A Course Module

on

HVDC & FACTS
(20A02604A)

Prepared by

Mr.B.ANIL KUMAR

Asst.Professor

Department of EEE

SREE RAMA ENGINEERING COLLEGE

Approved by AICTE, New Delhi – Affiliated to JNTUA, Ananthapuramu
Accredited by NAAC with 'A' Grade
An ISO 9001:2015 & ISO 14001:2015 certified Institution
Rami Reddy Nagar, Karakambadi road,Tirupati-517507

JAWAHARLAL NEHRU TECHNOLOGICAL UNIVERSITY ANANTAPUR

B.Tech (EEE)– III-II Sem	L	T	P	C
	3	0	0	3

(20A02604a) HVDC AND FACTS
(Professional Elective Course-II)

Course Objectives: To get the student exposed to:

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

Course Outcomes:

- Understand the necessity of HVDC systems as emerging transmission networks
- Understand the necessity of reactive power compensation devices
- Design equivalent circuits of various HVDC system configurations
- 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 60^0, 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.
3. R Mohan Mathur and Rajiv K Varma, Thyristor-Based FACTS Controllers for Electrical Transmission Systems, IEEE Press, Wiley-Interscience, New Jersey, 2002.

Online Learning Resources :https://nptel.ac.in/courses/108104013, https://nptel.ac.in/courses/108107114

HVDC & FACTS

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.

1.1 ELECTRICAL TRANSMISSION NETWORKS

The rapid growth in electrical energy use, combined with the demand for low cost energy, has gradually led to the development of generation sites remotely located from the load centers. In particular, the remote generating stations include hydroelectric stations, which exploit sites with higher heads and significant water flows; fossil fuel stations, located close to coal mines; geothermal stations and tidal-power plants, which are site bound; and, sometimes, nuclear power plants purposely built distant from urban centers. The generation of bulk power at remote locations necessitates the use of transmission lines to connect generation sites to load centers. Furthermore, to enhance system reliability, multiple lines that connect load centers to several sources, interlink neighboring utilities, andbuild the needed levels of redundancy have gradually led to the evolution of complex interconnected electrical transmission networks. These networks now exist on all continents.

An electrical power transmission network comprises mostly 3-phase alternating-current (ac) transmission lines operating at different transmission voltages (generally at 230 kV and higher). With increasing requirement of power-transmission capacity and/ or longer transmission distances, the transmission voltages continue to increase; indeed, increases in transmission voltages are linked closely to decreasing transmission losses. Transmission voltages have gradually increased to 765 kV in North America, with power transmission reaching 1500 MVA on a line limited largely by the risk that a power utility may be willing to accept because of losing a line.

An ac power transmission network comprises 3-phase overhead lines, which, although cheaper to build and maintain, require expensive right-of-ways. However, in densely populated areas where right-of-ways incur a premium price, underground cable transmission is used. Increasing pressures arising from ecological and aesthetic considerations, as well as improved reliability, favor underground transmission for future expansion.

In a complex interconnected ac transmission network, the source-to-a-load power flow finds multiple transmission paths. For a system comprising multiple sources and numerous loads, a load-flow study must be performed to determine the levels of active- and reactive-power flows on all lines. Its impedance and the voltages at its terminals determine the flow of active and reactive powers on a line. The result is that whereas interconnected ac transmission networks provide reliability of power supply, no control exists on line loading except to modify them by changing line impedances by adding series and/ or shunt-circuit elements (capacitors and reactors).

The long-distance separation of a generating station from a load center requiring long transmission lines of high capacity and, in some cases in which a transmission line must cross a body of water, the use of ac/ dc and dc/ ac converters at the terminals of an HVDC line, became a viable alternative many years ago. Consequently, beginning in 1954, HVDC transmission has grown steadily to the current ±600 kV lines with about 4000 A capacity. Also, direct current (dc) transmission networks, including multi terminal configurations, are already embedded in ac transmission networks. The most significant feature of an HVDC transmission network is its full controllability with respect to power transmission.

Until recently, active- and reactive-power control in ac transmission networks was exercised by carefully adjusting transmission line impedances, as well as regulating terminal voltages by generator excitation control and by transformer tap changers. At times, series and shunt impedances were employed to effectively change line impedances.

