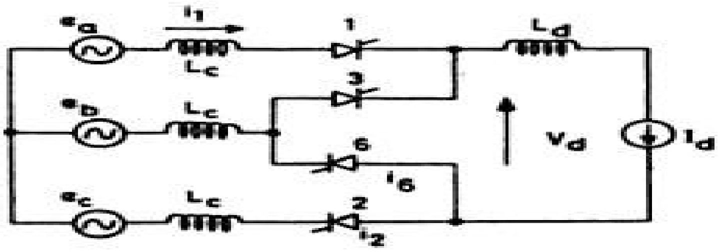
Where, $I_s = \frac{E_m}{\omega L_c} = \frac{2}{\sqrt{3}} I_s$

The constant A can be determined from the initial condition

$i_1(\omega t=\alpha) = I_d = I_s \sin(\alpha+60^o) + A$

The constant C can be determined from the final condition

$i_6(\omega t=\alpha+\mu-60^o) = 0 = I_d - I_s \sin(\alpha+\mu-60^o) + C = 0$



For, $\alpha+\mu-60^o \leq \omega t \leq \alpha+60^0$

$i_1 = I_s \cos\omega t + B$

The constant B can be determined from the continuity

equation $i_1 (\omega t=\alpha+\mu=60^o) = I_s \sin(\alpha+\mu) + A = I_s \cos(\alpha+\mu-60^o) + B$

Finally,

$$I_d = \frac{I_s}{2}[\cos(\alpha - 30^o) - \cos(\alpha + \mu + 30^o)]$$

The expression for average direct voltage is given by

$$V_d = \frac{3}{\pi}\int_{\alpha+\mu-60^o}^{\alpha+60^o} -\frac{\sqrt{3}}{2} e_c \, d(\omega t)$$

Since $e_c = E_m \cos\omega t$

$$V_d = -\frac{3\sqrt{3}}{2\pi} E_m[\sin(\alpha + 60^o) - \sin(\alpha + \mu - 60^o)]$$

$$V_d = \frac{\sqrt{3}}{2} V_{do}[\cos(\alpha - 30^o) + \cos(\alpha + \mu + 30^o)]$$

Finally

$$V_d = V_{do}[\sqrt{3}\cos(\alpha - 30^o) - \frac{3 I_d}{2 I_s}] = \sqrt{3}.V_{do}\cos(\alpha - 30^o) - 3R_c I_d$$

Converter Bridge Characteristics

A) Rectifier: The rectifier has three modes of operation.

1) First mode: Two and three valve conduction mode ($\mu < 60^o$)

2) Second mode: Three valve conduction mode only for $\alpha < 30^o$ ($\mu = 60^o$)

3) Third mode: Three and four valve conduction mode $\alpha \geq 30^o$ ($60^o \leq \mu \leq 120^o$)

As the DC current continues to increase, the converter operation changes over from mode 1 to 2 and finally to mode 3.

The DC voltage continues to decrease until it reaches zero.

For $\alpha \geq 30^o$, mode 2 is bypassed.

For Modes 1 and 3, we have

$$\frac{V_d}{V_{do}} = \cos\alpha - \frac{I_d}{2I_s}$$

$$\frac{V_d}{V_{do}} = \sqrt{3}\cos(\alpha - 30^o) - \frac{3I_d}{2I_s}$$

The voltage and current characteristics are linear with different slopes in these cases. For mode 2, $\mu = 60^o$, μ is constant, so the characteristics are elliptical and is given by

$$\left(\frac{V_d^|}{\cos\frac{\mu}{2}} \right)^2 + \left(\frac{I_d^|}{\sin\frac{\mu}{2}} \right)^2 = 1$$

where, $V_d^| = \frac{V_d}{V_{do}}$ and $I_d^| = \frac{I_d}{2I_s}$

B) Inverter:

The inverter characteristics are similar to the rectifier characteristics. However, the operation as an inverter requires a minimum commutation margin angle during which the voltage across the valve is negative. Hence the operating region of an inverter is different from that for a rectifier.

So, the margin angle (ξ) has different relationship to γ depending on the range of operation which are

First Range: $\beta < 60^o$ and $\xi = \gamma$

Second Range: $60^o < \beta < 90^o$ and $\xi = 60^o - \mu = \gamma - (\beta - 60^o)$

Third Range: $\beta > 90^o$ and $\xi = \gamma - 30^o$

In the inverter operation, it is necessary to maintain a certain minimum margin angle ξ_o which results in 3 sub-modes of the 1st mode which are

Mode 1

1(a) $\beta < 60^o$ for values of $\mu < (60^o - \xi_o)$

The characteristics are linear defined by

$$V_d^| = \cos\gamma_o - I_d^|$$

1(b) $60^o < \beta < 90^o$ for

$$\mu = 60^o - \xi_o = 60^o - \gamma_o = \text{constant}$$

The characteristics are elliptical.

1(c) $90^o < \beta < 90^o + \xi_o$ for values of μ in the range

$$60^o - \xi_o \leq \mu \leq 60^o$$

The characteristics in this case are line and defined by

$$V_d^{|} = \cos(\gamma_o + 30^o) - I_d^{|}$$

Mode 2

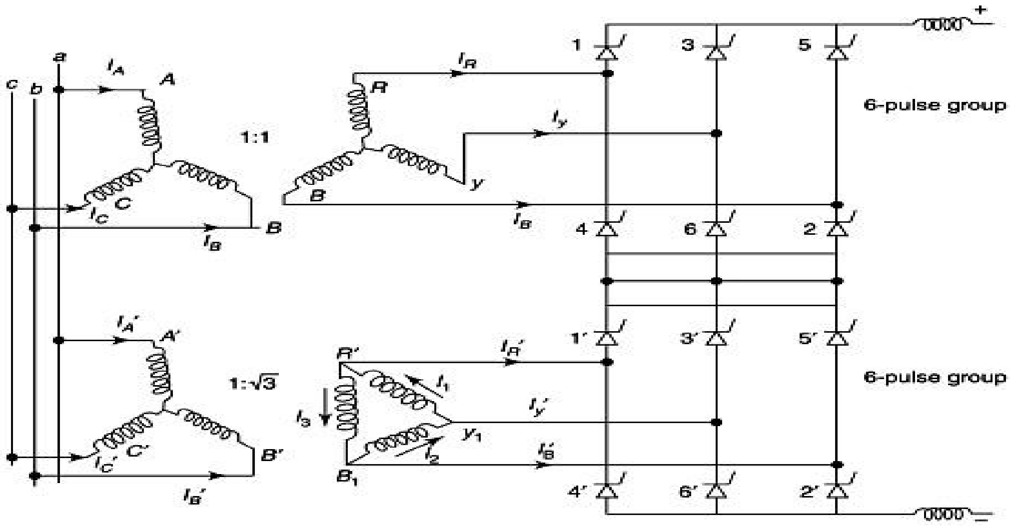
For $\mu > 60^o$ corresponding to $\beta > 90^o + \gamma_o$

The characteristics again are linear but with a different slope and is defined by

$$V_d^{|} = \sqrt{3}\cos\gamma_o - 3I_d^{|}$$

In the normal operation of the converter $I_d^{|}$ is in the range of 0.08 to 0.1 .

Characteristics of a twelve pulse converter



As long as the AC voltages at the converter bus remain sinusoidal (with effective filtering), the operation of one bridge is unaffected by the operation of the other bridge connected in series. The region of rectifier operation can be divided into five modes as Mode 1: 4 and 5 valve conduction

$$0 < \mu < 30^o$$

Mode 2: 5 and 6 valve conduction

$$30^o < \mu < 60^o$$

Mode 3: 6 valve conduction

$$0 < \alpha < 30^o, \mu = 60^o$$

Mode 4: 6 and 7 valve conduction

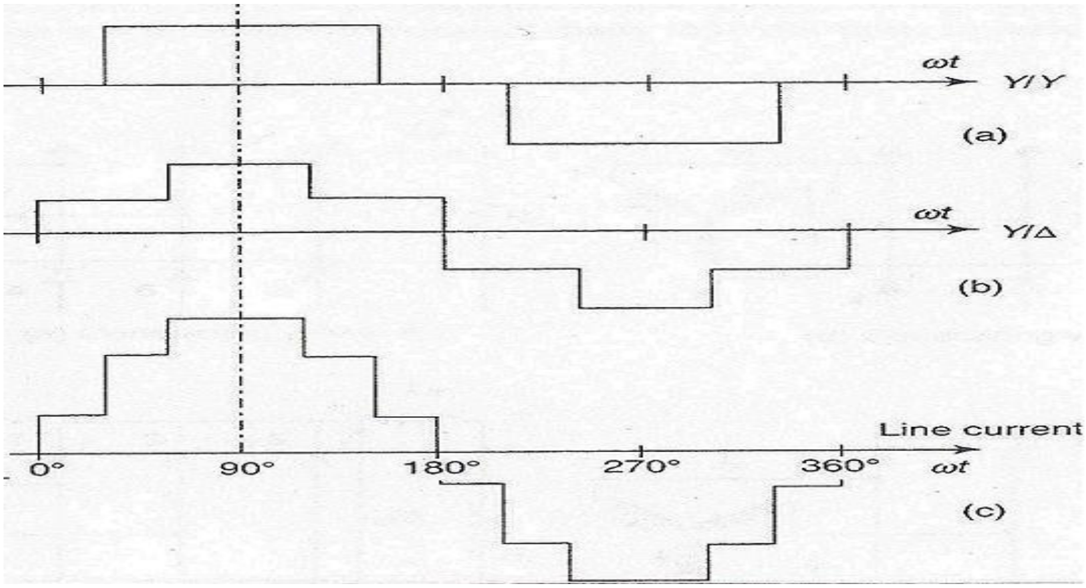
$$60^o < \mu < 90^o$$

Mode 5: 7 and 8 valve conduction

$$90^o < \mu < 120^o$$

The second mode is a continuation of the first and similarly fifth is a continuation of the fourth.

The equivalent circuit of the twelve pulse converter is the series combination of the equivalent circuits for the two bridges. This is because the two bridges are connected in series on the DC side and in parallel on the AC side. The current waveforms in the primary winding of the star/star and star/delta connected transformers and the line current injected into the converter bus are shown.



Questions

1) What is the need for interconnection of systems? Explain the merits of connecting HVAC systems by HVDC tie-lines?
2) (a) Discuss the different factors that favor HVDC transmission systems over EHVAC transmission over long distances.

(b) What are the different HVDC links normally adopted?

3) (a) With the help of a neat schematic diagram of a typical HVDC converter station explain the functions of various components available.

(b) What are the applications and merits of HVDC transmission system?

4) (a) Explain for what reasons as a system planner, you consider the applications of HVDC in India?

(b) Compare HVDC transmission system with AC system in all aspects.

5) For a 3-Φ, 6 pulse Graetz's circuit, draw the timing diagram considering overlap angle is less than 60^o and without overlap for the following:

(a) Voltage across load

(b) Voltage across any two pair of conduction values

6) Explain the operation of a 12 pulse bridge rectifier with the help of circuit diagram, voltage & current waveforms.

7) (a) Clearly explain how harmonics are produced and obtain the expression for rms value of the fundamental component of the current.

(b) Obtain a relation between firing angle and power factor angle in a 3-Φ bridge rectifier.

8) Derive the expression for average DC voltages of a six pulse bridge converter, considering gate control and source reactance.

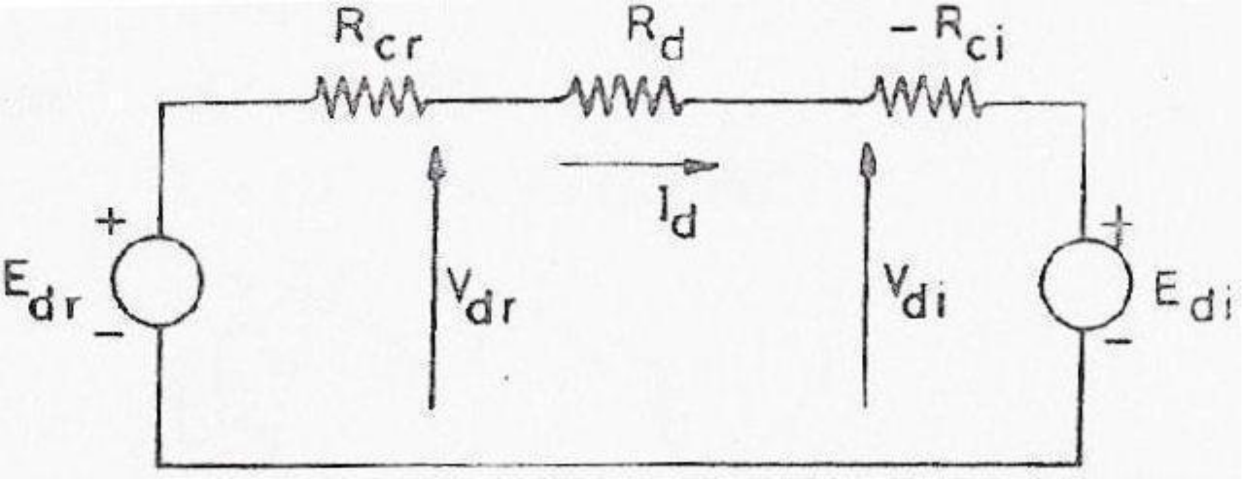
9) What is the reason for using star-star and star-delta transformer configurations for 12 pulse converter? Derive an equation for primary current using fourier analysis.

UNIT-III: CONTROL OF HVDC CONVERTER SYSTEMS

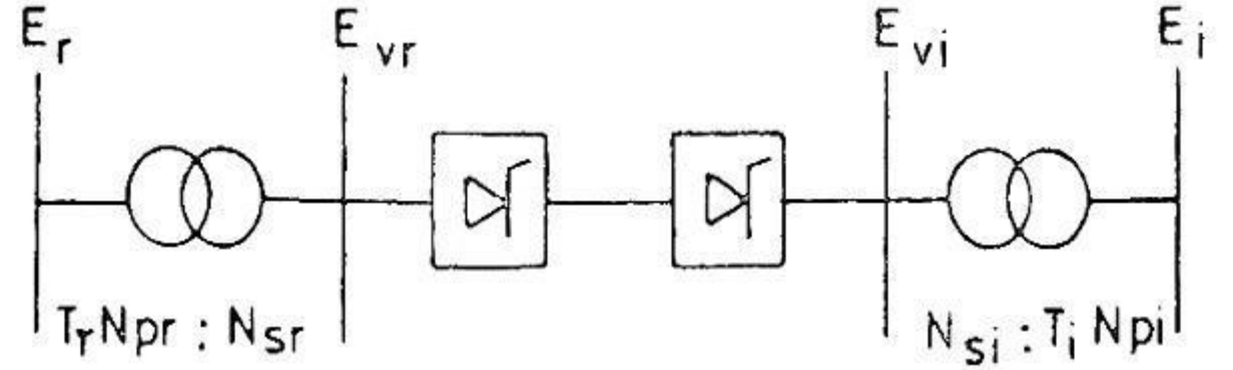
The major advantage of a HVDC link is rapid controllability of transmitted power through the control of firing angles of the converters. Modern converter controls are not only fast, but also very reliable and they are used for protection against line and converter faults.

Principles of DC Link Control

The control of power in a DC link can be achieved through the control of current or voltage. From minimization of loss considerations, we need to maintain constant voltage in the link and adjust the current to meet the required power.



Consider the steady state equivalent circuit of a two terminal DC link. This is based on the assumption that all the series connected bridges in both poles of a converter station are identical and have the same delay angles. Also the number of series connected bridges (n_b) in both stations (rectifier and inverter) are the same.



The voltage sources E_{dr} and E_{di} are defined by

$$E_{dr} = (3\sqrt{2}/\pi)\ n_b\ E_{vr} \cos\alpha_r \text{ ------ } (1)$$

$$E_{di} = (3\sqrt{2}/\pi)\ n_b\ E_{vi} \cos\gamma_i \text{ ------ } (2)$$

where E_{vr} and E_{vi} are the line to line voltages in the valve side windings of the rectifier and inverter transformer respectively. From the above figure these voltages can be obtained by

$$E_{vr} = \frac{N_{sr} E_r}{N_{pr} T_r} \quad , \qquad E_{vi} = \frac{N_{si} E_i}{N_{pi} T_i} \text{------------------}(3)$$

where E_r and E_i are the AC (line to line) voltages of the converter buses on the rectifier and inverter side. T_r and T_i are the OFF-nominal tap ratios on the rectifier and inverter side.

Combining equations (1), (2) and (3),

$$E_{dr} = (A_r E_r / T_r) \cos\alpha_r \text{----------}(4)$$

$$E_{di} = (A_i E_i / T_i) \cos\gamma_i \text{-----------}(5)$$

where A_r and A_i are constants.

The steady-state current I_d in the DC link is obtained as

$$I_d = \frac{(E_{dr} - E_{di})}{R_{cr} + R_d - R_{ci}}$$

Substituting equations (4) and (5) in the above equation, we get

$$I_d = \frac{(A_r E_r / T_r) \cos\alpha_r - (A_i E_i / T_i) \cos\gamma_i}{R_{cr} + R_d - R_{ci}}$$

The control variables in the above equation are T_r , T_i and α_r , β_i . However, for maintaining safe commutation margin, it is convenient to consider γ_i as control variable instead of β_i .

As the denominator in the final equation is small, even small changes in the voltage magnitude E_r or E_i can result in large changes in the DC current, the control variables are held constant. As the voltage changes can be sudden, it is obvious that manual control of converter angles is not feasible. Hence, direct and fast control of current by varying α_r or γ_r in response to a feedback signal is essential.

While there is a need to maintain a minimum extinction angle of the inverter to avoid commutation failure, it is economical to operate the inverter at Constant Extinction Angle (CEA) which is slightly above the absolute minimum required for the commutation margin. This results in reduced costs of the inverter stations, reduced converter losses and reactive power consumption. However, the main drawback of CEA control is the negative resistance characteristics of the converter which makes it difficult to operate stably when the AC system is weak (low short-circuit ratios). Constant DC Voltage (CDCV) control or Constant AC Voltage (CACV) control are the alternatives that could be used at the inverter.

Under normal conditions, the rectifier operates at Constant Current (CC) control and the inverter at the CEA control.

The power reversal in the link can take place by the reversal of the DC voltage. This is done by increasing the delay angle at the station initially operating as a rectifier, while reducing the delay angle at the station initially operating as the inverter. Thus, it is necessary to provide both CEA and CC controllers at both terminals.

The feedback control of power in a DC link is not desirable because

1) At low DC voltages, the current required is excessive to maintain the required level of power. This can be counterproductive because of the excessive requirements of the reactive power, which depresses voltage further.
2) The constant power characteristic contributes to negative damping and degrades dynamic stability.

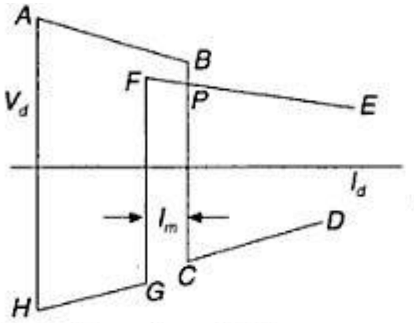
Converter Control Characteristics

Basic Characteristics:

The intersection of the two characteristics (point A) determines the mode of operation- Station I operating as rectifier with constant current control and station II operating at constant (minimum) extinction angle.

There can be three modes of operation of the link (for the same direction of power flow) depending on the ceiling voltage of the rectifier which determines the point of intersection of the two characteristics which are defined below

1) CC at rectifier and CEA at inverter (operating point A) which is the normal mode of operation.
2) With slight dip in the AC voltage, the point of intersection drifts to C which implies minimum α at rectifier and minimum γ at the inverter.
3) With lower AC voltage at the rectifier, the mode of operation shifts to point B which implies CC at the inverter with minimum α at the rectifier.

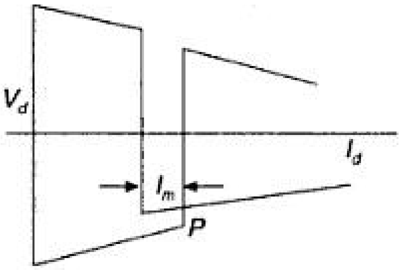


Controllers characteristics.

Types of Station Control Characteristics

Station-I	Station-II	Controller type
AB	HG	Minimum α
BC	GF	Constant current
CD	EF	CEA (minimum γ)

The characteristic AB has generally more negative slope than characteristic FE because the slope of AB is due to the combined resistance of (R_d + R_{cr}) while is the slope of FE is due to R_{ci} .



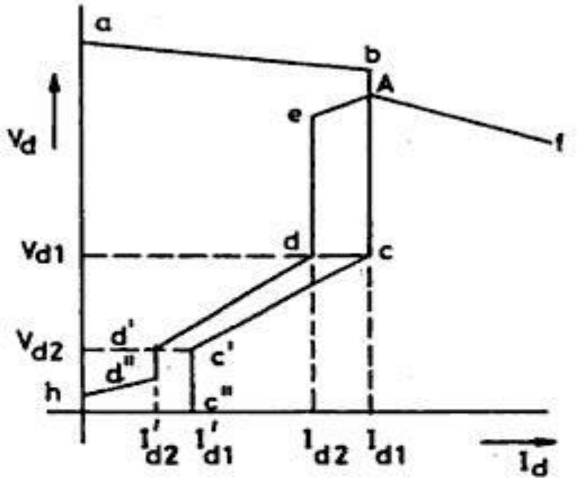
Power reversal controllers characteristics

The above figure shows the control characteristics for negative current margin I_m (or where the current reference of station II is larger than that of station I). The operating point shifts now to D which implies power reversal with station I (now acting as inverter) operating with minimum CEA control while station II operating with CC control.