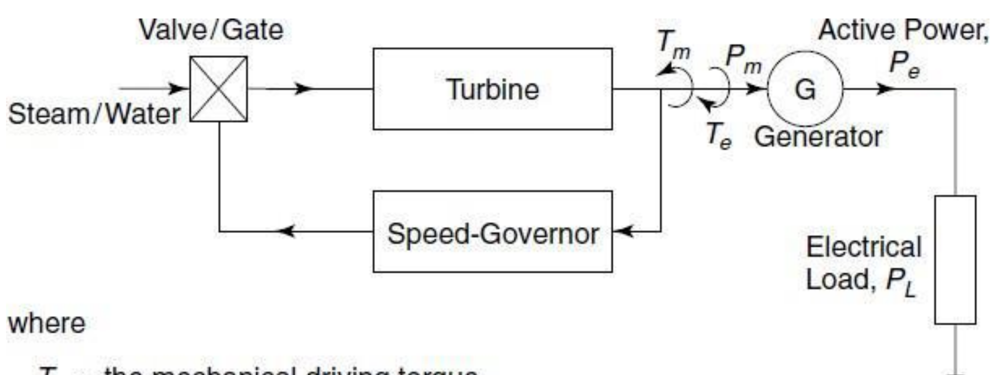
1.2 Conventional Control Mechanisms.

In the foregoing discussion, a lack of control on active- and reactive-power flow on a given line, embedded in an interconnected ac transmission network, was stated. Also, to maintain steady-state voltages and, in selected cases, to alter the power-transmission capacity of lines, traditional use of shunt and series impedances was hinted.

In a conventional ac power system, however, most of the controllability exists at generating stations. For example, generators called spinning reserves maintain an instantaneous balance between power demand and power supply. These generators, in fact, are purposely operated at reduced power. Also, to regulate the system frequency and for maintaining the system at the rated voltage, controls are exercised on selected generators.

1.3 Automatic Generation Control (AGC)

The megawatt (MW) output of a generator is regulated by controlling the driving torque, Tm, provided by a prime-mover turbine. In a conventional electromechanical system, it could be a steam or a hydraulic turbine. The needed change in the turbine-output torque is achieved by controlling the steam/water input into the turbine. Therefore, in situations where the output exceeds or falls below the input, a speed-governing system senses the deviation in the generator speed because of the load-generation mismatch, adjusts the mechanical driving torque to restore the power balance, and returns the operating speed to its rated value. The speed-governor output is invariably taken through several stages of mechanical amplification for controlling the inlet (steam/water) valve/ gate of the driving turbine. Figure 1.1 shows the basic speed-governing system of a generator supplying an isolated load. The operation of this basic feedback-control system is enhanced by adding further control inputs to help control the frequency of a large interconnection. In that role, the control system becomes an automatic generation control (AGC) with supplementary signals.



where

T_m = the mechanical driving torque
T_e = the mechanical load torque from the generator electrical output
P_m = the mechanical power input to the generator

Figure 1.1 A speed-governor system.

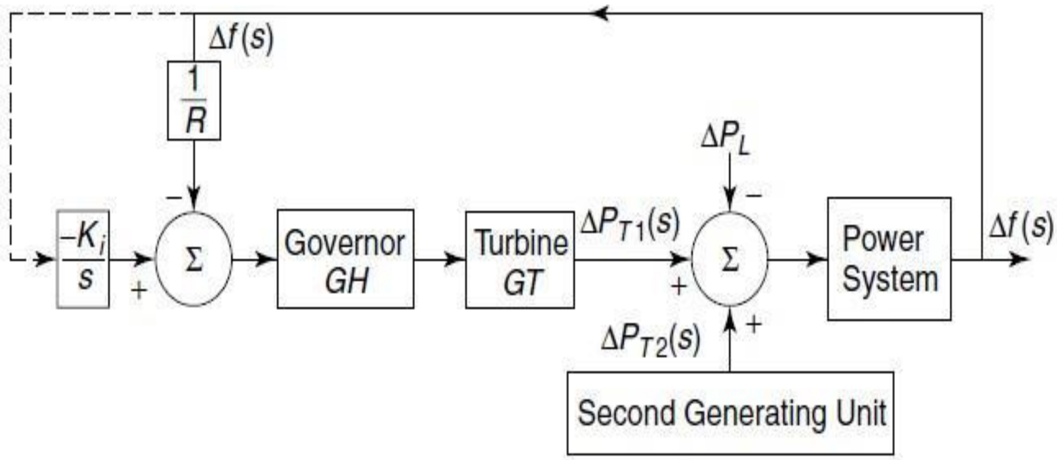


Figure 1.2 An AGC with supplementary control on the principal generating unit.

To avoid competing control actions, in a multi generator unit station each speed-governor system is provided with droop (*R*) characteristics through a proportional feedback loop (*R*, Hz/ MW). Figure 1.2 shows an AGC on the principal generating unit with supplementary control. In contrast, the second, third, and remaining generating units in a multiunit station operate with their basic AGCs. In a complex interconnected system, the supplementary control signal may be determined by a load- dispatch center

1.4 Excitation Control

The basic function of an exciter is to provide a dc source for field excitation of a synchronous generator. A control on exciter voltage results in controlling the field current, which, in turn, controls the generated voltage. When a synchronous generator is connected to a large system where the operating frequency and the terminal voltages are largely unaffected by a generator, its excitation control causes its reactive power output to change.