This shows the importance of maintaining the correct sign of the current margin to avoid inadvertent power reversal. The maintenance of proper current margin requires adequate telecommunication channel for rapid transmission of the current or power order.

Voltage Dependent Current Limit:

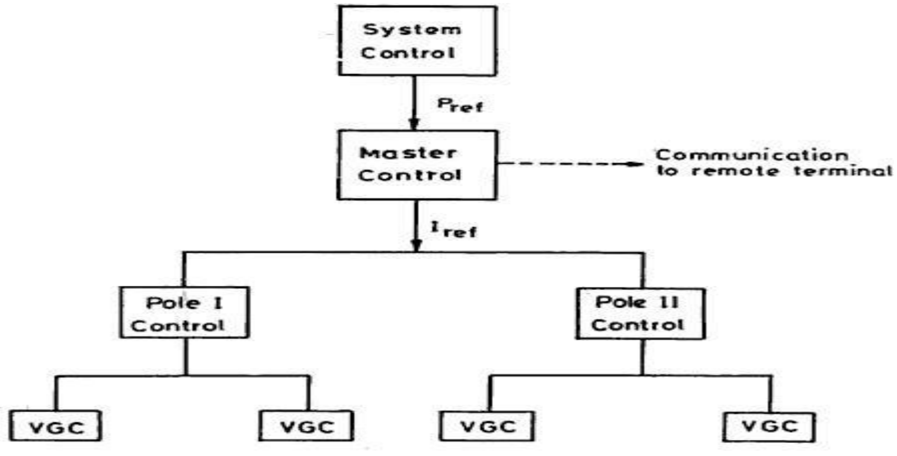
The low voltage in the DC link is mainly due to the faults in the AC system on the rectifier or inverter side. The low AC voltage due to faults on the inverter side can result in persistent commutation failure because of the increase of the overlap angle. In such cases, it is necessary to reduce the DC current in the link until the conditions that led to the reduced DC voltage are relieved. Also the reduction of current relieves those valves in the inverter which are overstressed due to continuous current flow in them.



If the low voltage is due to faults on the rectifier side AC system, the inverter has to operate at very low power factor causing excessive consumption of reactive power which is also undesirable. Thus, it becomes useful to modify the control characteristics to include voltage dependent current limits. The figure above shown shows current error characteristics to stabilize the mode when operating with DC current between I_{d1} and I_{d2} . The characteristic $cc^{|}$ and $c^{|}c^{||}$ show the limitation of current due to the reduction in voltage.

System Control Hierarchy

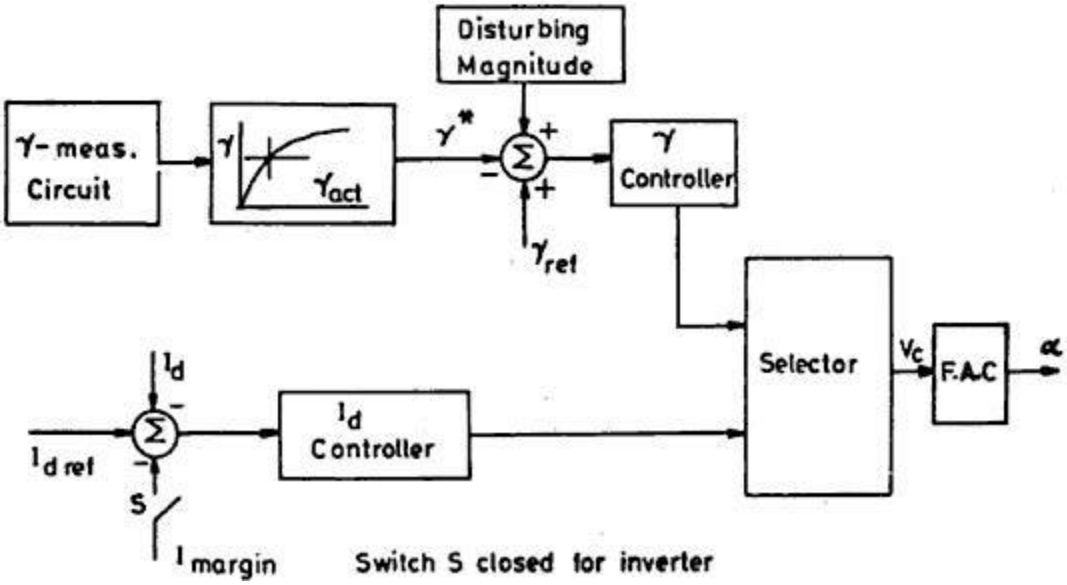
The control function required for the HVDC link is performed using the hierarchical control structure.



VGC – Valve Group Control

The master controller for a bipole is located at one of the terminals and is provided with the power order (P_{ref}) from the system controller (from energy control centre). It also has other information such as AC voltage at the converter bus, DC voltage etc. The master controller transmits the current order (I_{ref}) to the pole control units which in turn provide a firing angle order to the individual valve groups (converters). The valve group or converter control also oversees valve monitoring and firing logic through the optical interface. It also includes bypass pair selection logic, commutation failure protection, tap changer control, converter start/stop sequences, margin switching and valve protection circuits.

The pole control incorporated pole protection, DC line protection and optional converter paralleling and deparalleling sequences. The master controller which oversees the complete bipole includes the functions of frequency control, power modulation, AC voltage and reactive power control and torsional frequency damping control.



The current or extinction angle controller generates a control signal V_c which is related to the firing angle required. The firing angle controller generates gate pulses in response to the control signal V_c . The selector picks the smaller of the α determined by the current and CEA controllers.

Firing Angle Control

The operation of CC and CEA controllers is closely linked with the method of generation of gate pulses for the valves in a converter. The requirements for the firing pulse generation of HVDC valves are

1. The firing instant for all the valves are determined at ground potential and the firing signals sent to individual thyristors by light signals through fibre-optic cables. The required gate power is made available at the potential of individual thyristor.
2. While a single pulse is adequate to turn-on a thyristor, the gate pulse generated must send a pulse whenever required, if the particular valve is to be kept in a conducting state. The two basic firing schemes are
1. Individual Phase Control (IPC)
2. Equidistant Pulse Control (EPC)

Individual Phase Control (IPC)

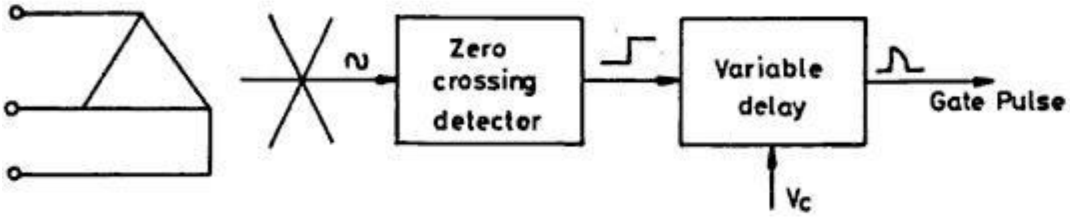
This was used in the early HVDC projects. The main feature of this scheme is that the firing pulse generation for each phase (or valve) is independent of each other and the firing pulses are rigidly synchronized with commutation voltages.

There are two ways in which this can be achieved

1. Constant α Control
2. Inverse Cosine Control

Constant α Control

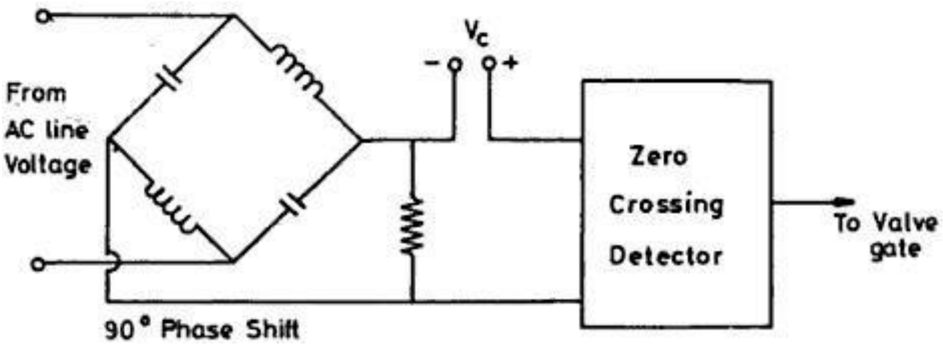
Six timing (commutation) voltages are derived from the converter AC bus via voltage transformers and the six gate pulses are generated at nominally identical delay times subsequent to the respective voltage zero crossings. The instant of zero crossing of a particular commutation voltage corresponds to $\alpha = 0^o$ for that valve.



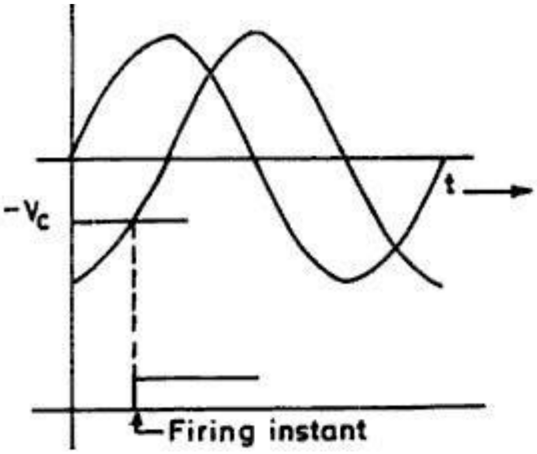
The delays are produced by independent delay circuits and controlled by a common control voltage V derived from the current controllers.

Inverse Cosine Control

The six timing voltages (obtained as in constant α control) are each phase shifted by 90^o and added separately to a common control voltage V.



The zero crossing of the sum of the two voltages initiates the firing pulse for the particular valve is considered. The delay angle α is nominally proportional to the inverse cosine of the control voltage. It also depends on the AC system voltage amplitude and shape.



The main advantage of this scheme is that the average DC voltage across the bridge varies linearly with the control voltage V_c .

Drawbacks of IPC Scheme

The major drawback of IPC scheme is the aggravation of the harmonic stability problem that was encountered particularly in systems with low short circuit ratios (less than 4). The harmonic instability, unlike instability in control systems, is a problem that is characterized by magnification of noncharacteristic harmonics in steady-state.

This is mainly due to the fact that any distortion in the system voltage leads to perturbations in the zero crossings which affect the instants of firing pulses in IPC scheme. This implies that even when the fundamental frequency voltage components are balanced, the firing pulses are not equidistant in steady-state. This in turn leads to the generation of noncharacteristic harmonics (harmonics of order $h \neq np \pm 1$) in the AC current which can amplify the harmonic content of the AC voltage at the converter bus. The problem of harmonic instability can be overcome by the following measures

1. Through the provision of synchronous condensers or additional filters for filtering out noncharacteristic harmonics.
2. Use of filters in control circuit to filter out noncharacteristic harmonics in the commutation voltages.
3. The use of firing angle control independent of the zero crossings of the AC voltages. This is the most attractive solution and leads to the Equidistant Pulse Firing scheme.

Equidistant Pulse Control (EPC)

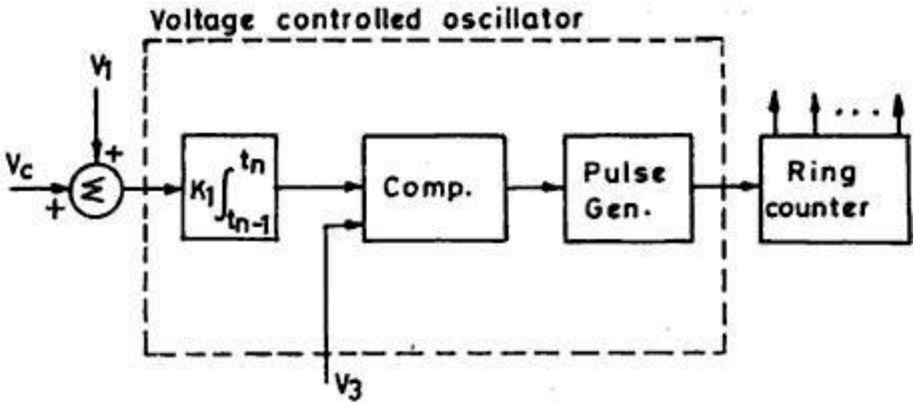
The firing pulses are generated in steady-state at equal intervals of 1/pf , through a ring counter. This control scheme uses a phase locked oscillator to generate the firing pulses. Thre are three variations of the EPC scheme

1. Pulse Frequency Control (PFC)
2. Pulse Period Control
3. Pulse Phase Control (PPC)

Pulse Frequency Control (PFC)

A Voltage Controlled Oscillator (VCO) is used, the frequency of which is determined by the control voltage V_c which is related to the error in the quantity (current, extinction angle or DC voltage) being regulated. The frequency in steady-state operation is equal to pf_o where f_o is the nominal frequency of the AC system. PFC system has an integral characteristic and has to be used along with a feedback control system for stabilization.

The Voltage Controlled Oscillator (VCO) consists of an integrator, comparator and a pulse generator.



The output pulses of the generator drive the ring counter and also reset the integrator. The instant (t_n) of the firing pulse is determined by

$$\int_{t_{n-1}}^{t_n} K_1 (V_c + V_1)dt = V_3$$

where V_1 is a bias (constant) voltage and V_3 is proportional to the system period. In steady-state, $V_c = 0$, and from the above equation, we get

$$K_1 V_1 (t_n - t_{n-1}) = V_3$$

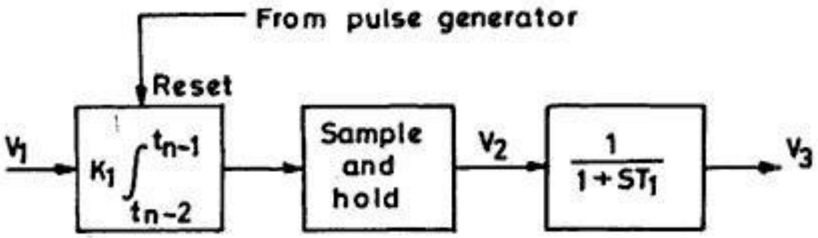
Since, $t_n - t_{n-1} = 1/pf_o$

in steady-state, the gain K_1 of the integrator is chosen as

$$K_1 = pf_o V_3 / V_1$$

The circuit does not incorporate frequency correction (when the system frequency deviates from f_o). The frequency correction is obtained by deriving V_3 as

$$V_3 = V_2 / (1+ST_1), \; V_2 = K_1 V_1 (t_{n-1} - t_{n-2})$$



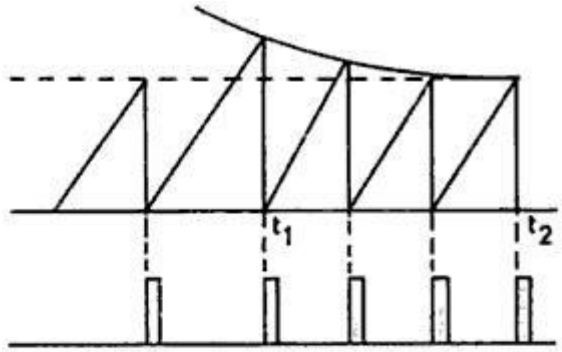
Pulse Period Control

It is similar to PFC except for the way in which the control voltage V_c is handled. The structure of the controller is the same, however, V_c is now summed with V_3 instead of V_1. Thus, the instant t_n of the pulse generation is

$$\int_{t_{n-1}}^{t_n} K_1 V_1 dt = V_3 + V_c$$

$$K_1 V_1 (t_n - t_{n-1}) = V_3 + V_c$$

With $V_c = 0$, the interval between consecutive pulses, in steady-state, is exactly equal to $1/pf_o$.



The frequency correction in this scheme is obtained by either updating V_1 in response to the system frequency variation or including another integrator in the CC or CEA controller.

Pulse Phase Control (PPC)

An analog circuit is configured to generate firing pulses according to the following equation

$$\int_{t_{n-1}}^{t_n} K_1 V_1 dt = V_{cn} - V_{c(n-1)} + V_3$$

where V_{cn} and $V_{c(n-1)}$ are the control voltages at the instants t_n and t_{n-1} respectively.

For proportional current control, the steady-state can be reached when the error of V_c is constant.

The major advantages claimed for PPC over PFC are (i) easy inclusion of α limits by limiting V_c as in IPC and (ii) linearization of control characteristic by including an inverse cosine function block after the current controller. Limits can also be incorporated into PFC or pulse period control system.

Drawbacks of EPC Scheme

EPC Scheme has replaced IPC Scheme in modern HVDC projects; it has certain limitations which are

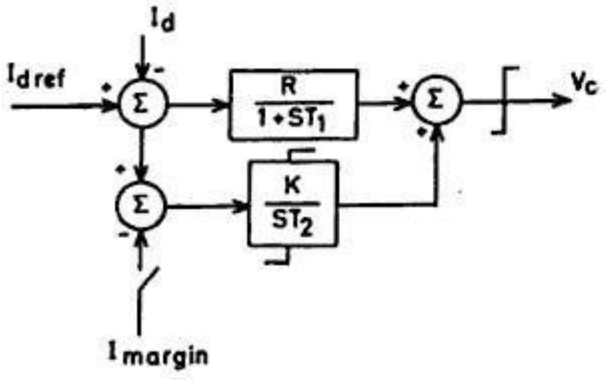
1. Under balanced voltage conditions, EPC results in less DC voltage compared to IPC. Unbalance in the voltage results from single phase to ground fault in the AC system

which may persist for over 10 cycles due to stuck breakers. Under such conditions, it is desirable to maximize DC power transfer in the link which calls for IPC.

2. EPC Scheme also results in higher negative damping contribution to torsional oscillations when HVDC is the major transmission link from a thermal station.

Current and Extinction Angle Control

The current controller is invariably of feedback type which is of PI type.



The extinction angle controller can be of predictive type or feedback type with IPC control. The predictive controller is considered to be less prone to commutation failure and was used in early schemes. The feedback control with PFC type of Equidistant Pulse Control overcomes the problems associated with IPC.

The extinction angle, as opposed to current, is a discrete variable and it was felt the feedback control of gamma is slower than the predictive type. The firing pulse generation is based on the following equation

$$0 = \int_{\pi-\gamma+\omega t_{n-1}}^{\omega t_n} e_{cj}\, d(\omega t) + 2 X_c I_d$$

where e_{cj} is the commutation voltage across valve j and t_n is the instant of its firing. In general, the prediction of firing angle is based on the equation

$$B_j = \gamma_{ref} + \mu_j$$

where μ_j is the overlap angle of valve j, which is to be predicted based on the current knowledge of the commutation voltage and DC current.

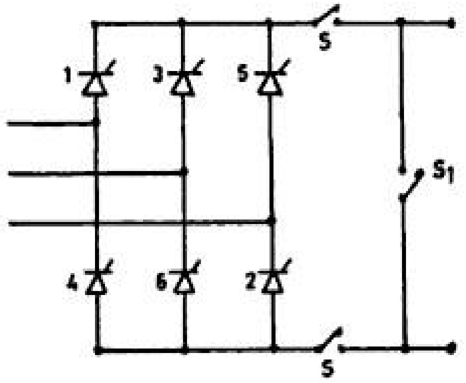
Under large disturbances such as a sudden dip in the AC voltage, signals derived from the derivative of voltage or DC current aid the advancing of delay angle for fast recovery from commutation failures.

Starting and Stopping of DC Link

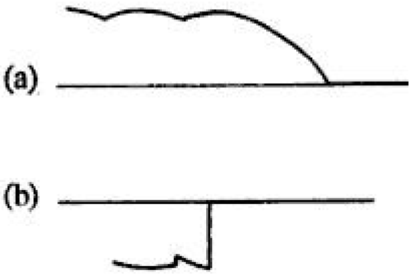
Energization and Deenergization of a Bridge:

Consider N series connected bridges at a converter station. If one of the bridges is to be taken out of service, there is need to not only block, but bypass the bridge. This is because of the fact that just blocking the pulses does not extinguish the current in the pair of valves that are left conducting at the time of blocking. The continued conduction of this pair injects AC voltage into the link which can give rise to current and voltage oscillations due to lightly damped oscillatory circuit in the link formed by smoothing reactor and the line capacitance. The transformer feeding the bridge is also subjected to DC magnetization when DC current continues to flow through the secondary windings.

The bypassing of the bridge can be done with the help of a separate bypass valve or by activating a bypass pair in the bridge (two valves in the same arm of the bridge). The bypass valve was used with mercury arc valves where the possibility of arc backs makes it impractical to use bypass pairs. With thyristor valves, the use of bypass pair is the practice as it saves the cost of an extra valve.



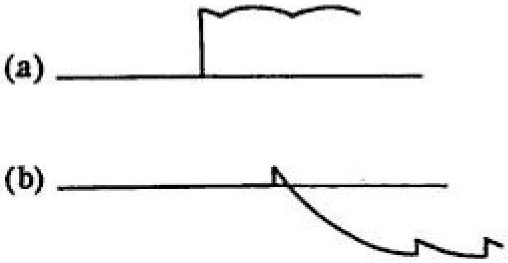
With the selection of bypass pair 1 and 4, the commutation from valve 2 to4 is there, but the commutation from valve 3 to valve 5 is prevented. In the case of a predetermined choice of the bypass path, the time lapse between the blocking command and the current transfer to bypass path can vary from 60^0 and 180^0 for a rectifier bridge. In the inverter, there is no time lag involved in the activation of the bypass pair. The voltage waveforms for the rectifier and inverter during de-energisation are shown below where the overlap is neglected.



The current from bypass pair is shunted to a mechanical switch S_1 . With the aid of the isolators S, the bridge can be isolated. The isolator pair S and switch S_1 are interlocked such that one or both are always closed.

The energisation of a blocked bridge is done in two stages. The current is first diverted from S_1 to the bypass pair. For this to happen S_1 must generate the required arc voltage and to minimize this voltage, the circuit inductance must be small. In case the bypass pair fails to take over the current, S_1 must close automatically if the current in that does not become zero after a predetermined time interval. AC breakers with sufficient arc voltage, but with reduced breaking capacity are used as switch S_1 .

In the second stage of energisation, the current is diverted from the bypass pair. For the rectifier, this can take place instantaneously neglecting overlap. The voltage waveforms for this case are shown below.



Start-Up of DC Link:

There are two different start-up procedures depending upon whether the converter firing controller provides a short gate pulse or long gate pulse. The long gate pulse lasts nearly 120^0 , the average conduction period of a valve.

Start-up with long pulse firing:

1. Deblock inverter at about $\gamma = 90^0$
2. Deblock rectifier at $\alpha = 85^0$ to establish low direct current
3. Ramp up voltage by inverter control and the current by rectifier control.

Start-up with short pulse firing:

1. Open bypass switch at one terminal
2. Deblock that terminal and load to minimum current in the rectifier mode
3. Open bypass switch at the second terminal and commutate current to the bypass pair
4. Start the second terminal also in the rectifier mode
5. The inverter terminal is put into the inversion mode
6. Ramp up voltage and current.

The voltage is raised before raising the current. This permits the insulation of the line to be checked before raising the power. The ramping of power avoids stresses on the generator shaft. The switching surges in the line are also reduced.

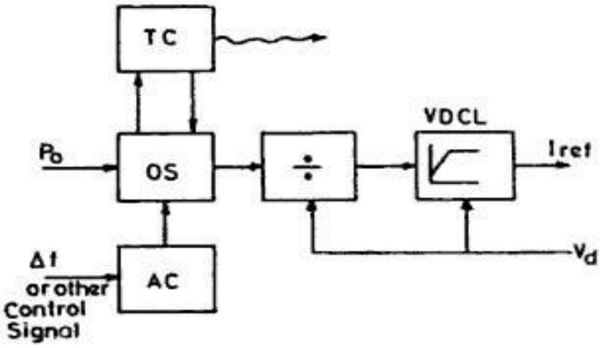
The required power ramping rate depends on the strength of the AC system. Weaker systems require fast restoration of DC power for maintaining transient stability.

Power Control

The current order is obtained as the quantity derived from the power order by dividing it by the direct voltage. The limits on the current order are modified by the voltage dependent current order limiter (VDCOL). The objective of VDCOL is to prevent individual thyristors from carrying full current for long periods during commutation failures.

By providing both converter stations with dividing circuits and transmitting the power order from the leading station in which the power order is set to the trailing station, the fastest response to the DC line voltage changes is obtained without undue communication requirement.

The figure below shows the basic power controller used.



TC-Telecommunication equipment
OS-Order Setting unit

VDCL-Voltage dependent current limiter

When the DC line resistance is large and varies considerably e.g., when the overhead line is very long and exposed to large temperature variations, the DC line voltage drop cannot be compensated individually in the two stations. This problem can be solved by using a current order calculated in one substation only and transmitting its output to the other substation.

Questions:

1) Write detailed notes on the following
   (a) Preductive commutation margin control
   (b) Equidistant firing control.

2) (a) Differentiate between the two start-up procedures based upon the pulse.
   (b) Describe about starting and stopping of DC link.

3) (a) Explain with neat sketch, constant extinction angle control.
   (b) What is meant by current margin between two stations in a HVDC link? Why is the inverter station, operated as a constant voltage controller under normal conditions?

4) Enumerate the relative merits and demerits of constant current control and constant voltage control of HVDC link.

5) (a) Explain the necessity of “VDCOL" control in a HVDC link with the help of VI characteristics..
   (b) Explain the procedure of Energization and Deenergization of a converter bridge.

6) (a) Draw the complete converter control characteristics and explain the principle of power control in a DC link.
   (b) Explain Inverse cosine control scheme for firing pulse generations.

7) (a) Explain pulse frequency control scheme for firing pulse generation and discuss its drawbacks.
   (b) Explain clearly the procedure for start up of a DC link.

8) Explain the individual characteristics of a Rectifier and an Inverter with sketches.

9) With block diagram, discuss the principle of operation of a basic power controller.

10) Write short notes on the following:
   (a) Constant Alpha control
   (b) Inverse cosine control.

11) Explain the drawbacks in Individual phase control and equidistant pulse control schemes used in HVDC projects.

Introduction, generation of harmonics, AC & DC Filters, Reactive power requirements at steady state, sources of reactive power, static VAR systems

Electrical energy transmitted through AC transmission or DC transmission is to be delivered at the consumer's terminals at specified voltage level of constant magnitude without deviation from the ideal waveform.

An HVDC transmission system generates harmonic currents on the AC side and harmonic voltages on the DC side during operation. The harmonic currents generated at the AC bus of the converter get transmitted to the AC network and then cause the following adverse effects.

a) Heating of the equipments connected.
b) Instability of converter control.
c) Generates telephone and radio interference in adjacent communication lines, thereby inducing harmonic noise.
d) Harmonics can lead to generation of overvoltages due to resonance when filter circuits are employed.

An HVDC transmission system consists of a rectifier and an inverter whose operation generates harmonics on AC and DC side of the converter. The three distinct sources of harmonics in HVDC systems are

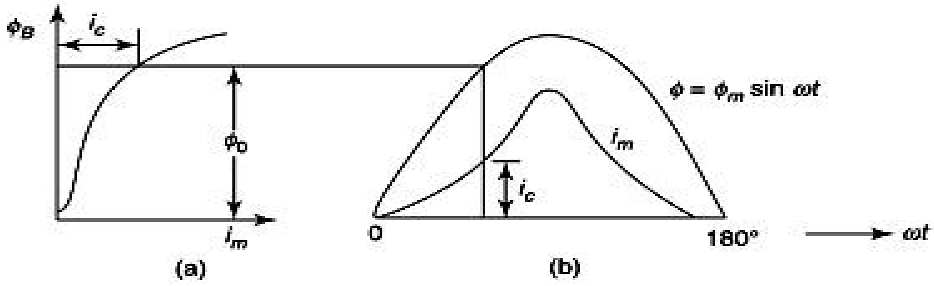
1) Transformer.
2) AC Generator.
3) Converter along with its control devices.

Transformer as source of harmonics

Transformers can be considered as source of harmonic voltages, which arise from magnetic distortion and magnetic saturation due to the presence of a DC component in its secondary. The magnitude of these harmonics depends upon the operating flux density. Converter transformers are usually operated at high flux densities than conventional 3-phase transformers, and therefore the possibility of generation of harmonics is more.

Although the waveform is usually good, an AC generator may be regarded as a source of balanced harmonics because of non-uniform distribution of flux on the armature windings.

The converter which forms the basic unit in HVDC transmission imposes changes of impedances in the current.

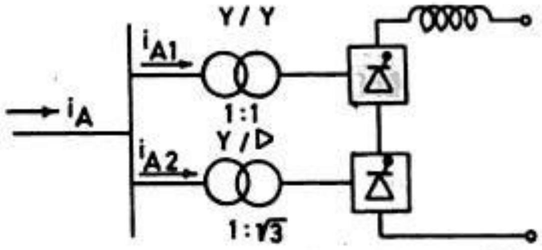


Transformer magnetisation (without hysteresis)
(a) Magnetisation curve (b) Flux and magnetisation current waveforms

When hysteresis effect is considered, then the non-sinusoidal magnetizing current waveform is no longer symmetrical which is mainly caused by triple n harmonics and particularly the third harmonic. Thus, in order to maintain a reasonable sinusoidal voltage supply, it is necessary to supply a path for triple n harmonics which is achieved by the use of delta-connected windings.

Harmonics due to Converters

A 12-pulse connection consists of two 6-pulse groups. One group having Y-Y connected converter transformer with 1:1 turns ratio and the other group having Y-Δ converter transformer bank with 1:√3 turns ratio.



Schematic Diagram of a 12 Pulse Converter Unit

Generation of Harmonics

The harmonics which are generated are of two types.

(i) Characteristic harmonics.

(ii) Non- characteristic harmonics.

Characteristic Harmonics

The characteristic harmonics are harmonics which are always present even under ideal operation.

In the converter analysis, the DC current is assumed to be constant. But in AC current the harmonics exist which are of the order of

$$h = np \pm 1$$

and in DC current it is of the order of

$$h = np$$

where n is any integer and p is pulse number.

Neglecting overlap, primary currents of Y-Y and Y-Δ connection of the transformer are considered taking the origin symmetrical where

$$\left.\begin{aligned} i &= I_d \text{ for } -\pi/3 \le \omega t \le \pi/3 \\ &= 0 \text{ for } \pi/3 \le \omega t \le 2\pi/3 \text{ and } \\ &\qquad -\pi/3 \le \omega t \le -2\pi/3 \\ &= -I_d \text{ for } -2\pi/3 \le \omega t \le -\pi \text{ and } \\ &\qquad 2\pi/3 \le \omega t \le \pi \end{aligned}\right\} \text{for Y-Y connection converter transformer}$$

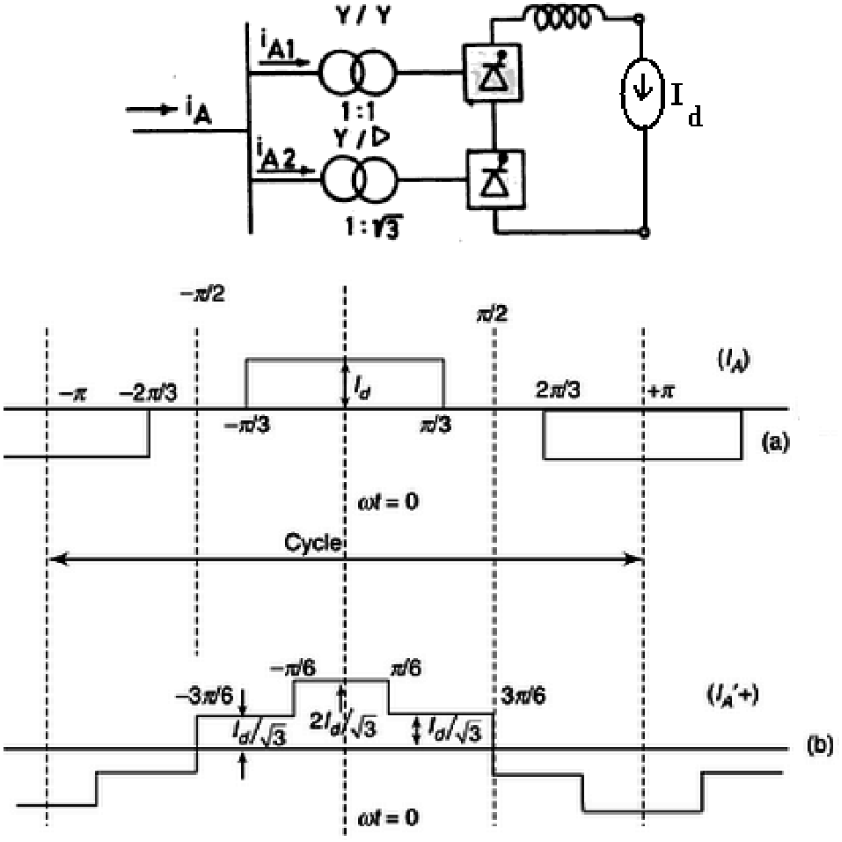


Figure (a): Phase current on primary side of Y-Y connection converter transformer

Figure (b): Phase current on primary side of Y-Δ connection converter transformer

For convenience, the ordinate axis (corresponding to ωt = 0) is chosen such that the waveform has even symmetry. So, generally, by fourier series

$$f(t) = \frac{1}{2}a_0 + \sum_{n=0}^{\infty} a_n \cos n\omega t + \sum_{n=0}^{\infty} b_n \sin n\omega t$$

As positive and negative half cycle cancel each other, so $a_0 = 0$ and as it is (waveform is) even symmetry, so $b_n = 0$ due to which f(t) becomes

$$f(t) = \sum_{n=0}^{\infty} a_n \cos n\omega t (or) \sum_{n} a_n \cos n\omega t$$

$$\text{Therefore, } i_{A1} = \sum_{n} a_{n1} \cos n\omega t$$

$$\text{where, } a_{n1} = \frac{2}{T} \int_{0}^{PeriodOfConduction} f(t)dt$$

Here total time period is T = π and period of conduction is

π/3 So,

$$a_{n1} = 2X\frac{2}{\pi} \int_{0}^{\pi/3} I_d \cos n\omega t d(\omega t)$$

(Here as it is symmetry)

$$a_{n1} = \frac{4I_d}{\pi} \int_{0}^{\pi/3} \cos n\omega t d(\omega t) = \frac{4I_d}{\pi} \left[\frac{\sin n\omega t}{n} \right]_{0}^{\pi/3}$$

$$a_{n1} = \frac{4I_d}{n\pi} \left[\sin n\frac{\pi}{3} \right]$$

For triplen harmonics, $a_{n1} = 0$

Questions

1) Derive the relationship between pulse conversion and harmonics generated.

2) What are the various sources of harmonics generation in a HVDC line?

3) (a) Discuss the effect of pulse number and overlap angle on harmonics generated by HVDC converters.

   (b) Using fourier analysis show that the lowest order voltage harmonic present in Graetz circuit output voltage is six.

4) Analyze the harmonics in the AC current during 6-pulse and 12-pulse operations using fourier analysis. What orders of harmonics predominate in the current wave?

5) (a) Discuss about characteristic and non-characteristic harmonics generated in HVDC systems.

(b) What are the adverse affects of Harmonics produced by the HVDC converters?

6) It is required to eliminate harmonics of order 10 and below 10 other than fundamental in a 12 pulse converter. Suggest a suitable transformer configuration and derive an equation for primary current of transformer.

7) Give reasons for selecting star-star and star-delta transformer configuration instead of two star-star configurations for 12 pulse converter. Derive an equation for primary current.

8) How do you estimate the harmonic order based upon pulse number of HVDC converter station? Give a detailed harmonic analysis of a 12 pulse converter for characteristic harmonics.

9) What are the different harmonics generated in voltage and current waveform on both AC and DC side in case of a 6 pulse converter?

10) Discuss the following filters:

(a) Double Tuned Filter (b) High Pass C Type Filter

11) Draw the loci of Network impedance and filter impedance and analyze the impact of network impendence or admittance on the design of single tuned filter.

12) While listing out the problems associated with the injection of harmonics in a system, explain what is the major design objective of AC filters? How is their performance measured?

13) What do you understand by term filter? Why is it increasing in a system? Classify filters and choose the one required for HVDC transmission system.

14) (a) Discuss about various types of AC filters employed in HVDC systems for harmonic suppression.

(b) Discuss the design aspects of high pass filter.

15) Discuss the design aspects of a single tuned filter and obtain the expression for optimum value of Q for minimum harmonic voltage.

16) What are the various types of filters that are employed in HVDC converter station?

17) What are the filter configurations that are employed for HVDC converter station? Give design aspect of one such filter.

18) Derive an equation for harmonic voltage and current for single tuned filter and discuss the influence of network admittance on design aspects.

19) Explain in detail, the different configurations of static VAR system.

20) (a) Describe the method of compensation of reactive power in HVDC substation.

(b) Draw simple single line schematics for each.

21) What is a Static VAR system? How many types of SVS schemes are present and what are they?

22) (a) Discuss about alternate converter control strategies for reactive power control.

(b) Discuss how shunt capacitors can be used to meet reactive power requirement of a converter.

23) (a) Why Reactive power control is required for HVDC stations? Discuss about conventional control strategies for Reactive power control in HVDC link.

(b) Discuss how reactive power requirement is met using synchronous condensers.

25) Write a note on the following sources of reactive power

(a) Synchronous condensers

(b) Static VAR system

Design of AC Filters

1. Harmonic Distortion:

Harmonic Distortion is given by,

$$D = \frac{\sum_{n=2}^{m} I_n Z_n}{E_1} \times 100$$

where,

I_n – harmonic current injected

Z_n – harmonic impedance of the system

E_1 – fundamental component of line to neutral voltage

m – highest harmonic considered

Harmonic Distortion is also given by,

$$D_{RSS} = \frac{\left[\sum_{n=2}^{m} (I_n Z_n)^2\right]^{1/2}}{E_1} \times 100$$

2. Telephone Influence Factor (TIF):

An index of possible telephone interference and is given by,

$$TIF = \frac{\left[\sum_{n=2}^{m} (I_n Z_n F_n)^2\right]^{1/2}}{E_1}$$

where,

$F_n = 5\, n\, f_1\, p_n$

P_n is the c message weighting used by Bell Telephone Systems (BTS) and Edison Electric Institute (EEI) in USA. This weighting reflects the frequency dependent sensitivity of the human ear and has a maximum value at the frequency of 1000Hz.

3. Telephone Harmonic Form Factor (THFF): It is similar to TIF and is given by,

$$F_n = (n\, f_1 / 800)\, W_n$$

where,

W_n – weight at the harmonic order n, defined by the Consultative Commission on Telephone and Telegraph Systems (CCITT).

TIF is used in USA.

THFF is popular in Europe.

4. IT Product:

In BTS-EEI system, there is another index called IT product and is defined by,

$$IT = \left[\sum_{n=2}^{m} (I_n F_n)^2 \right]^{1/2}$$

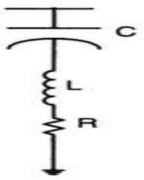
Types of AC Filters

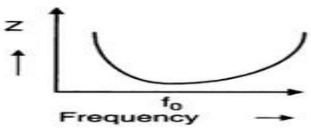
The various types of filters that are used are

1. Single Tuned Filter
2. Double Tuned Filter
3. High Pass Filter
    a) Second Order Filter
    b) C Type Filter

Single Tuned Filter

Single Tuned Filters are designed to filter out characteristic harmonics of single frequency.



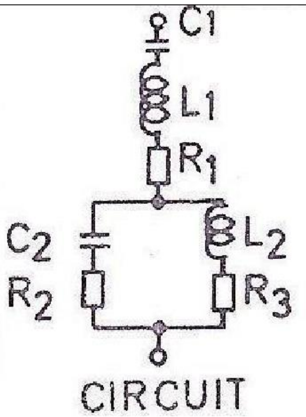


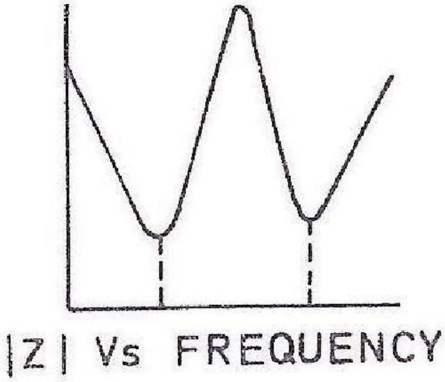
Double Tuned Filter

The Double Tuned Filters are used to filter out two discrete frequencies, instead of using two Single Tuned Filters. Their main disadvantages are

i. only one inductor is subject to full line impulse voltage.

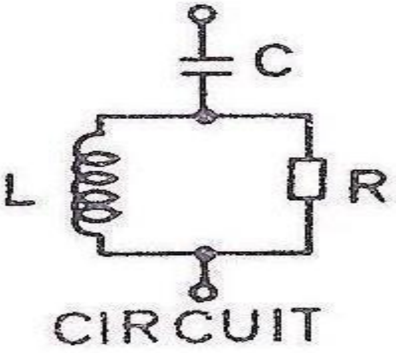
ii. power loss at the fundamental frequency is considerably reduced.

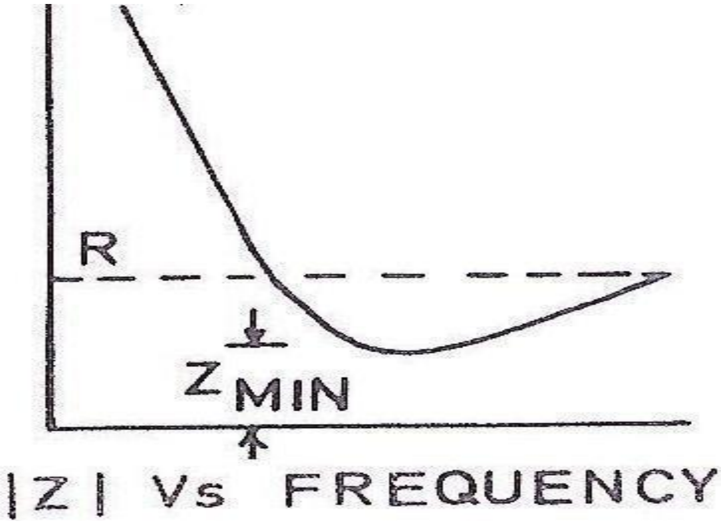




Second Order High Pass Filter

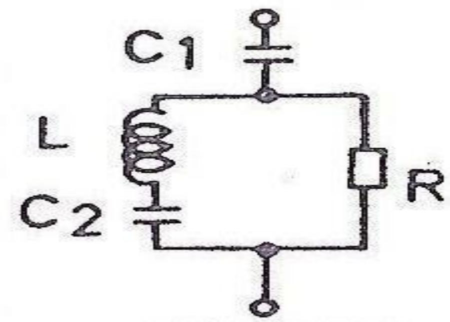
The Second Order High Pass Filters are designed to filter out higher harmonics.