In older power plants, a dc generator, also called an exciter, was mounted on the main generator shaft. A control of the field excitation of the dc generator provided a controlled excitation source for the main generator. In contrast, modern stations employ either a brushless exciter (an inverted 3-phase alternator with a solid-state rectifier connecting the resulting dc source directly through the shaft to the field windings of the main generator) or a static exciter (the use of a station supply with static rectifiers).

An excitation-control system employs a voltage controller to controlthe excitation voltage. This operation is typically recognized as an automatic Voltage regulator (AVR). However, because an excitation control operates quickly, several stabilizing and protective signals are invariably added to the basic voltage regulator. A power-system stabilizer (PSS) is implemented by adding auxiliary damping signals derived from the shaft speed, or the terminal frequency, or the power—an effective and frequently used technique for enhancing small-signal stability of the connected system. Figure 1.3 shows the functionality of an excitation-control system.

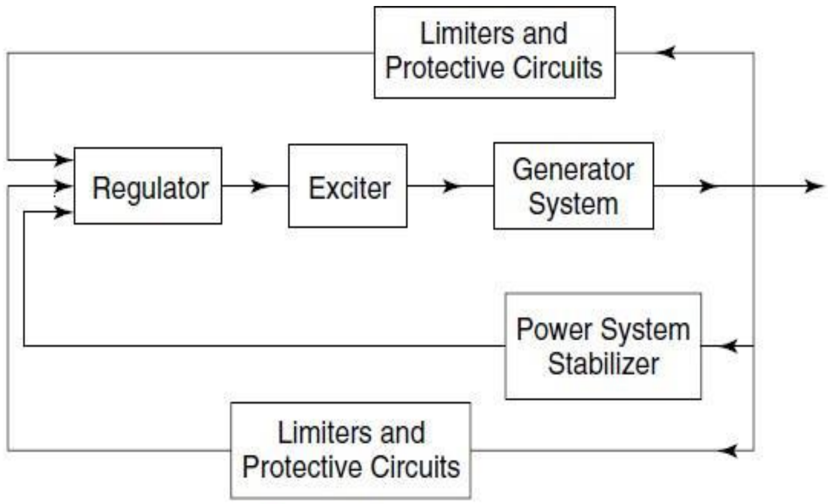


Figure 1.3 A conceptual block diagram of a modern excitation controller.

1.5 Transformer Tap-Changer Control:

Next to the generating units, transformers constitute the second family of major power-transmission-system apparatuses. In addition to increasing and decreasing nominal voltages, many transformers are equipped with tap-changers to realize a limited range of voltage control. This tap control can be carried out manually or automatically. Two types of tap changers are usually available: offload tap changers, which perform adjustments when de-energized, and on-load tap changers, which are equipped with current-commutation capacity and are operated under load. Tap changers may be provided on one of the two transformer windings as well as on autotransformers.

Because tap-changing transformers vary voltages and, therefore, the reactive power flow, these transformers may be used as reactive-power-control devices. On-load tap-changing transformers are usually employed to correct voltage profiles on an hourly or daily basis to accommodate load variations. Their speed of operation is generally slow, and frequent operations result in electrical and mechanical wear and tear.

1.6 Phase-Shifting Transformers:

A special form of a 3-phase–regulating transformer is realized by combining a transformer that

is connected in series with a line to a voltage transformer equipped with a tap changer. The windings of the voltage transformer are so connected that on its secondary side, phase-quadrature voltages are generated and fed into the secondary windings of the series transformer. Thus the addition of small, phase-quadrature voltage components to the phase voltages of the line creates phase-shifted output voltages without any appreciable change in magnitude.
A phase-shifting transformer is therefore able to introduce a phase shift in a line.

Figure 1.4 shows such an arrangement together with a phasor diagram. The phasor diagram shows the phase shift realized without an appreciable change in magnitude by the injection of phase- quadrature voltage components in a 3-phase system. When a phase-shifting transformer employs an on-load tap changer, controllable phase-shifting is achieved. The interesting aspect of such phase shifters isthat despite their low MVA capacity, by controlling the phase shift they exercise a significant real- power control. Therefore, they are used to mitigate circulating power flows in interconnected utilities.A promising application of these devices is in creating active-power regulation on selected lines and securing active-power damping through the incorporation of auxiliary signals in their feedback controllers. From this description, it is easy to visualize that an incremental in-phase component can also be added in lines to alter only their voltage magnitudes, not their phase.

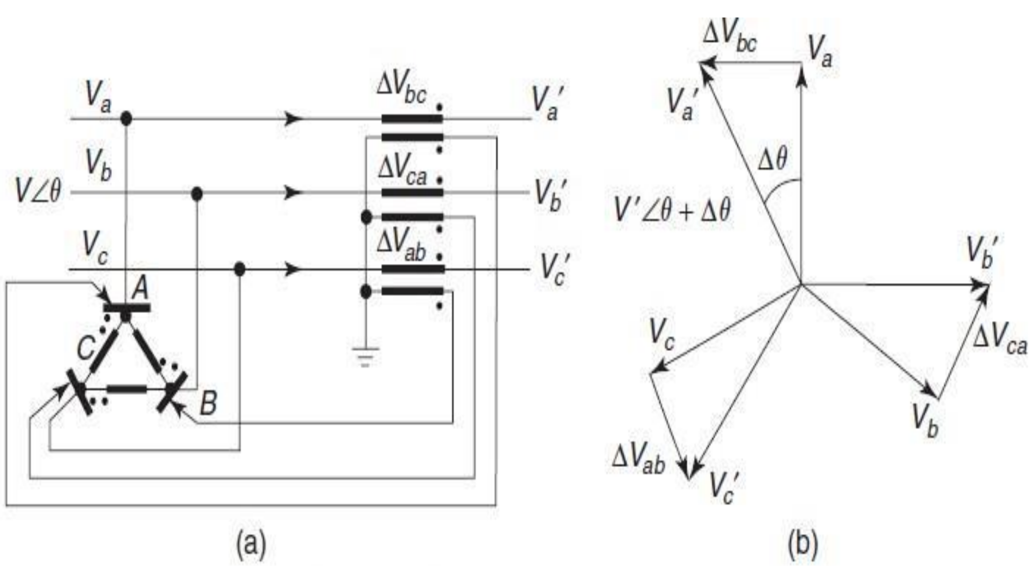


Figure 1.4 A phase-shifting transformer: (a) a schematic diagram and (b) a phasor diagram.

1.7 Advances in Power-Electronics Switching Devices

As we know that , the full potential of ac/ dc converter technology was better realized once mercury-arc valves were replaced by solid-state switching devices called thyristors. Thyristors offered controlled turn-on of currents but not their interruption. The rapid growth in thyristor voltage and current ratings accelerated their application, and the inclusion of internal light triggering simplified the converter controls and their configurations even more. Most applications, however, were based on the natural commutation of currents. In special cases where forced commutation was required, elaborate circuitry using discharging capacitors to create temporary current zeroes were employed.

Thyristors are now available in large sizes, eliminating the need for paralleling them for high-current applications. Their voltage ratings have also increased so that relatively few are required to be connected in series to yield switches or converters for power-transmission applications. Actually, the present trend is to produce high-power electronic building blocks (HPEBBs) to configure high-power switches and converters, thus eliminating the custom-design needs at the device level. Availability of HPEBBs should accelerate development of new FACTS devices. The HPEBB thyristors are available in compact packaging and in sufficiently large sizes (e.g., 125-mm thyristors: 5.5 kV, 4 kA or 4.5 kV, 5.8 kA) for most applications. For switching applications, such as that for tap changers or static phase shifters, anti-parallel–connected thyristor modules, complete with snubber circuits, are available. These switches provide sufficiently high transient-current capacity to endure fault currents.

The GTO semiconductor devices facilitate current turn-on as well as turnoff by using control signals. This technology has grown very rapidly; consequently, high-power GTOs are now available (100 mm, 6 kV or 150 mm, 9kV). Full on–off control offered by GTOs has made pulse width–modulated (PWM) inverters easy to realize.

Advances in semiconductor technology are yielding new efficient, simple to-operate devices. The insulated gate bipolar transistor (IGBT) and the metal oxide semiconductor (MOS)–controlled thyristor (MCT) control electric power using low levels of energy from their high-impedance MOS gates, as compared to high-current pulses needed for thyristors or GTOs. Unfortunately, the available voltage ratings of these devices are still limited.