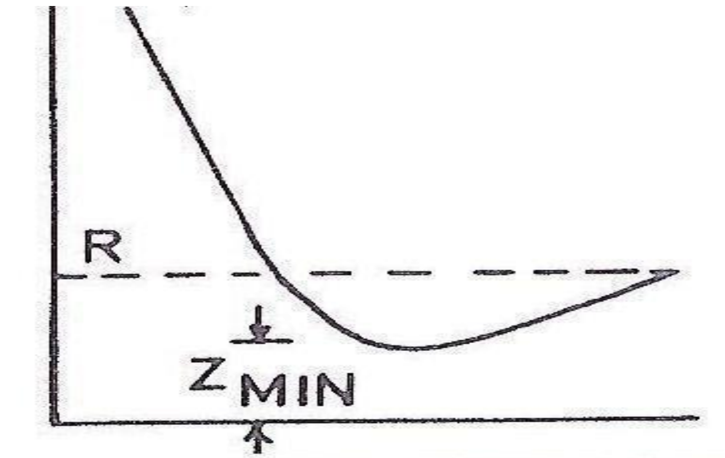


High Pass C Type Filter

The losses at the fundamental frequency can be reduced by using a C Type Filter where capacitor C_2 is in series with inductor L, which provides a low impedance path to the fundamental component of current.



CIRCUIT



|Z| Vs FREQUENCY

A converter system with 12 pulse converters has Double Tuned (or two Single Tuned) Filter banks to filter out 11th and 13th harmonics and a High Pass Filter bank to filter the rest of harmonics. Sometimes a third harmonic filter may be used to filter the non-characteristic harmonics of the 3rd order particularly with weak AC systems where some voltage unbalance is expected.

All filter branches appear capacitive at fundamental frequency and supply reactive power.

Design of Single Tuned Filter

The impedance Z_{Fh} of the single tuned filter at the harmonic order 'h' is given by

$$Z_{Fh} = R + j\left(h\omega L - \frac{1}{h\omega C}\right)$$

where ω is the fundamental frequency which can vary with the power system operating conditions.

A tuned filter is designed to filter a single harmonic of order h_r . If $h_r\omega=\omega_r$, then $Z_{Fh}=R=\frac{X_0}{Q}$ and is minimum.

Since ω is variable and there could be errors in the tuning($\omega_r \neq h_r \omega_n$ where ω_n is the nominal (rated) frequency), it is necessary to compute the impedance of the tuned filter as a function of the detuning parameter (δ) defined by

$$\delta = \frac{h_r\omega - \omega_r}{h_r\omega_n}$$

Considering variations in the frequency (f), inductance (L) and capacitance (C),

$$\delta = \left(1 + \frac{\Delta f}{f_n}\right)\left[\left(1+\frac{\Delta L}{L_n}\right)\left(1 + \frac{\Delta C}{C_n}\right)\right]^{1/2}$$

$$\simeq \frac{\Delta f}{f_n} + \frac{1}{2}\frac{\Delta L}{L_n} + \frac{1}{2}\frac{\Delta C}{C_n}$$

where L_n and C_n are the nominal values of L and C such that $h_r\omega_n=(L_nC_n)^{-1/2}$ The variation in C can be due to

(i) error in the initial setting of C

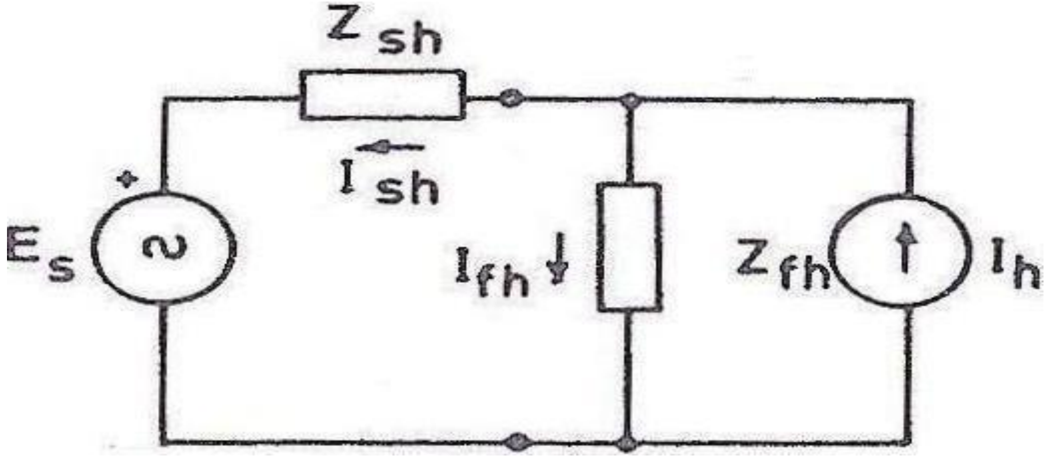
(ii) the variation in C due to the temperature dependence of the dielectric constant.

$$Z_{Fh} = R + jX_0\left(\frac{\omega}{\omega_n}\frac{L}{L_n} - \frac{\omega_n}{\omega}\frac{C_n}{C}\right)$$

where $$X_0 = h_r\omega_n L_n = \frac{1}{h_r\omega_n C_n}$$

The single tuned filters are designed to filter out characteristic harmonics of single frequency. The harmonic current in the filter is given by

$$I_{Fh} = \frac{I_h|Z_{Sh}|}{|Z_{Sh} + Z_{Fh}|}$$

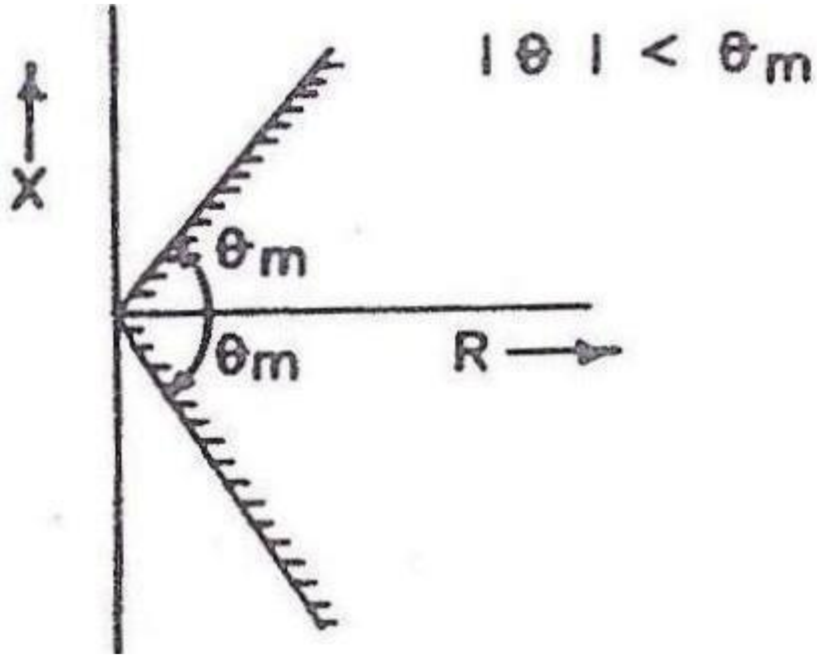


The harmonic voltage at the converter bus is

$$V_h = I_{Fh}|Z_{Fh}| = \frac{I_h}{|Y_{Fh} + Y_{Sh}|} = \frac{I_h}{|Y_h|}$$

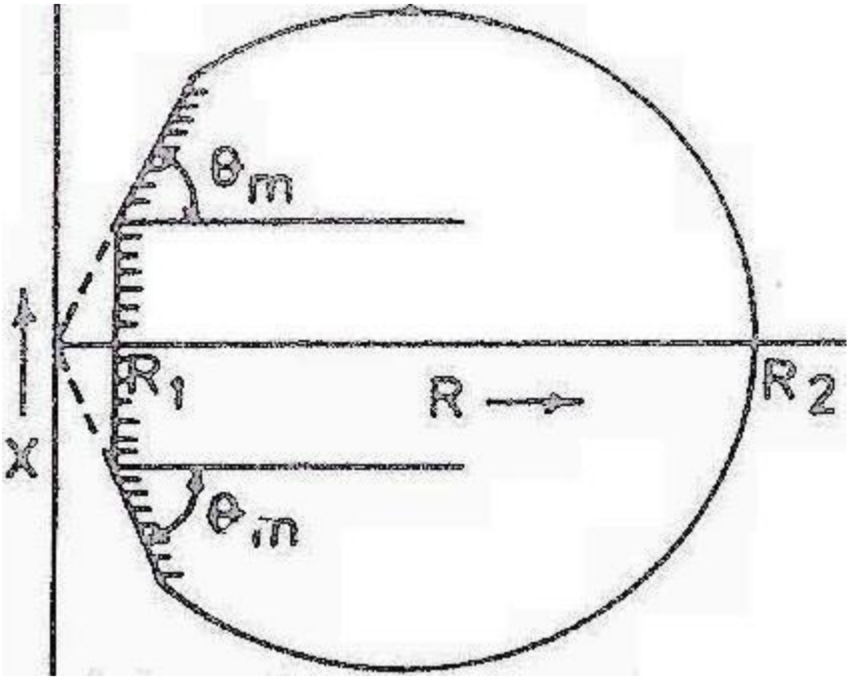
The basic objective in designing the filter is to select the filter admittance Y_{Fh} in order to minimize V_h or satisfy the constraints on V_h . The problem of designing a filter is complicated by the uncertainty about the network admittance (Y_{Sh}). There are two possible representations of system impedance in the complex plane where

(a) impedance angle is limited

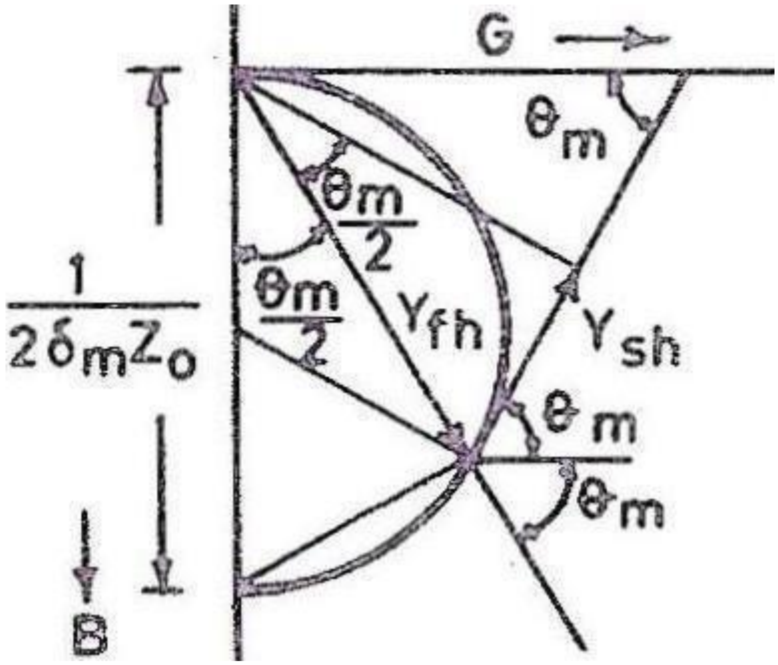


This allows a simplified computation of the optimum value of Q. In computing the optimum value of Q, we need to minimize the maximum value of V_h . The optimum value of Q corresponds to the lowest value of the upper limit on V_h .

(b) the impedance is limited both in angle and impedance



The value of Y_h is reduced if the detuning parameter δ is maximum = δ_m . For a specified value δ_m and X_0 , the locus of the filter impedance as Q is varied is a semicircle in the 4th quadrant of the G-B plane as shown below.



The optimum value of Q can be obtained from game-theoretic analysis. If one selects Y_{Fh} arbitrarily (the tip of Y_{Fh} lying along the semicircle), the network can select Y_{Sh} such that the vector Y_h is perpendicular to the vector Y_{Sh} and ensure Y_h is minimum. To maximize the minimum magnitude of Y_h , it is necessary to have Y_{Sh} tangential to the circle. Thus, we select Y_{Fh} to maximize Y_h when the network tries to minimize it.

Design of High Pass Filter

For harmonic frequencies of order equal to or higher than 17, a common second order high pass filter is provided. By defining the following parameters

$$h_0\omega_1 = 1/\sqrt{LC}\ ,\ Z_0 = \sqrt{L/C}\ ,\ \sigma = R/Z_0$$

The following values can be chosen

$$0.5 < \sigma < 2$$

$$h_0 \leq \sqrt{2}\, h_{min}$$

where h_{min} is the smallest value of h to be handled by the filter. The choice of h_0 given above implies that the filter impedance at h_{min} has decreased approximately to the value of R.

The filter impedance is given by

$$Z_f = \frac{Z_0\,[\sigma + j(h_0/h).(\sigma^2 - 1 - (\sigma h_0/h)^2)]}{1 + (\sigma h_0/h)^2}$$

The reactive power supplied by the filter is

$$Q_f = (\,h_0 / (\,h_0^2 - 1\,)\,)\,.\,(\,V_1^2 / Z_0\,)$$

The filtering is improved if Q_f is increased and higher value of h_0 can be chosen. Hence, it is advantageous in designing high pass filter to exclude six pulse operation.

Protection of Filters

The filter is exposed to overvoltage during switching in and the magnitude of this overvoltage is a function of the short-circuit ratio (higher with low values of SCR) and the saturation characteristics of the converter transformer.

During switching in, the filter current (at filter frequencies) can have magnitudes ranging from 20 to 100 times the harmonic current in normal (steady-state) operation. The lower values for tuned filters and higher values are applicable to high pass filters. These overcurrents are taken into consideration in the mechanical design of reactor coils.

When filters are disconnected, their capacitors remain charged to the voltage at the instant of switching. The residual direct voltages can also occur on bus bars. To avoid, the capacitors may be discharged by short-circuiting devices or through converter transformers or by voltage transformers loaded with resistors.

If the network frequency deviates from the nominal value, higher currents and losses will result in AC filters. If they exceed the limits,

LECTURE NOTES

ON

FLEXIBLE AC TRANSMISSION SYSTEMS

FACTS CONTROLLERS

INTRODUCTION

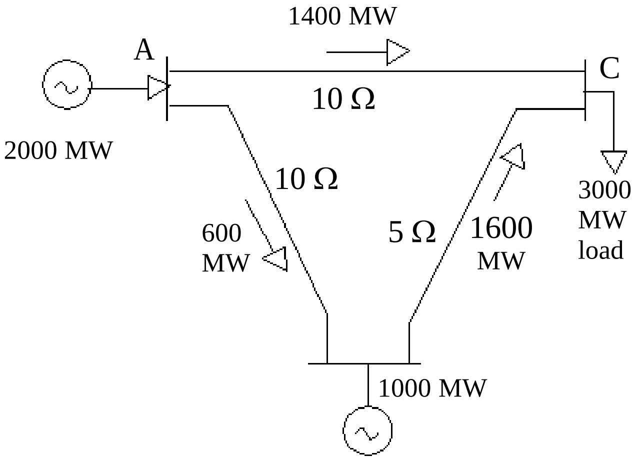
The electric power supply systems of whole world are interconnected, involving connections inside the utilities, own territories with external to inter-utility, internationals to inter regional and then international connections. This is done for economic reasons, to reduce the cost of electricity and 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.

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)

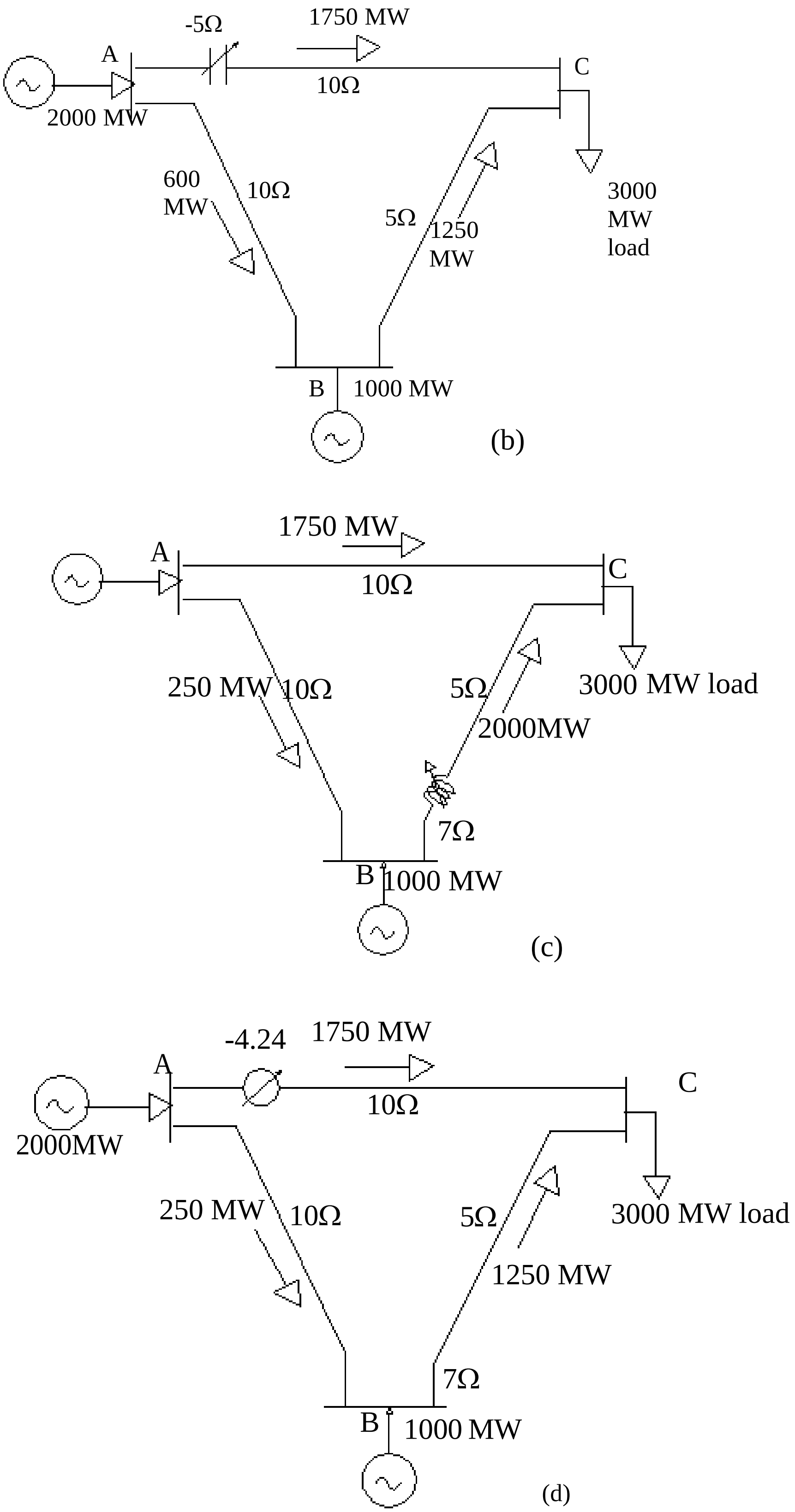


Fig 2.1 Power Flow in Meshed Paths

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 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.

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

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 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.

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.

Limitations of Stability

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

- Transient Stability
- Dynamic Stability

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

IMPORTANCE OF CONTROLLABLE PARAMETERS

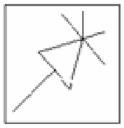
- Control of line impedance „X‟ with a Thyristor controlled series capacitor can provide a powerful means of current control.
- When the angle is not large in some cases the control of „X‟ or the angle provides the control of active power.
- Control of angle with a phase angle regulator controls the 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 90^o, 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.

- 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.

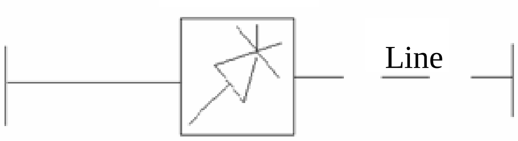
TYPES OF FACTS CONTROLLERS

In general FACTS controllers can be classified into four categories.

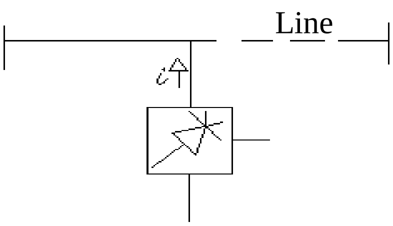
- Series controllers
- Shunt controllers
- Combined series-series controllers
- Combined series-shunt controllers



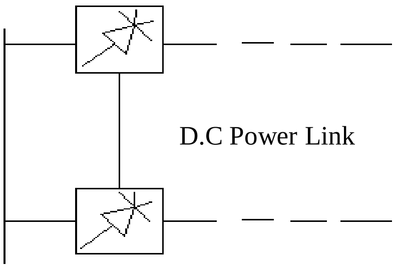
(a) General symbol of FACTS controller



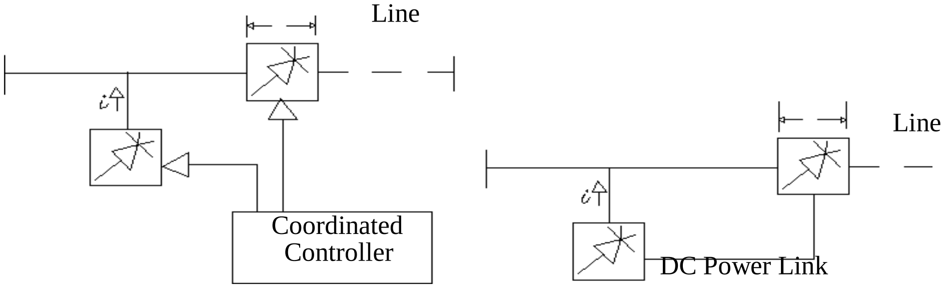
(b) Series controller



(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.

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.

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.

- 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

VOLTAGE SOURCE CONVERTERS

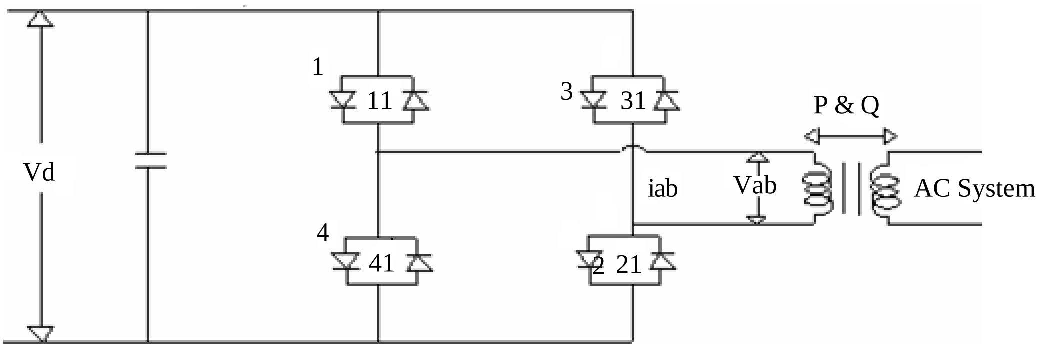
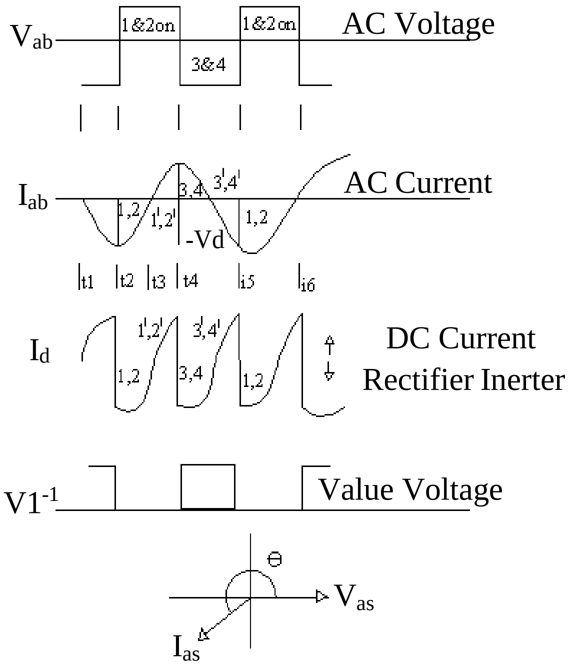


Fig 2.3 (a) Single Phase Full Wave Bridge Converters

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)

-

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).

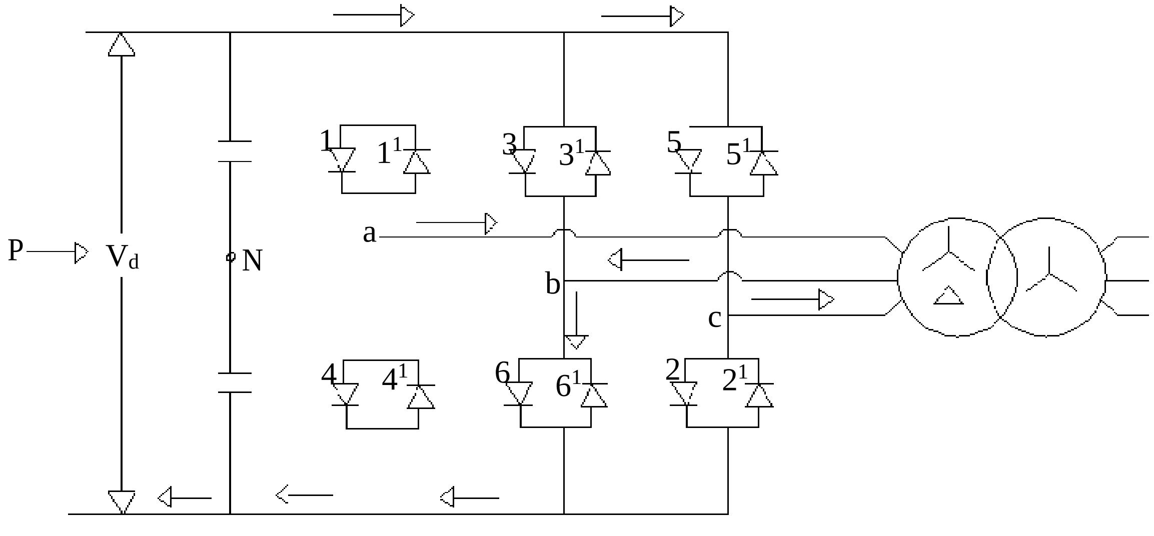
Fig 2.3(d) shows D.C. current wave form and Fig 2.3(e) shows Voltage across valve (1-1') Fig 2.3(f) shows phasor of power flow from A.C. to D.C. with lagging power factor. Four operating modes in one cycle of a single phase converter are shown in table

Table 2.1 Operational mode of Single Phase Full Wave Bridge Converter

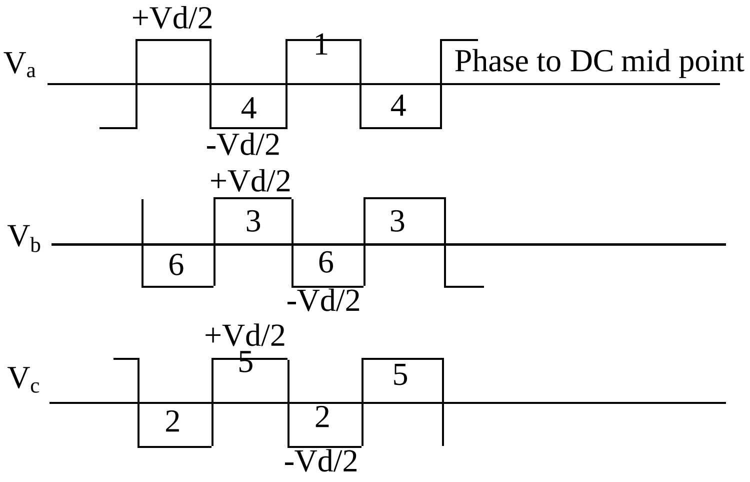
ORD	Devices	V_{ab}	I_{ab}	Conducting devices	conversion
1	1 & 2 ON 3 & 4 OFF	+ve	-ve	1 and 2	Inverter
2	1 & 2 ON 3 & 4 OFF	+ve	+ve	1' and 2'	Rectifier
3	1 & 2 OFF 3 & 4 ON	-ve	+ve	3 and 4	Inverter
4	1 & 2 OFF 3 & 4 ON	-ve	-ve	3' and 4'	Rectifier

-

-



(a) Three Phase Full Wave Bridge Converters

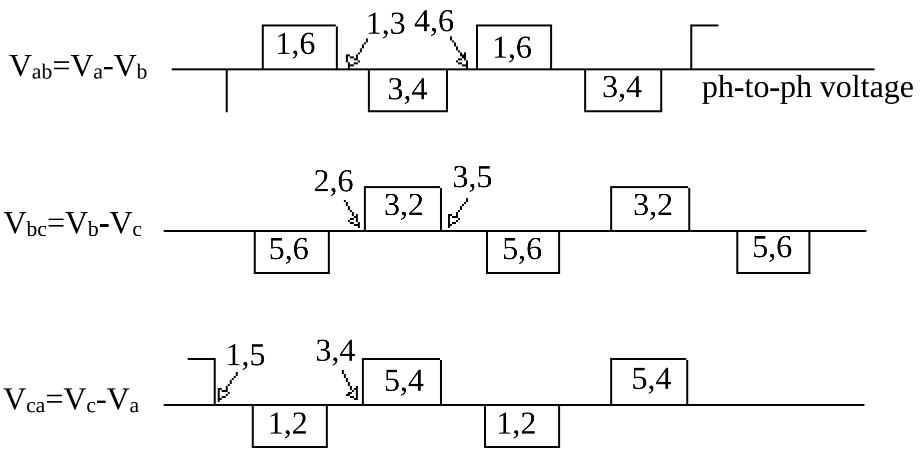


(b)

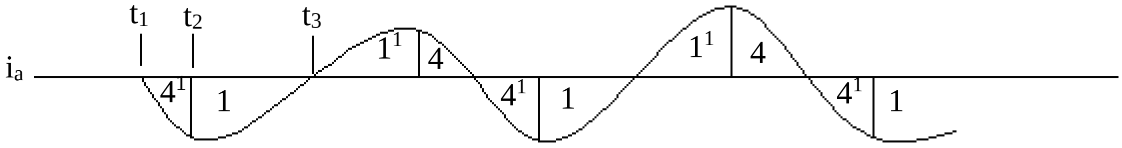
(b)

-

-


Vab=Va-Vb
1,6
1,3
4,6
1,6
3,4
3,4
ph-to-ph voltage
Vbc=Vb-Vc
2,6
3,2
3,5
3,2
5,6
5,6
5,6
Vca=Vc-Va
1,5
3,4
5,4
5,4
1,2
1,2

(c) (c)


t1
t2
t3
ia
4¹
1
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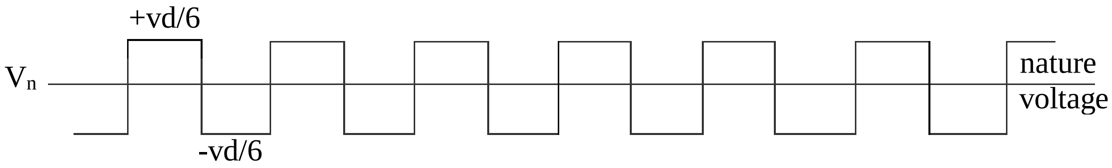
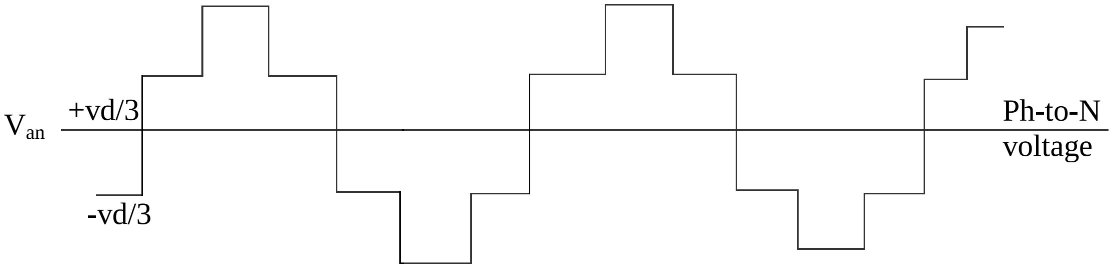
4¹
1

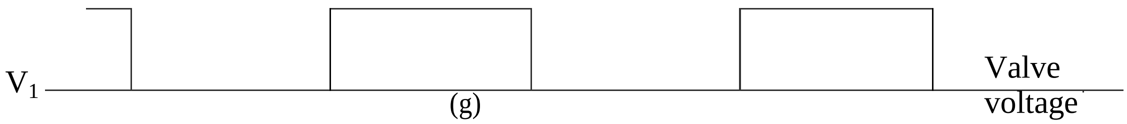
(d) (d)


+vd/6
Vn
-vd/6
nature
voltage

(e) (e)


Van
+vd/3
-vd/3
Ph-to-N
voltage

(f) (f)


V1
Valve
voltage

(g)

-

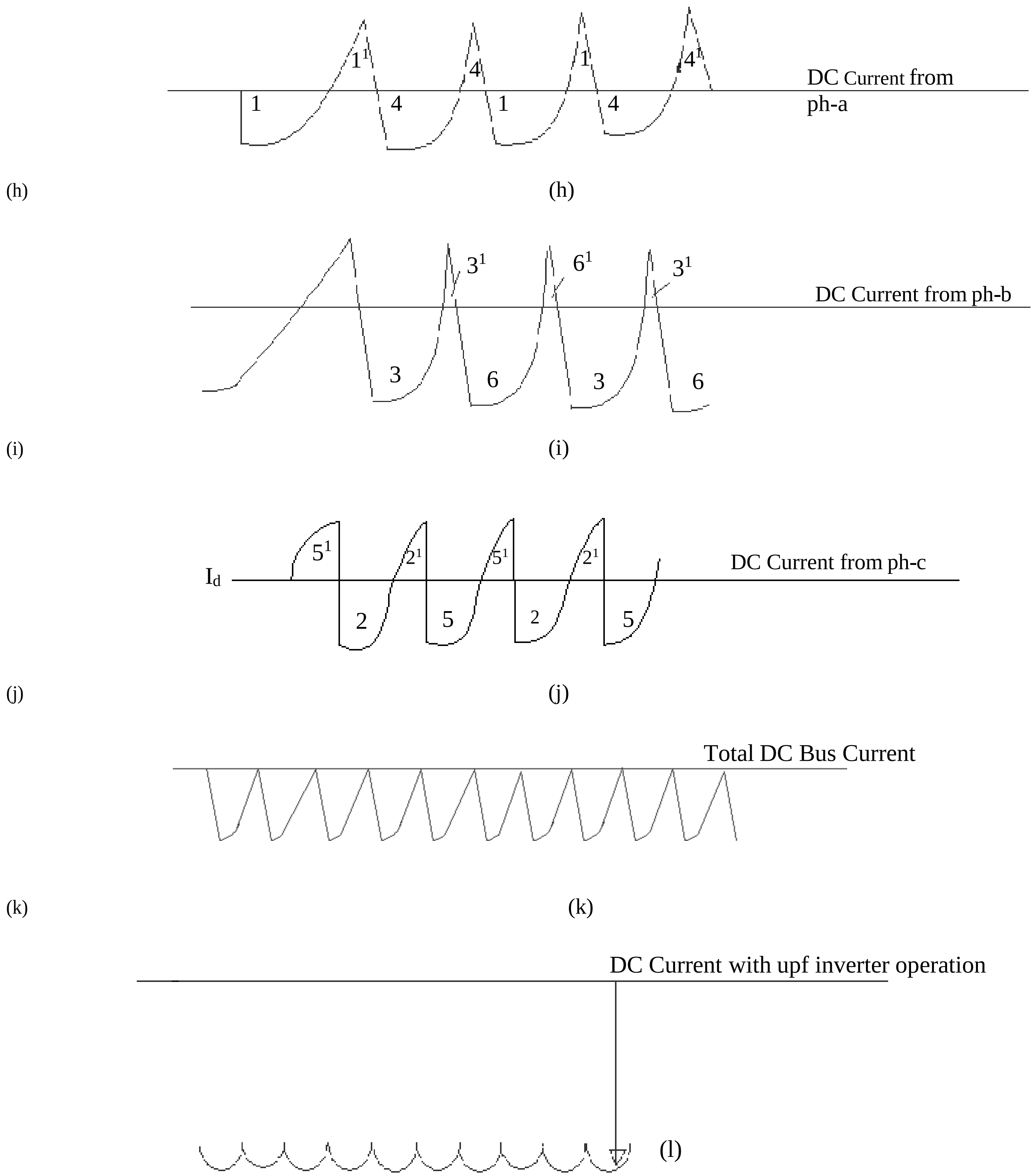


Fig 2.4 Three phase full wave bridge converter

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, 120^o apart. The three legs operate in a square wave mode; each valve alternately closes for 180^o 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 120^o apart with respect to each other to a 6-phase converter operation phase leg (3-6) switches 120^o after phase leg (1-4) and phase leg (5-2) switches 120^o 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 120^o 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.

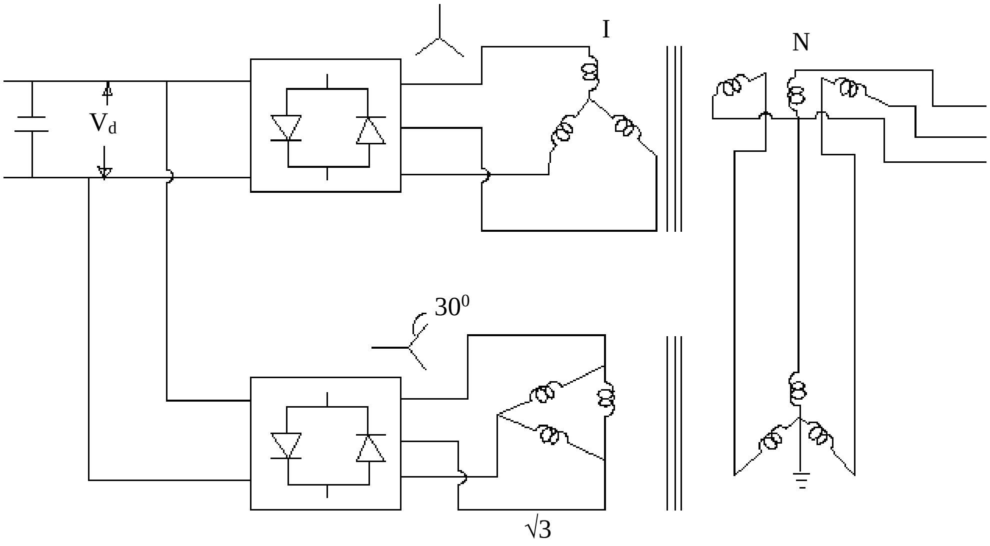
For example the waveform for V_{ab} shows voltage V_d when device „1‟ connects A.C. bus „a‟ to the D.C. + $V_{d/2}$, and device 6 connects A.C. bus „b‟ to the D.C. bus -$V_{d/2}$, giving a total voltage $V_{ab} = V_a$-$V_b = V_d$. It is seen 120^o later, when device „6‟ is turned OFF and device „3‟ is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

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]

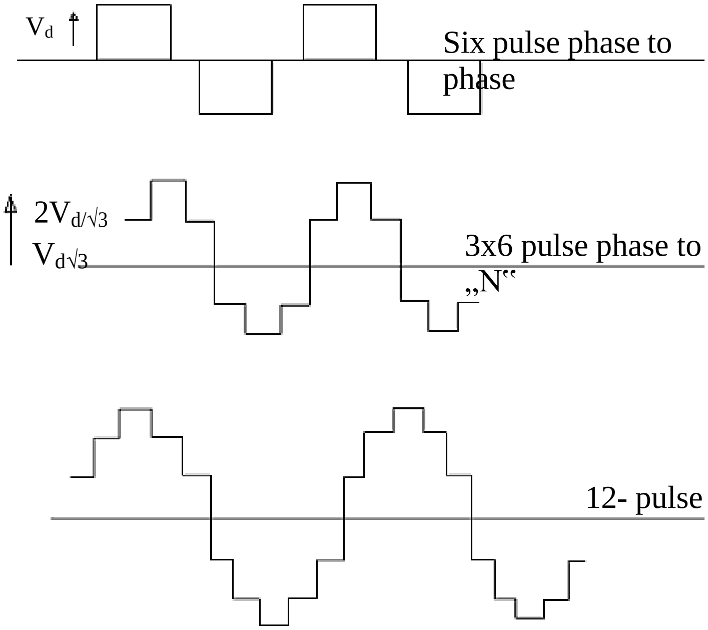
TRANSFORMER CONNECTION FOR 12-PULSE OPERATION

The harmonics content of the phase to phase voltage and phase to neutral voltage are 30° 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/√3 times the amplitude.

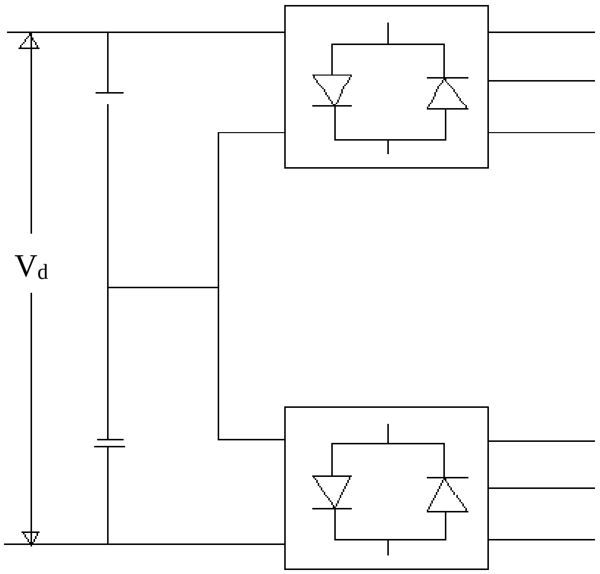
In Fig 2.5 (a) if the phase to phase voltages of a second converter were connected to a delta-connected secondary of a second transformer, with √3 times the turns compared to the star connected secondary, and the pulse train of one converter was shifted by 30° with respect to the other “in order to bring „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. 11th , 13th , 23rd , 25th …. And with amplitudes of 1/11th, 1/13th, 1/23rd 1/25th. respectively, compared to the fundamental.