The MOS turn-off (MTO) thyristor combines the advantages of both thyristors and MOS devices by using a current-controlled turn-on (thyristor) and a voltage-controlled turn-off having a high-impedance MOS structure. Hybrid MTOs are being proposed that show substantially low device losses relative to GTOs. Because MTOs use nearly half the parts of GTOs, their application promises significant reliability improvement

1.8 Principles and Applications of Semiconductor Switches

In high-power applications, semiconductor devices are used primarily as switches. To accommodate switching in an ac system, two unidirectional conducting devices are connected in an anti parallel configuration, as shown in Fig. 1.6. Such a switch may be employed per phase to connect or disconnect a shunt-circuit element, such as a capacitor or reactor, or to short-circuit a series connected–circuit element, such as a capacitor. A reverse-biased thyristor automatically turns off at current zero, for which reason an anti parallel thyristor connection is used to control the current through a reactor by delaying its turn on instant, as shown in Fig. 1.6(b). It is easy to see that the current through a connected reactor may be controlled from full value to zero by adjusting the delay angle, a, of the gate's firing signal from 90^0 to 180^0

Thus a thyristor switch offers current control in a reactor, rendering it a controlled reactor. However, because a capacitor current leads the applied voltage by approximately 90^0, the capacitor switching always causes transient in-rush currents that must be minimized by switching charged capacitors at instants when the voltage across the switch is near zero. Therefore, a thyristor switch is used only to turn on or turn off a capacitor, thereby implementing a switched capacitor.

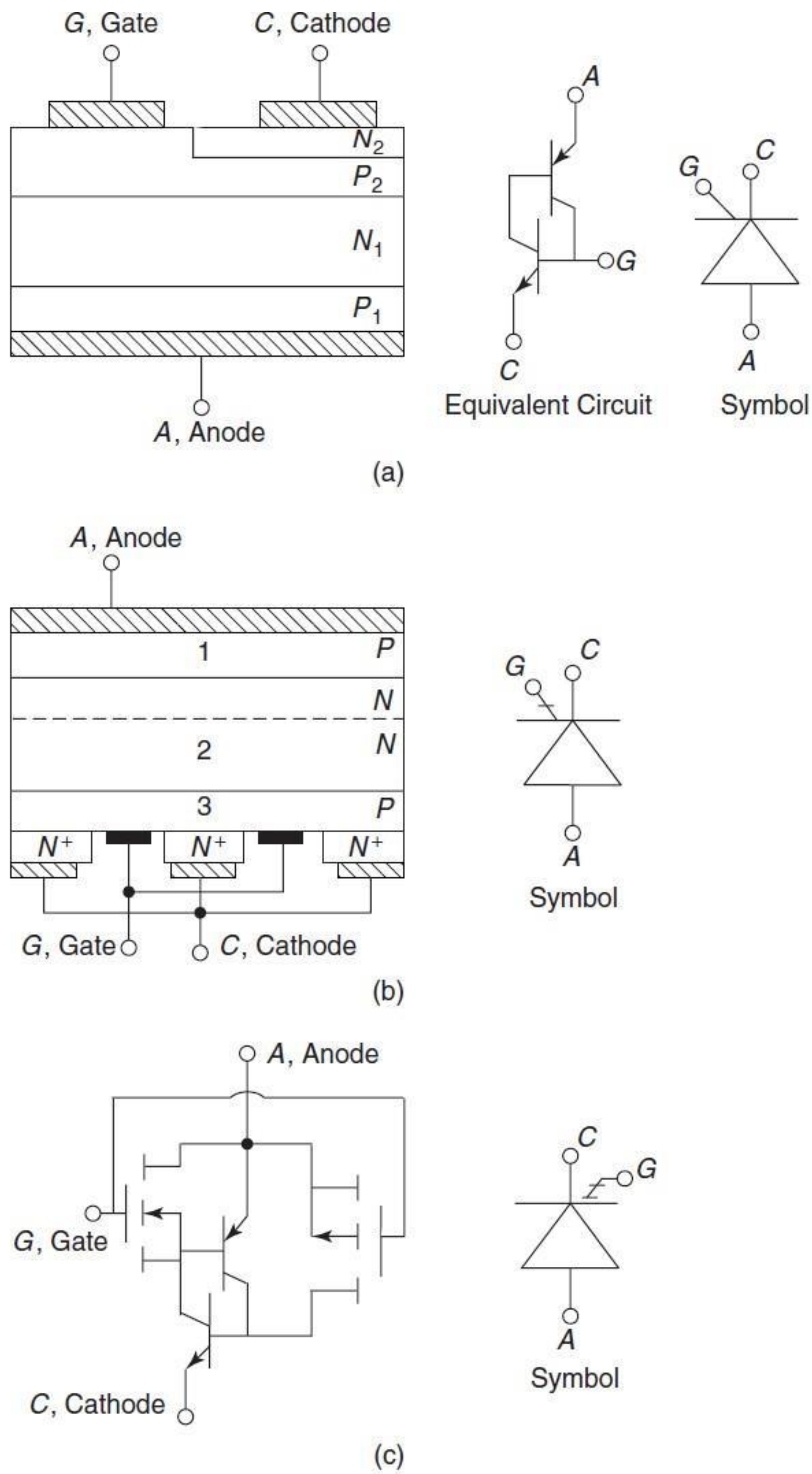


Figure 1.5 Semiconductor switching devices for power-electronics applications: (a) a thyristor (silicon-controlled rectifier); (b) a gate turn-off (GTO) thyristor; and (c) a P-MCT equivalent circuit.