(a)



(b)



(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. 5th, 7th, 17th, 19th …. 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. 5th, 7th, 17th, 19th …. 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 5th, 7th, 17th, 19th…. 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.

TRANSFORMER CONNECTIONS FOR 24-PULSE AND 48-PULSE OPERATION

Two 12-pulse converters phase shifted by 15° 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. 23rd, 25th, 47th, 49th …. , with magnitudes of 1/23rd, 1/25th, 1/47th, 1/49th …. respectively, of the fundamental A.C. voltage. The question now is, how to arrange this phase shift. One approach is to provide 15° phase shift windings on the two transformers of one of the two 12-pulse converters. Another approach is to provide phase shift windings for (+7.5°) phase shift on the two transformers of one 12-pulse converter and (-7.5°) 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.

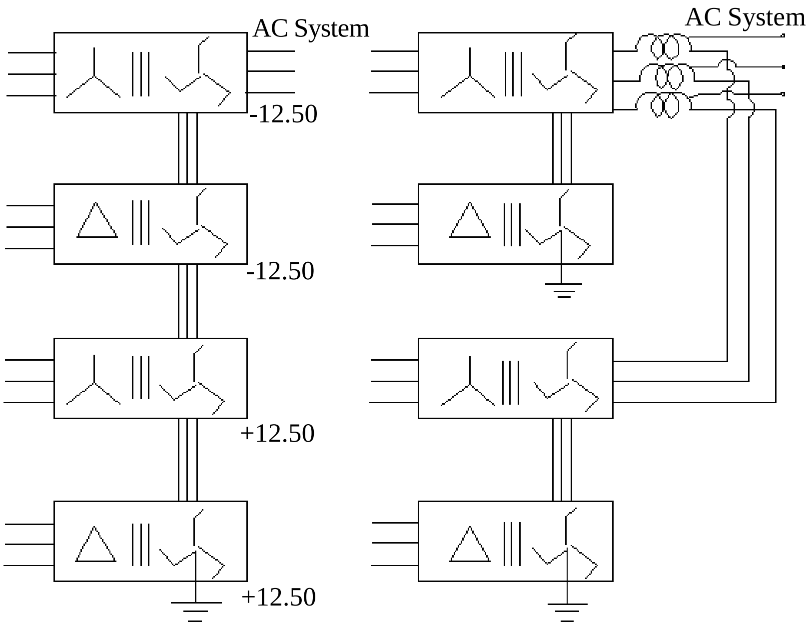

Fig 2.6 Transformer connections in series & parallel

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. 11th, 13th, and 23rd, 24th. 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.

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.

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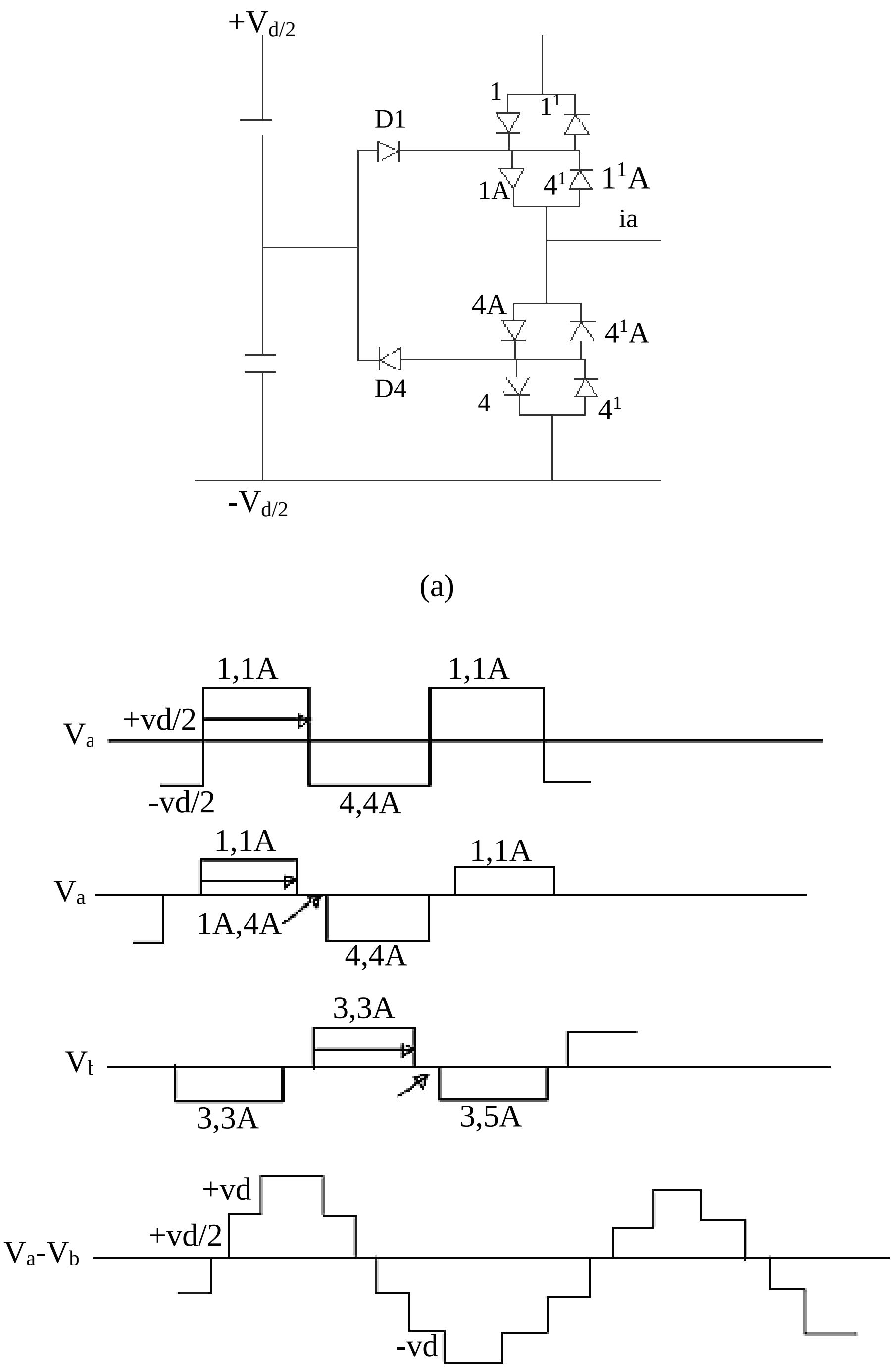

(a)

(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 180^o square wave obtained by the closing of devices 1 and 1_A to give ($+V_{d/2}$**)** for 180^o and the closing of valves 4 and 4_A for180^o to give ($-V_{d/2}$) for 180^o . 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 180^o 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 $\sigma = 180^o - 2\alpha^o$ square waves. This variable period σ per half cycle allows the

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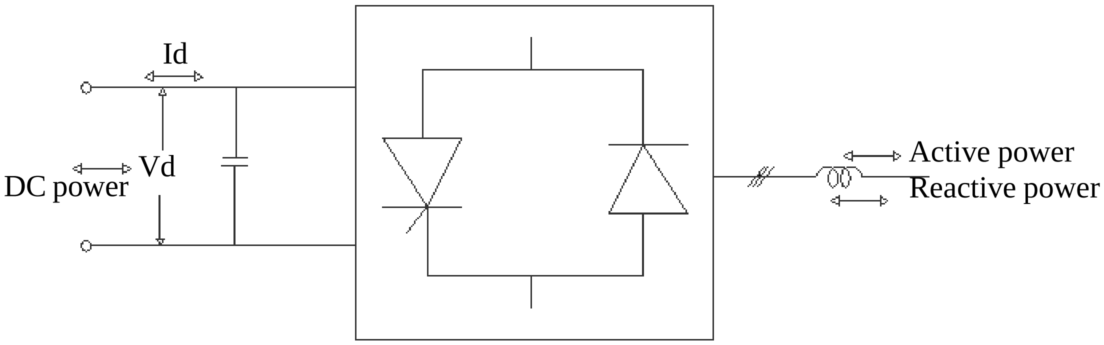
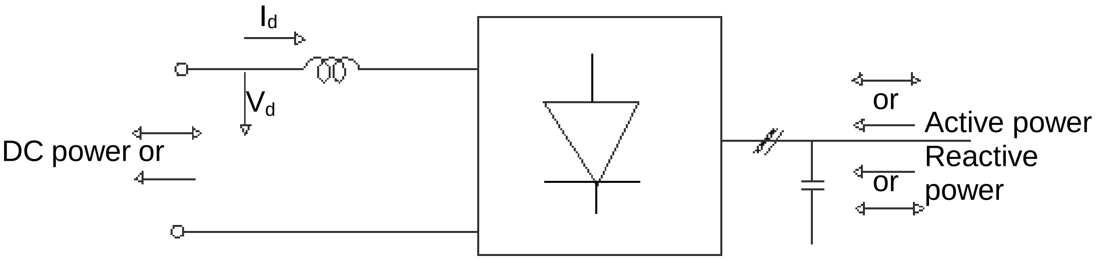
voltage V_a to be independently variable with a fast response. It is seen that devices 1_A and 4_A are turned ON for 180° during each cycle devices 1 and 4 are turned ON for $\sigma = 180^o - 2\alpha^o$ during each cycle, while diodes D_1 and D_4 conduct for $2\alpha^o = 180^o\sigma$ each cycle. The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

CURRENT SOURCE CONVERTERS

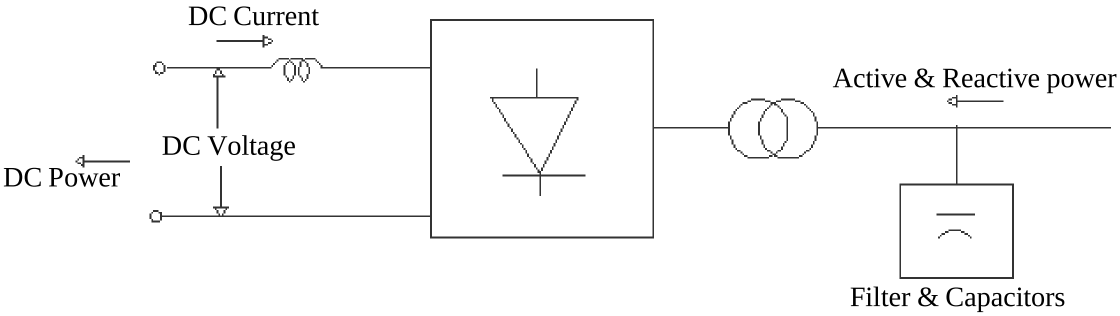
A current source converter is characterized by the fact that the D.C. current flow is always in one direction and the power flow reverses with the reversal of D.C. voltage shows in Fig 2.8 (b). Where as the voltage source converter in which the D.C. voltage always has one polarity and the power reversal 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).



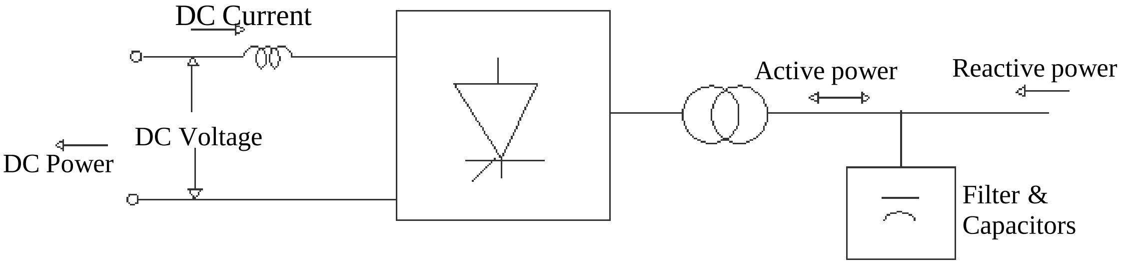
(a) Voltage source converter



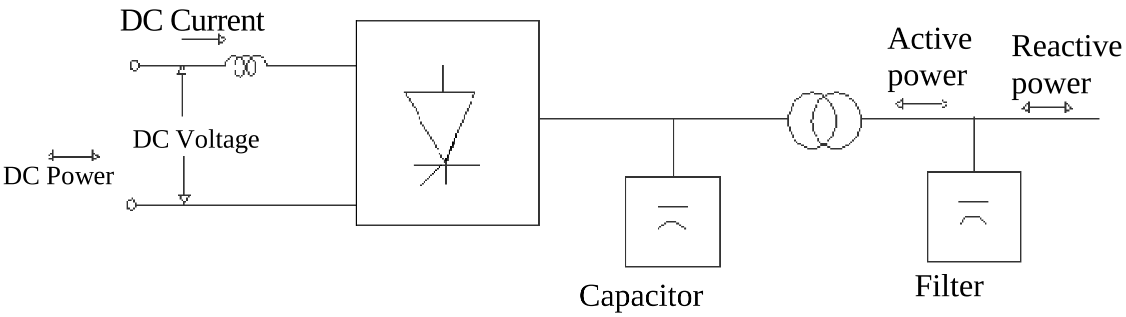
(b) Current source converter



(c) Diode Rectifier



(d) Thyristor line commutated converter



(e) Self commutated converters

Fig 2.8 Current source converters

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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.

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.

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.

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- 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 3^{rd} 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.

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- 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.

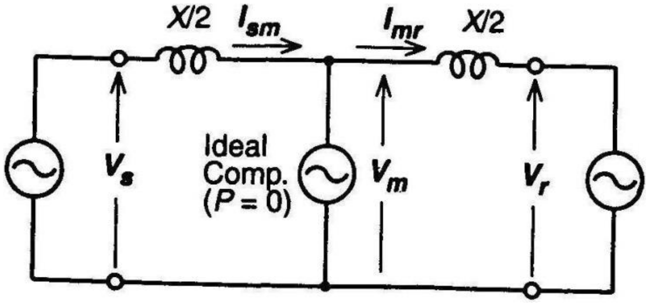
i. At the midpoint to segment the transmission line and
ii. At the end of the line

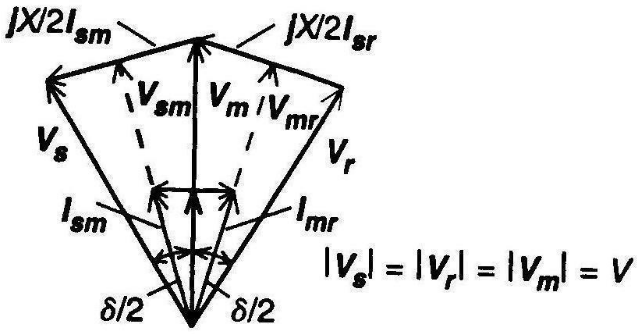
To prevent "voltage intangibility as well as for dynamic voltage control to increase transient stability and to damp out power oscillations".

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

i. The first segment, with an impedance of $\left(\frac{X}{2}\right)$ carries power from the sending end to mid-point.

ii. The second segment also with an impedance of $\left(\frac{X}{2}\right)$ carries power from midpoint to the receiving end

The relationship between voltages V_s, V_r and V_m line currents I_{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,

$$P=V_{sm}I_{sm} = V_{mr}I_{mr}$$

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

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

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

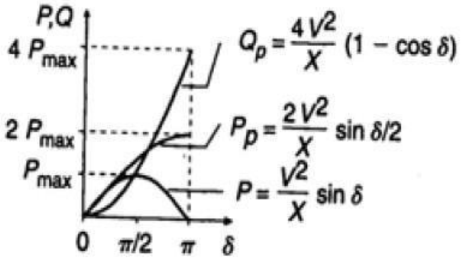
$$=\frac{2V^2}{X} sin\left(2.\frac{\delta}{4}\right)$$

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

Active power, $Q=VI\ sin\left(\frac{\delta}{2}\right)$

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

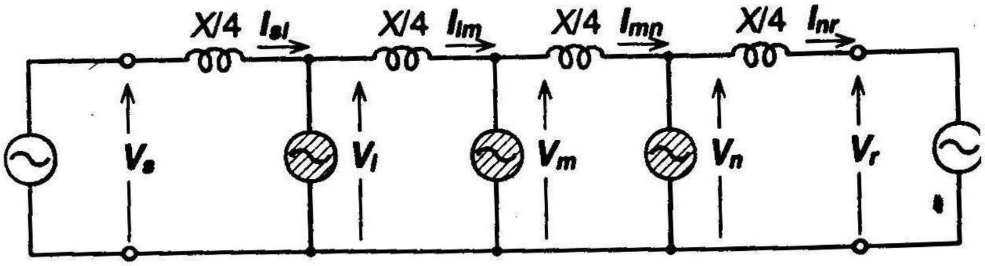
The relationship between real power (P), reactive power(Q) and 'δ' for ideal shunt compensation is shown in fig



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

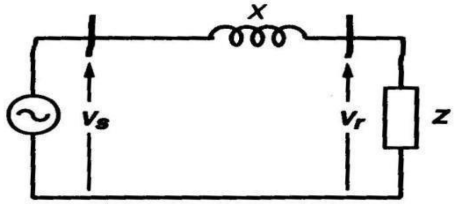
NOTE:

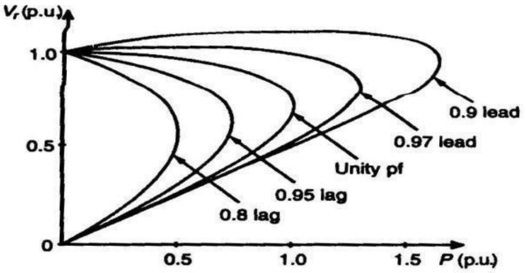
i. The midpoint of the transmission line is the best location for compensator because the voltage sage along the uncompensated transmission line is the longest at the midpoint
ii. The concept of transmission line segmentation can be expanded to use of multiple compensators, located at equal segments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



END OF LINE VOLTAGE TO SUPPORT TO PREVENT VOLTAGE INSTABILITY:

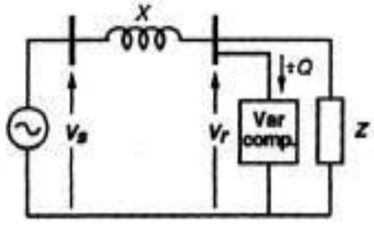
A simple radial system with feeder line reactance X and load impedance Z is shown.

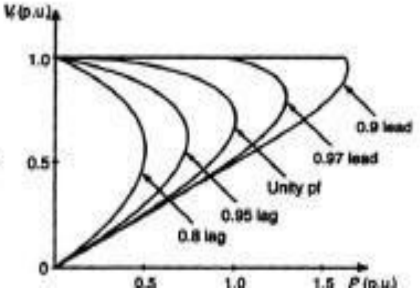




The plot shows variation of normalized voltage(V_r) ,(V_s) power at different power factors ranging from 0.8 lag to 0.9 lo9ad. It should be that noted that voltage stability limit decreases with inductive loads and increases with capacitive loads.

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





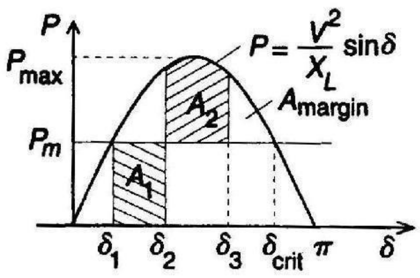
NOTE:

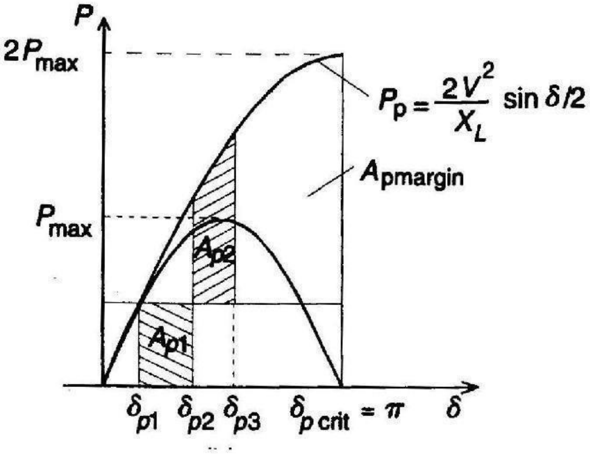
1. For a radial line , the end of the line, where the largest voltage variation is experienced, is the best location for the compensator.
2. Reactive shunt compensation is often used too regulate voltage support for the load when capacity of sending –end system becomes impaired.

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.

Variable Impedance Type Static Var Generators

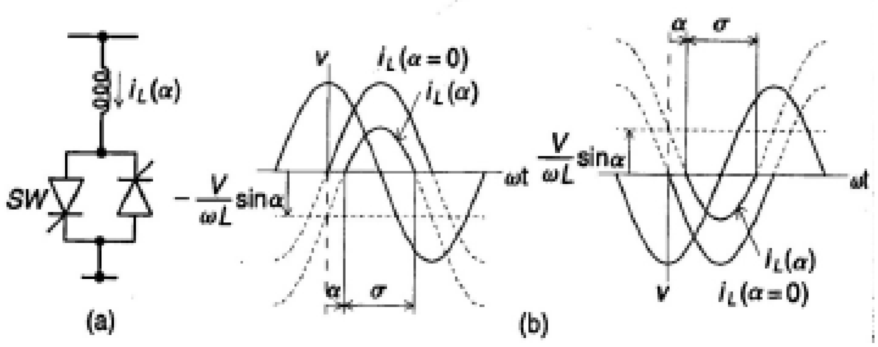
The performance and operating characteristics of the impedance type var generators are determined by their major thyristors-controlled constituents:

(i)Thyristor Controlled Reactor(TCR)

(ii)Thyristor Switched Capacitor(TSC)

Thyristor Controlled Reactor:

An elementary single-phase thyristors-controlled reactor is shown in fig.



It consists of a fixed (usually air-core) reactor of inductance L, and a bidirectional thyristors valve(or switch). Currently available large thyristors can block voltage up to 4000 to 9000 volts and conduct current up to 3000 to 6000 amperes. Thus, in practical many thyristors are connected in series to meet the required blocking voltage levels at a given power rating.

A thyristors valve can be brought into conduction by simultaneous application of a gate pulse to all thyristors of the same polarity. The valve will automatically block immediately after the a.c current crosses zero, unless the gate signal is reapplied.

The current in the reactor can be controlled from maximum(thyristor valve closed) to zero(thyristor valve open) by the method of firing delay angle control. That is, the closure of the thyristors valve is delayed w.r.t. the peak of the applied voltage in each half cycle, and thus the duration of the current conduction intervals is controlled.

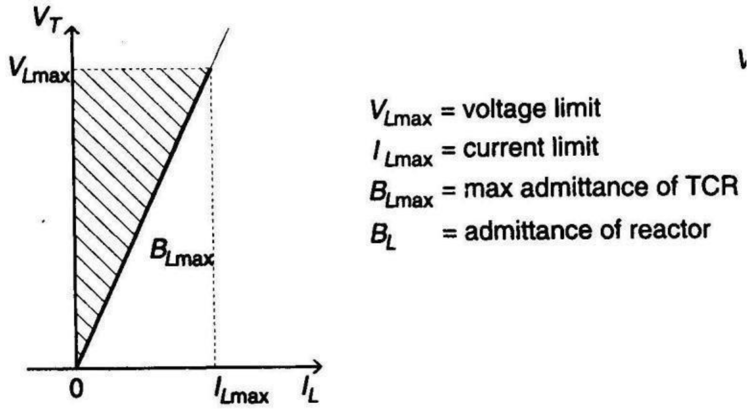
The method of current control is illustrated separately for the positive and negative current half cycles in fig.(b). where applied voltage υ and the reactor current $i_L(\alpha)$ at zero delay angle and at arbitrary α delay angle are shown.

- When α=0, the valve closes at the crest of the applied voltage and evidently the resulting current in the reactor will be the same as that obtained in steady state with a permanently closed switch.
- When the gating of the valve is delayed by an angle $\alpha(0\leq \alpha\leq 90)$ with respect to the crest of the voltage, The current in the reactor can be expressed with $\upsilon(t)= V \cos \omega t$ as follows:

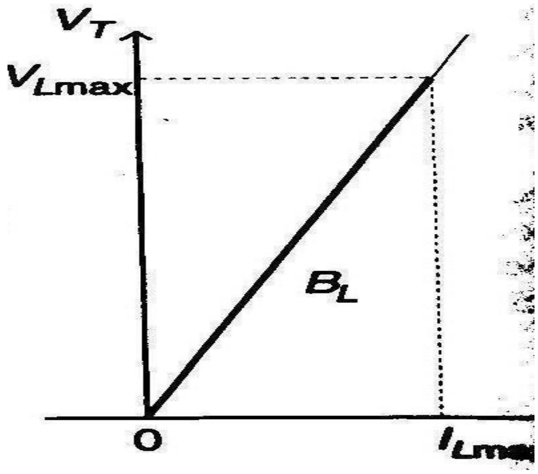
$$i_L(t) = \frac{1}{L}\int_{\alpha}^{wt} v(t)dt = \frac{V}{\omega L}(\sin \omega t - \sin \alpha)$$

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.



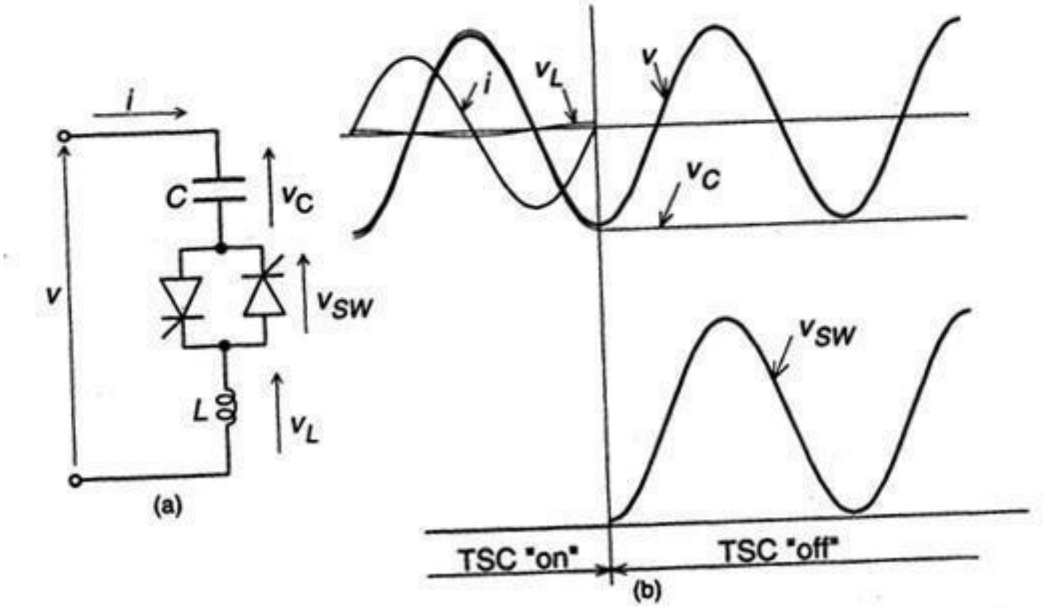
Note: If Thyristor Controlled Reactor(TCR) switching is restricted to a fixed delay angle, usually α=0, then it becomes a thyristors – switched reactor (TSR). The TSR provides a fixed inductive admittance. Thus, when connected to the a.c. system, the reactive current in it will be proportional to the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

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

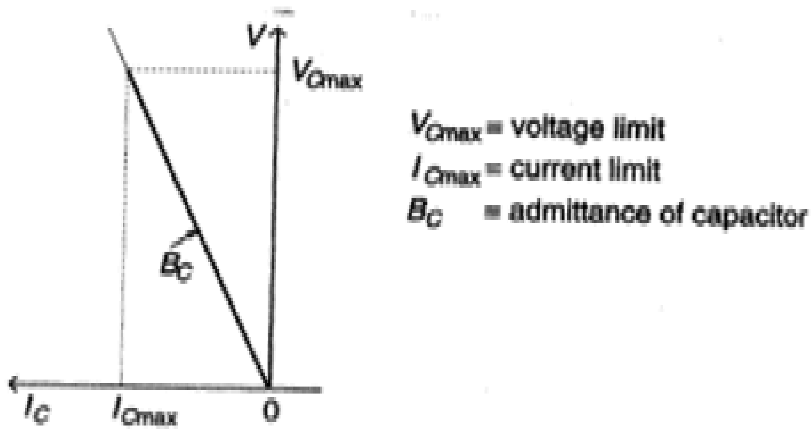
$$\text{where}\ \ n = \frac{1}{\sqrt{\omega^2 LC}} = \sqrt{\frac{X_c}{X_L}}$$

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

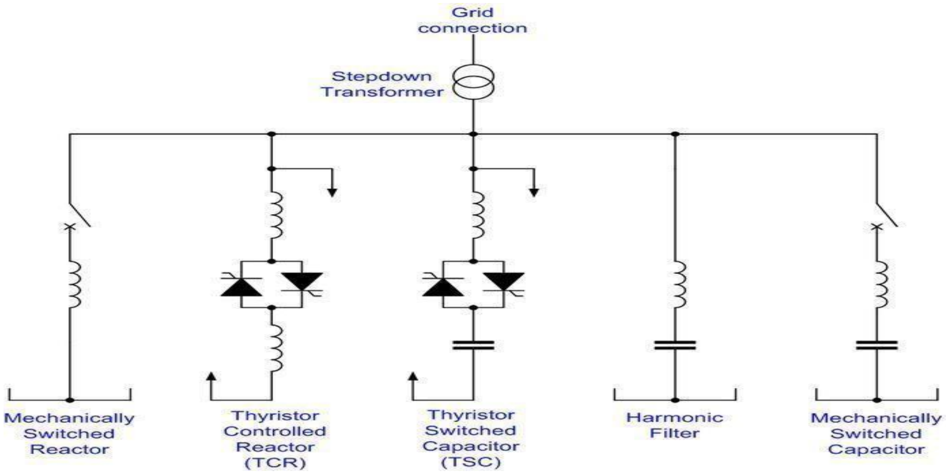
Direct voltage support to maintain sufficient line voltage for facilitating increased power flow under heavy loads and for preventing voltage instability.

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.

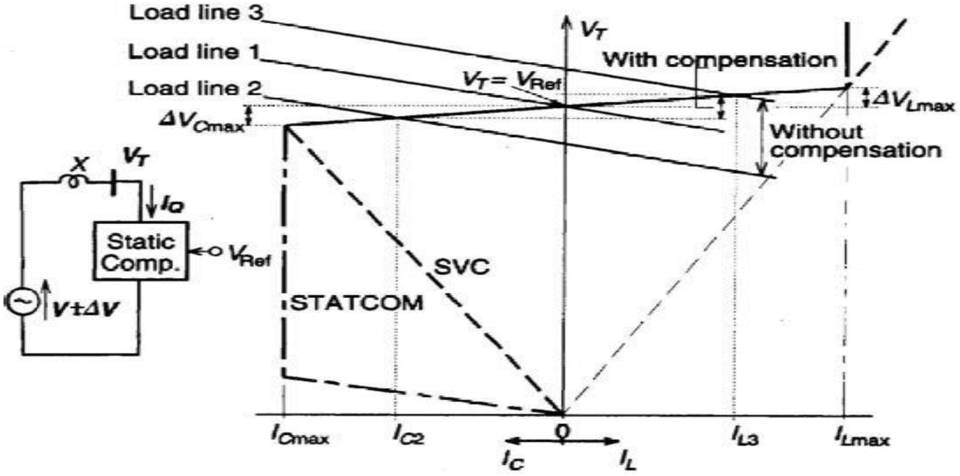
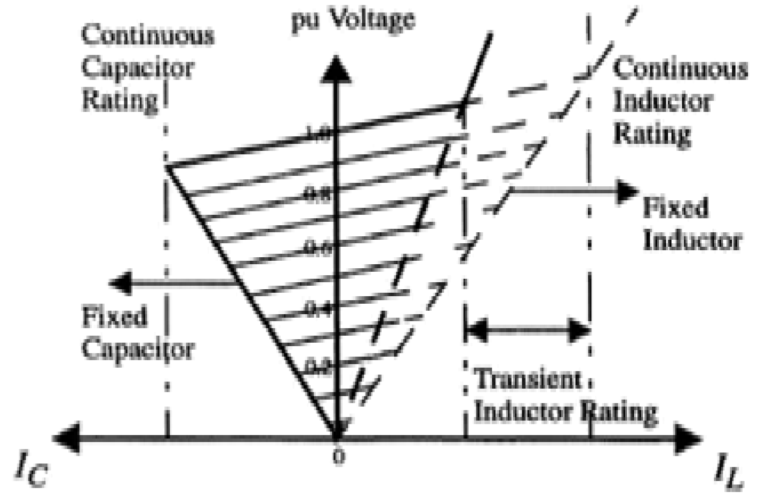


Figure 5.45 *V-I* characteristic of the SVC and the STATCOM.



(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.

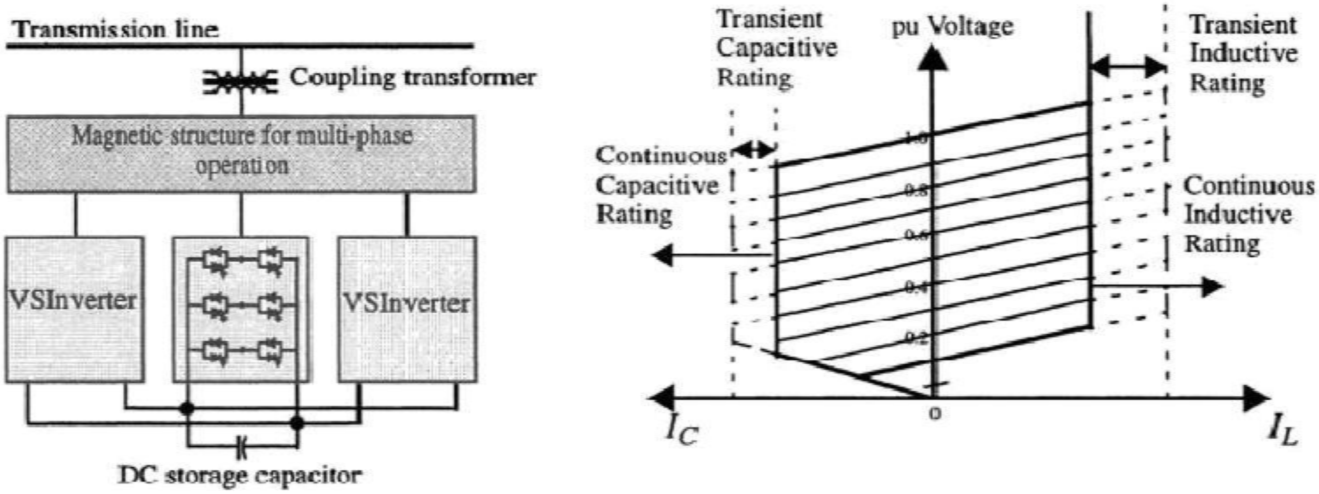
In industrial applications, SVCs are typically placed near high and rapidly varying loads, such as arc furnaces, where they can smooth flicker voltage.

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.



(a) (b)

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

INTRODUCTION

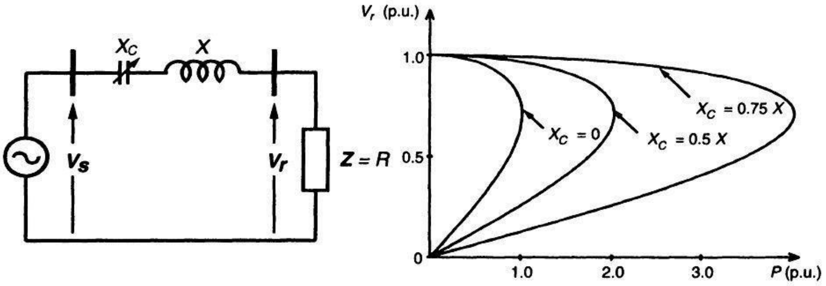
Series compensation is a means of controlling the power transmitted across transmission lines by altering or changing the characteristic impedance of the line. The power flow problem may be related to the length of the transmission line. The transmission line may be compensated by a fixed capacitor or 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.

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).

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

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.

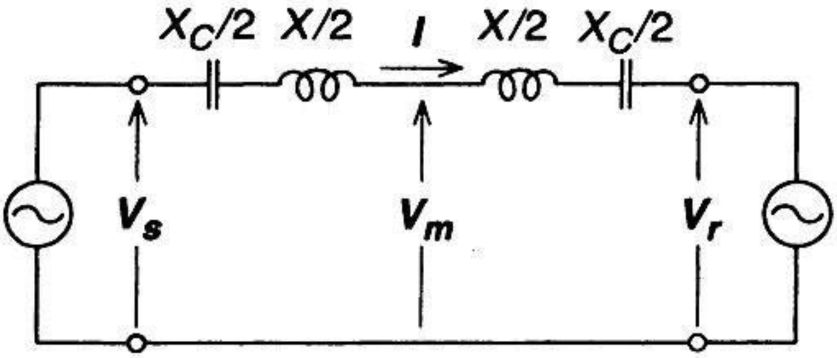


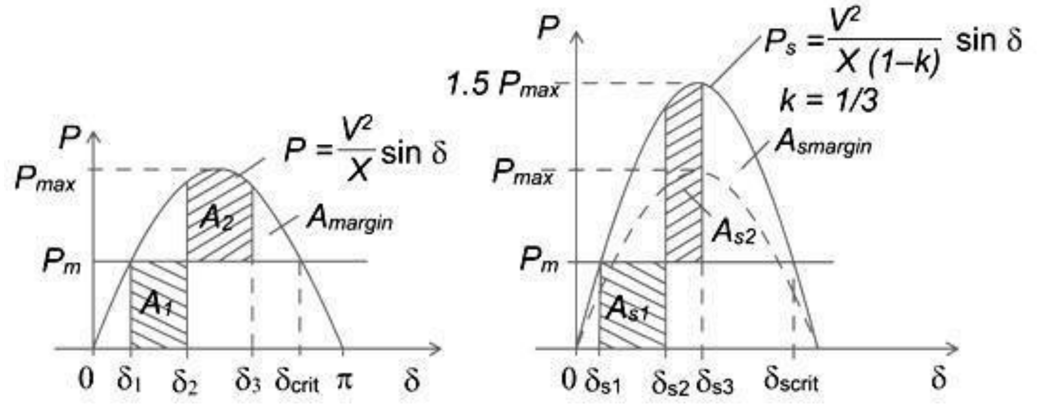
Figure 3.2 Two machine system with series capacitive compensation

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.

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.

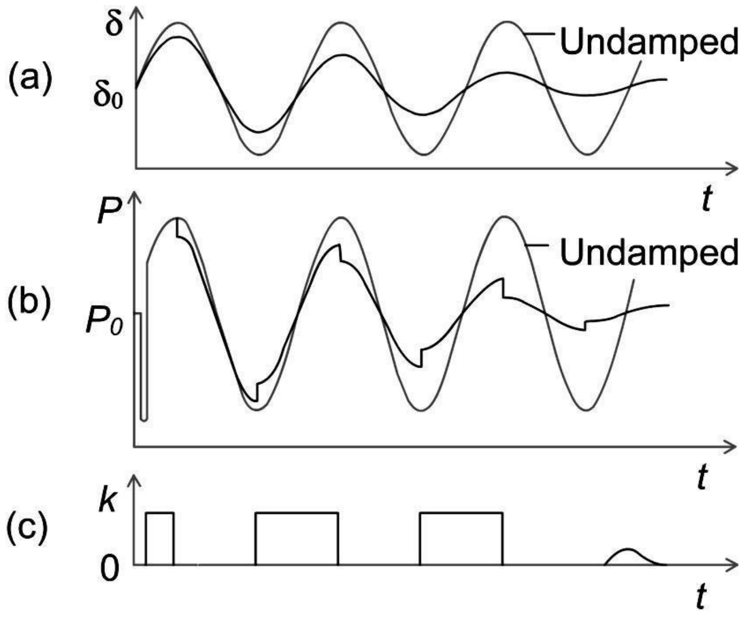


Figure 3.4 Waveforms illustrating power oscillation damping by controllable series compensation (a) generator angle (b) transmitted power and (c) degree of series compensation

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 $d6/dt < 0$.

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.

Types of Series Compensators

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

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.

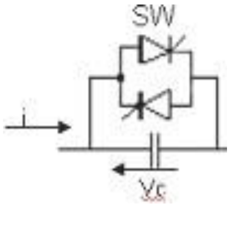


Figure 3.5 GTO Controlled Series Capacitor

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.

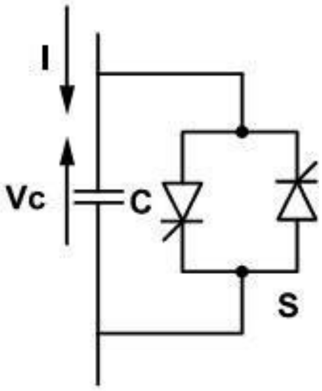


Figure 3.6 Thyristor Switched Series Capacitor

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.

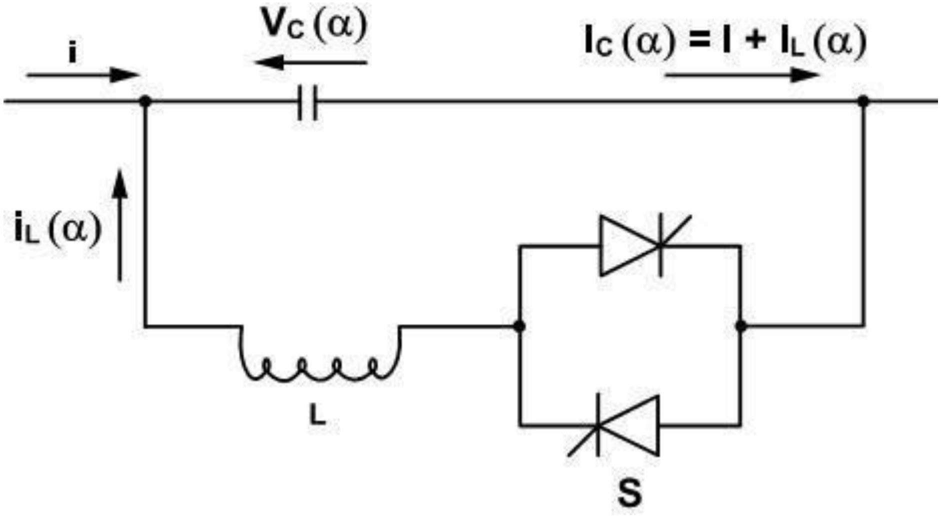


Figure 3.7 Thyristor Controlled Series Capacitor

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.

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°.