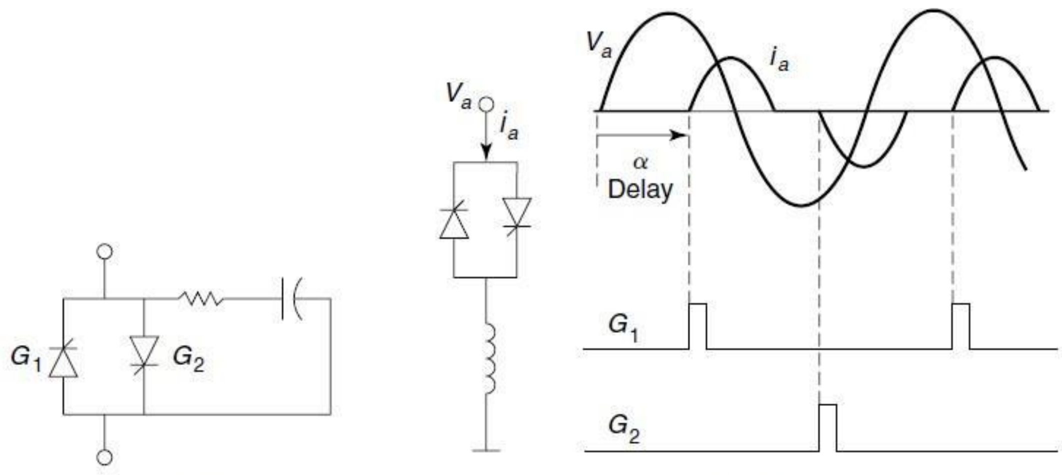


Figure 1.6 A thyristor switch for ac applications: (a) a switch and (b) a controlled reactor current.

Parallel combination of switched capacitors and controlled reactors provides a smooth current-control range from capacitive to inductive values by switching the capacitor and controlling the current in the reactor. Shunt combinations of thyristor-controlled reactors (TCRs) and thyristor-switched capacitors (TSCs) yield static var compensators (SVCs).

Thyristor switches may be used for shorting capacitors; hence they find application in step changes of series compensation of transmission lines. A blocked thyristor switch connected across a series capacitor introduces the capacitor in line, whereas a fully conducting thyristor switch removes it. In reality, this step control can be smoothed by connecting an appropriately dimensioned reactor in series with the thyristor switch—as shown in Fig. 1.7—to yield vernier control. This application of thyristor switches creates the thyristor-controlled series capacitor (TCSC) FACTS controller.

In the foregoing applications, thyristor switches were used to control the current through circuit elements, such as capacitors and reactors. The switches are also used to perform switching actions in on-load tap changers, which may be employed as thyristor-controlled phase-shifting transformers(TCPSTs).

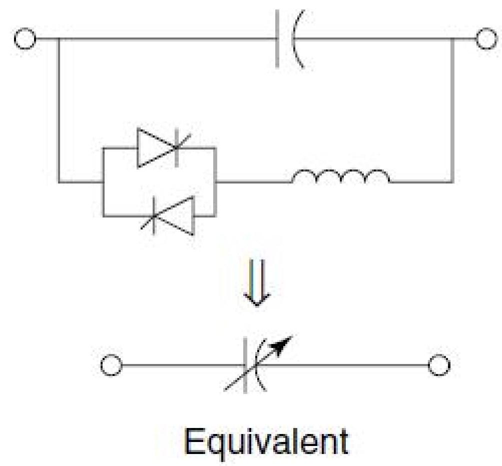


Figure 1.7 A thyristor-controlled series capacitor (TCSC).