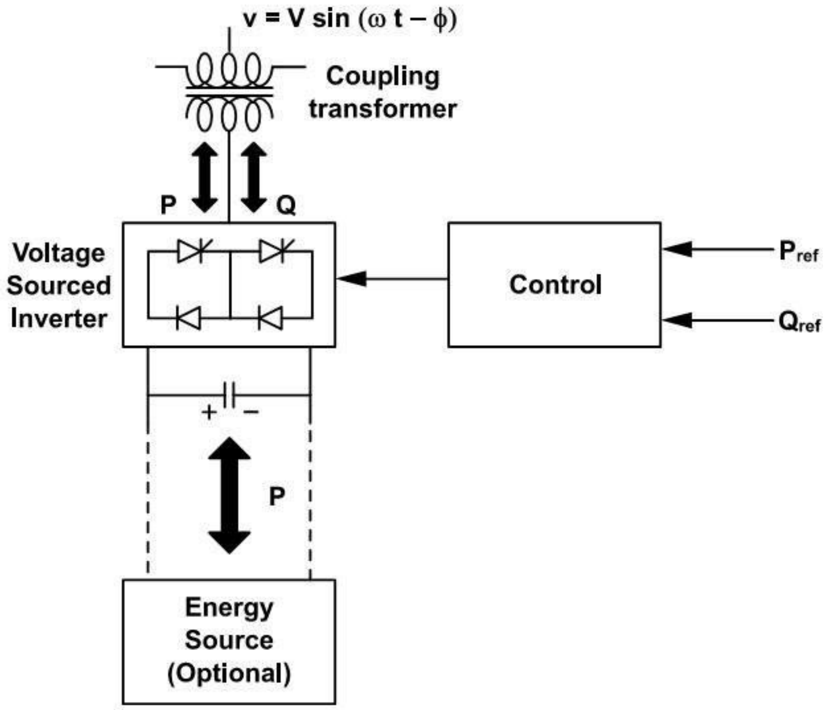


Figure 3.8 Schematic diagram of SSSC

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.

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.

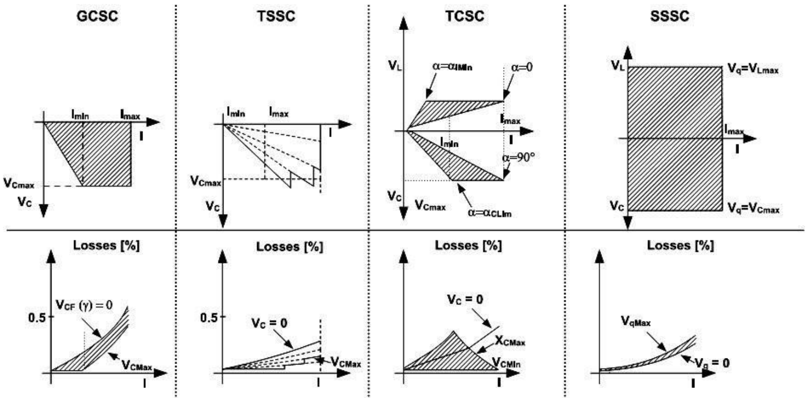


Figure 3.9 Comparison of Variable Type Series Compensators to Converter Type Series Compensator

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.

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.

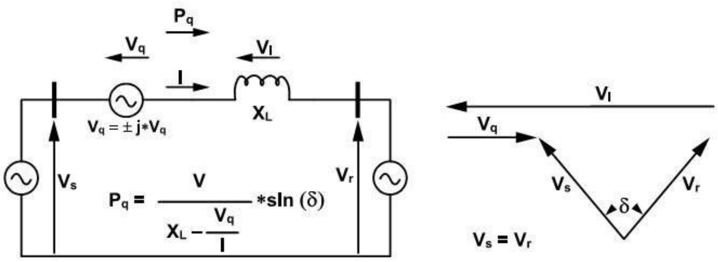


Figure 3.10 Simplified diagram of series compensation with the phasor diagram.

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°. During normal capacitive compensation, the output voltage lags the line current by 90°. 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°) 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.

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

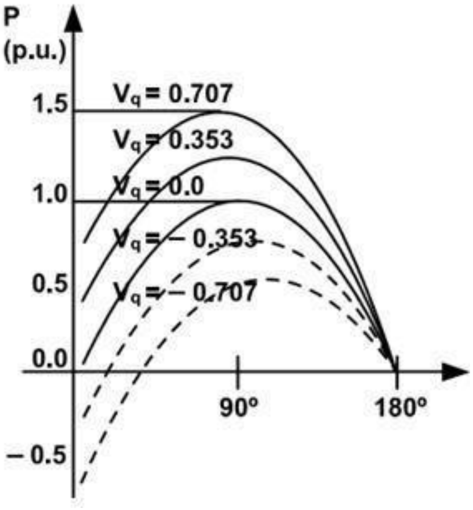


Figure 3.11 Transmitted power verses transmitted angle as a function of series compensation

CONVERTERS

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:

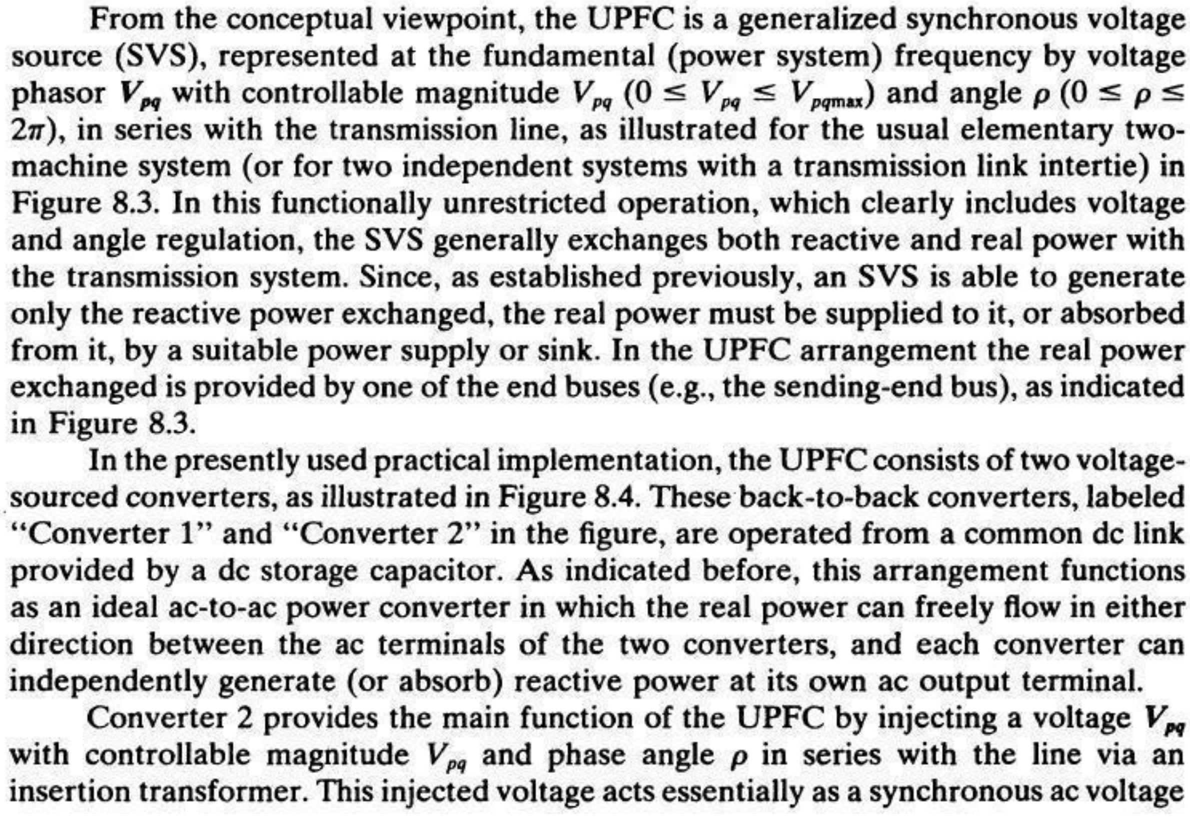
UNIT-V

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

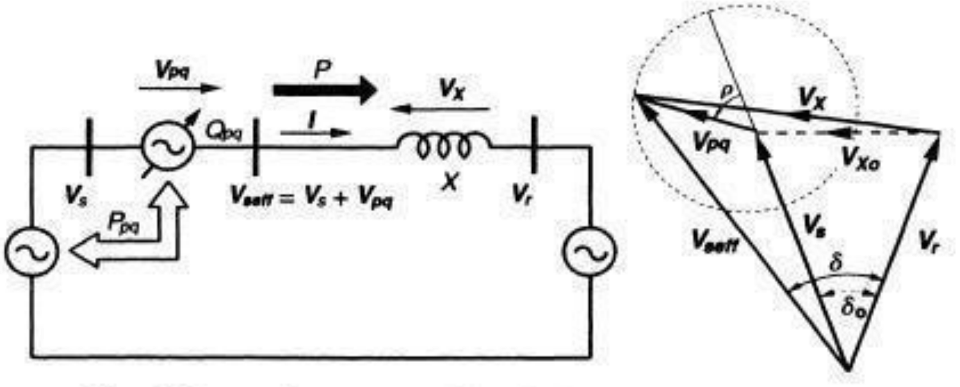


Figure 8.3 Conceptual representation of the UPFC in a two-machine power system.

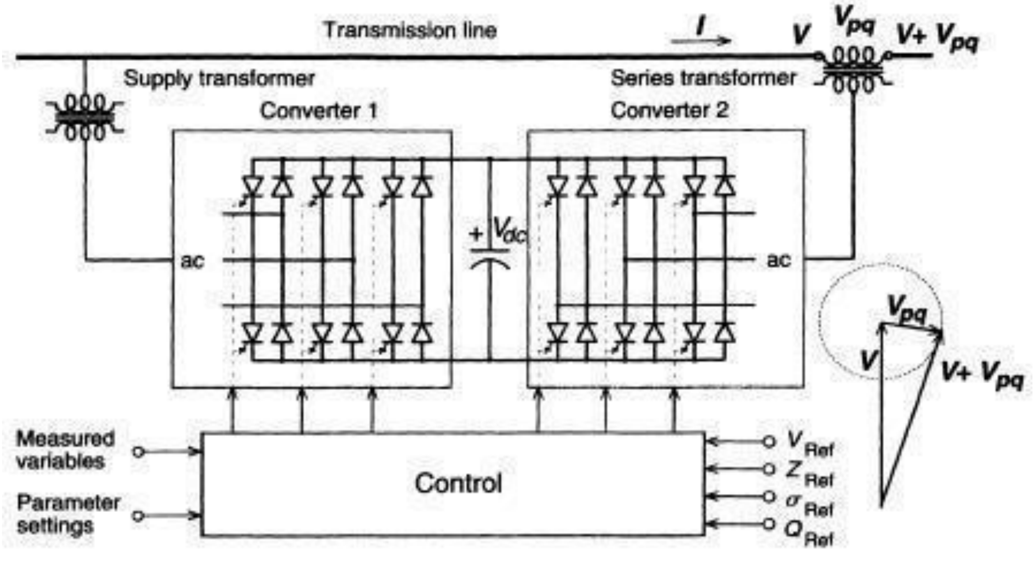


Figure 8.4 Implementation of the UPFC by two back-to-back voltage-sourced converters.

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 real and reactive power flow in the transmission line, refer to Figure 8.7(a). Let it first be assumed that the injected compensating voltage, $\boldsymbol{V}_{pq}$, is zero. Then the original elementary two-machine (or two-bus ac intertie) system with sending-end voltage $\boldsymbol{V}_s$, receiving-end voltage $\boldsymbol{V}_r$, transmission angle δ, and line impedance X is restored. With these, the normalized transmitted power, $P_0(\delta) = \{V^2/X\} \sin \delta = \sin \delta$, and the normalized reactive power, $Q_0(\delta) = Q_{0s}(\delta) = -Q_{0r}(\delta) = \{V^2/X\}\{1-\cos \delta\} = 1-\cos \delta$, supplied at the ends of the line, are shown plotted against angle (δ) in Figure 8.8(a). The relationship between real power $P_0(\delta)$ and reactive power $Q_{0r}(\delta)$ can readily be expressed with $V^2/X = 1$ in the following form:

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

or

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

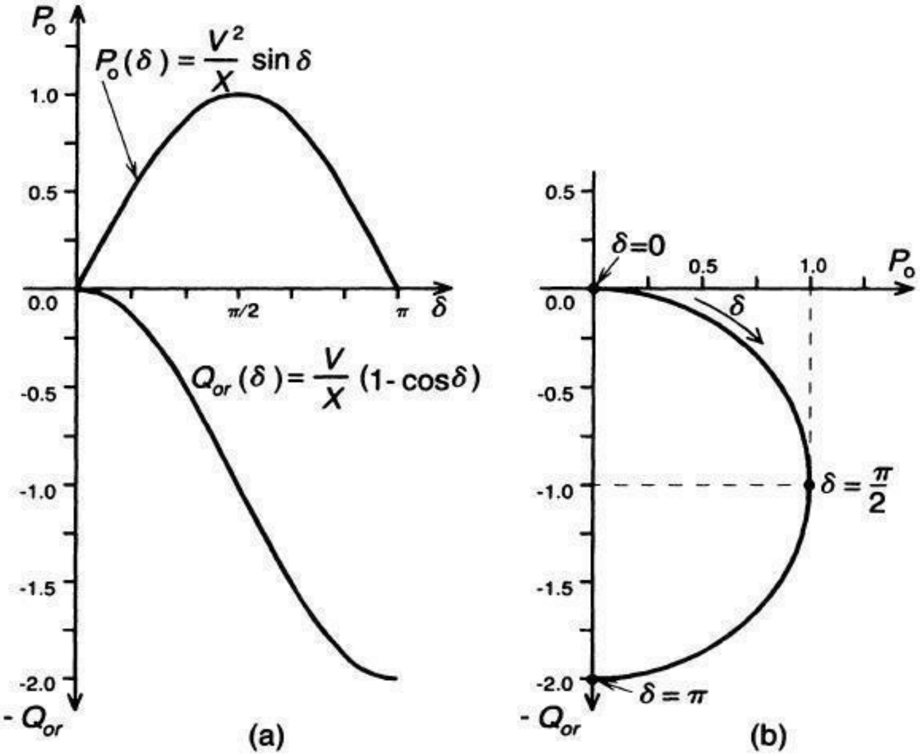


Figure 8.8 Transmittable real power P_0 and receiving-end reactive power demand Q_{or} vs. transmission angle δ of a two-machine system (a) and the corresponding Q_{or} vs. P_0 loci (b).

Equation (8.14) describes a circle with a radius of 1.0 around the center defined by coordinates $P = 0$ and $Q_r = -1$ in a $\{Q_r, P\}$ plane, as illustrated for positive values of P in Figure 8.8(*b*). Each point of this circle gives the corresponding P_0 and Q_{0r} values of the uncompensated system at a specific transmission angle δ. For example, at $\delta = 0$, $P_0 = 0$ and $Q_{0r} = 0$; at $\delta = 30°$, $P_0 = 0.5$ and $Q_{0r} = -0.134$; at $\delta = 90°$, $P_0 = 1.0$ and $Q_{0r} = -1.0$; etc.

Refer again to Figure 8.7(a) and assume now that $\boldsymbol{V_{pq}} \neq 0$. It follows from (8.3), or (8.7) and (8.8), and from Figure 8.7(b), that the real and reactive power change from their uncompensated values, $P_0(\delta)$ and $Q_{0r}(\delta)$, as functions of the magnitude V_{pq} and angle ρ of the injected voltage phasor $\boldsymbol{V_{pq}}$. Since angle ρ is an unrestricted variable $(0 \leq \rho \leq 2\pi)$, the boundary of the attainable control region for $P(\delta, \rho)$ and $Q_r(\delta, \rho)$ is obtained from a complete rotation of phasor $\boldsymbol{V_{pq}}$ with its maximum magnitude $V_{pq\max}$. It follows from the above equations that this control region is a circle with a center defined by coordinates $P_0(\delta)$ and $Q_{0r}(\delta)$ and a radius of $V_r V_{pq}/X$. With $V_s = V_r = V$, the boundary circle can be described by the following equation:

$$\{P(\delta, \rho) - P_0(\delta)\}^2 + \{Q_r(\delta, \rho) - Q_{0r}(\delta)\}^2 = \left\{\frac{VV_{pq\max}}{X}\right\}^2 \qquad (8.15)$$

The circular control regions defined by (8.15) are shown in Figures 8.9(a) through (d) for $V = 1.0$, $V_{pq\max} = 0.5$, and $X = 1.0$ (per unit or p.u. values) with their centers on the circular arc characterizing the uncompensated system (8.14) at transmission angles $\delta = 0°$, 30°, 60°, and 90°. In other words, the centers of the control regions are defined

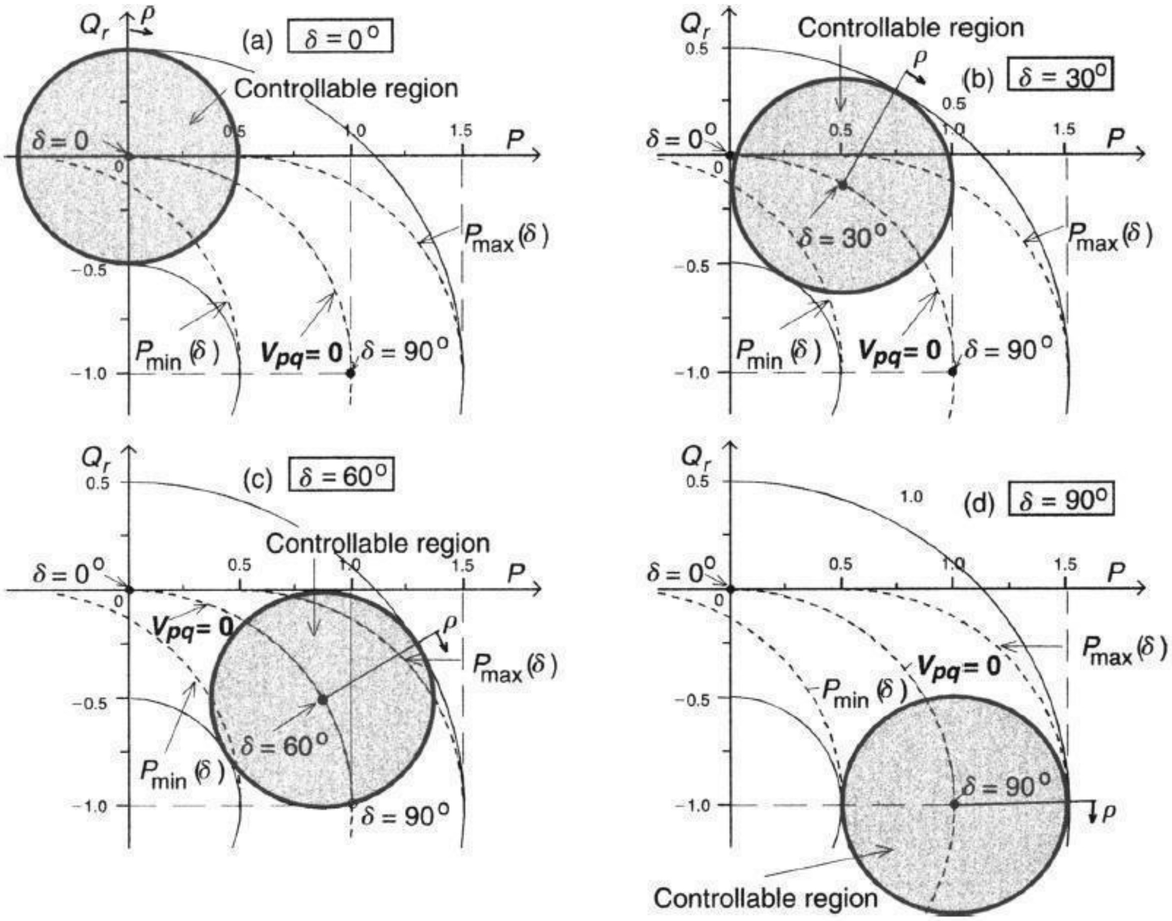


Figure 8.9 Control region of the attainable real power P and receiving-end reactive power demand Q_r with a UPFC-controlled transmission line at $\delta = 0°$ (a), $\delta = 30°$ (b), $\delta = 60°$ (c), and $\delta = 90°$ (d).

by the corresponding $P_0(\delta)$, $Q_{0r}(\delta)$ coordinates at angles $\delta = 0, 30°, 60°$, and $90°$ in the $\{Q_r, P\}$ plane.

Consider first Figure 8.9(a), which illustrates the case when the transmission angle is zero ($\delta = 0$). With $V_{pq} = 0$, P, Q_r, (and Q_s) are all zero, i.e., the system is at standstill at the origin of the Q_r, P coordinates. The circle around the origin of the $\{Q_r, P\}$ plane is the loci of the corresponding Q_r and P values, obtained as the voltage phasor $\boldsymbol{V_{pq}}$ is rotated a full revolution ($0 \leq \rho \leq 360°$) with its maximum magnitude $V_{pq\max}$. The area within this circle defines all P and Q_r values obtainable by controlling the magnitude V_{pq} and angle ρ of phasor $\boldsymbol{V_{pq}}$. In other words, the circle in the $\{Q_r, P\}$ plane defines all P and Q_r values attainable with the UPFC of a given rating. It can be observed, for example, 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 reactive 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) clearly 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.