Generally, the use of fully rated circuit elements is expensive, so to perform similar functions, another important class of FACTS controllers is realized by dc/ ac converters. The application of GTO devices makes forced commutation possible, and therefore PWM converters offer a more elegant solution. The output voltages of PWM converters contain low-harmonic content. The voltage source converters (VSCs) form the basic element of this new class of FACTS controllers, and numerous applications of this technology exist

An alternative to a thyristor-controlled SVC is a GTO-based VSC that uses charged capacitors as the input dc source and produces a 3-phase ac voltage output in synchronism and in phase with the ac system. The converter is connected in shunt to a bus by means of the impedance of a coupling transformer. A control on the output voltage of this converter—lower or higher than the connecting bus voltage—controls the reactive power drawn from or supplied to the connected bus. This FACTS controller is known as a *static compensator* (STATCOM) [20] and is shown symbolically in Fig. 1.8

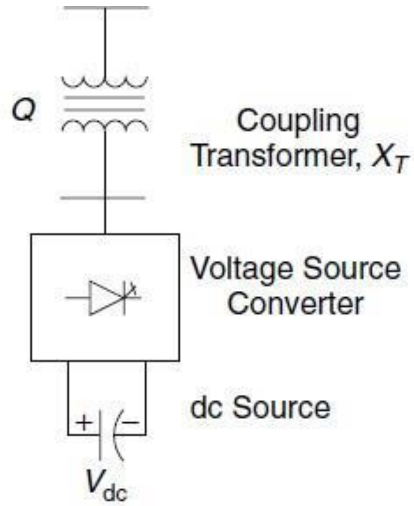


Figure 1.8 A GTO-based static synchronous compensator (STATCOM). The use of voltage-source converters to inject a voltage by way of series-connected transformers leads to another interesting group of FACTS controllers: the SSSCs, which inject voltages to compensate for the line-reactance voltage drops. It is easy to visualize that if the reactive drop of a line is partly compensated by an SSSC, it amounts to reducing the line reactance (*XL*), or in other words, it is akin to controlled series compensation. The injected voltage in the line is independent of the line current. Figure 1.9 shows a 1-line diagram of an SSSC, which controls the active-power flow on a line.

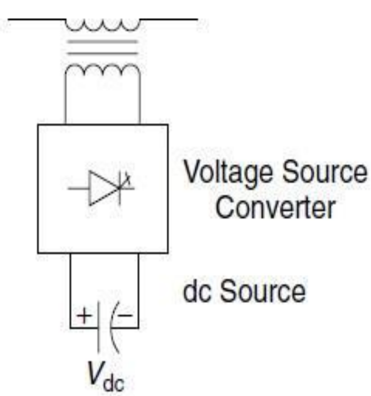


Figure 1.9 A 1-line diagram of a static synchronous series compensator (SSSC). The functions of an SSSC and a STATCOM, in fact, may be combined to produce a unified power-flow controller (UPFC), A 1-line diagram of a UPFC is shown in Fig. 1.10. In the UPFC shown, a dc energy source is shared between the STATCOM and SSSC. Normally, no net energy is drawn from this source, but to compensate for the controller losses, the STATCOM can operate so that it draws the

compensating active power from the connected ac bus. Thus a UPFC offers a fast, controllable FACTS device for the flow of combined active–reactive power in a line.

Finally, there are FACTS controllers classified as power-conditioning equipment. These controllers are employed as battery-energy–storage systems (BESSs) or superconducting magnetic-energy–storage (SMES) systems. These controllers also use GTO-based converters, which operate in dual roles as rectifiers for energy storage and inverters for energy return.

1.9 EMERGING TRANSMISSION NETWORKS

A historic change is overtaking electrical power utility businesses. Customers are demanding their right to choose electrical energy suppliers from competing vendors—a movement that has arisen from the benefits of lower costs of such services as long-distance telephone calls, natural-gas purchases,and air travel. The industries embracing these activities have been recently deregulated, and in these sectors, competition has been introduced. The basic belief is that competition leads to enhanced efficiency and thus lower costs and improved services.

For nearly 100 years, electrical power utilities worldwide have been vertically integrated, combining generation, transmission, distribution, and servicing loads. Also, most such utilities have operated as monopolies within their geographic regions. Their method of operation has been “power at cost,” and their principal financers have been governments. Therefore, to many people the pressure of electrical power utilities to operate efficiently has been missing many people the pressure of electrical power utilities to operate efficiently has been missing

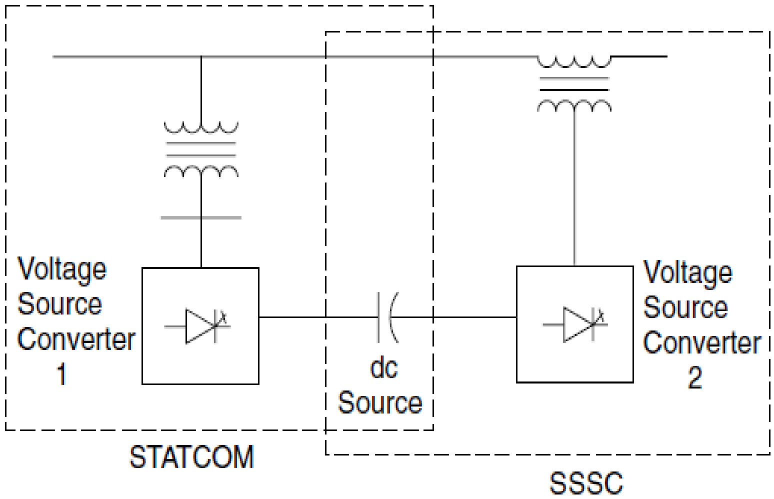


Figure 1.10 A 1-line diagram of a unified power-flow controller (UPFC).

On becoming responsible for its own business, a power-transmission company must make the best use of its transmission capacity and ensure that transmission losses are reduced to their lowest values. Also, any loss of transmission capacity means loss of income for the company; therefore, all actions must be taken to ensure that unwanted circulating power is not clogging the available transmission capacity. In addition, energy congestion in critical transmission corridors must be avoided to eliminate the risk of missed business opportunities.

Finally, to offer the greatest flexibility to market operators, a transmission company must create the maximum safe operating limits to allow power injection and tapping from its buses without risking stable operation. The success of a transmission company depends on offering the maximum available transmission capacity (ATC) on its lines

1.10 Part A-2 Marks Questions and Answers

1. Compare AC and DC transmission.(Remembering)

DC Transmission.

It requires only two conductors as compared to three for a.c transmission There is no skin effect in a d.c system.

A d.c line has less corona loss and reduced interference.

AC Transmission

The power can be generated at high voltages

The maintenance of a.c sub-station is easy and cheaper

2. List the types of power devices for HVDC transmission.

1. Thyristor
2. Insulated fiats bipolar transistor
3. GTO-gate turn-off thyristor
4. LTT- Light hissered thyrisor
5. Mos-controlled thyristo(MCT)

3. What is LASCR? How does it differ from a conventional SCR?

Light activated thyristor, also called LASCR. It is turned on by throwing a Pulse of light on the silicon wafer of thyristor. This is the major difference to Others.

4. Why circuit turn off time should be greater than the thyristor turn-off time

Circuit turn off time should be greater than the thyristor turn-off time for re liable turn-off, otherwise the device may turn-on at an undesired instant, a process called commutation failure

UNIT – II:
HIGH VOLTAGE DC TRANSMISSION – I

Syllabus: 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.

2.1 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 wherecables were required. Thyristors were applied to DC transmission and solid state valves became areality.

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 powertransmission. In the beginning all HVDC schemes used mercury arc valves, invariably single phase in construction, in contrast to the low voltage poly phase 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.

2.1.1 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.

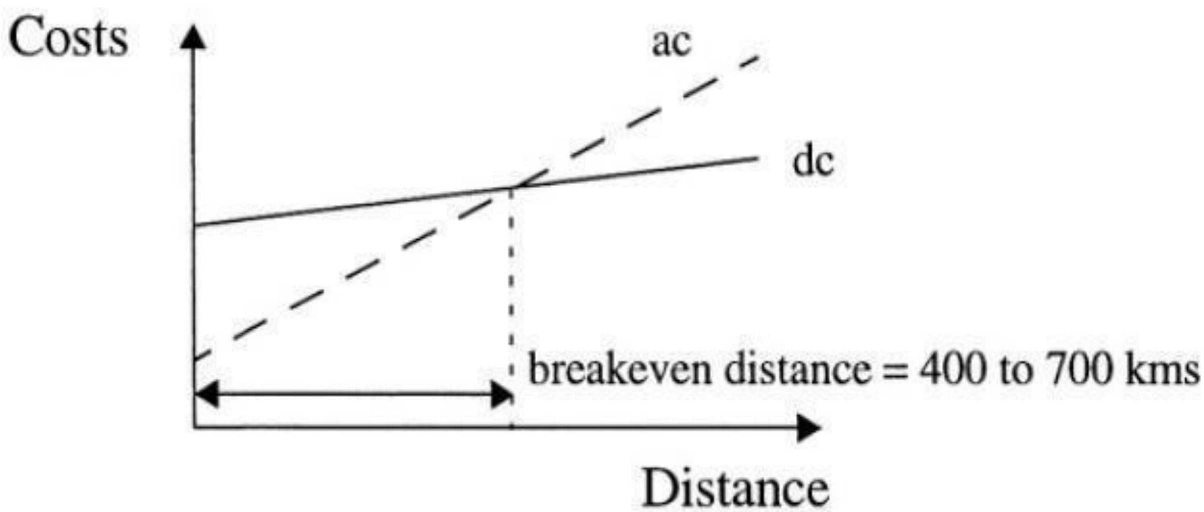
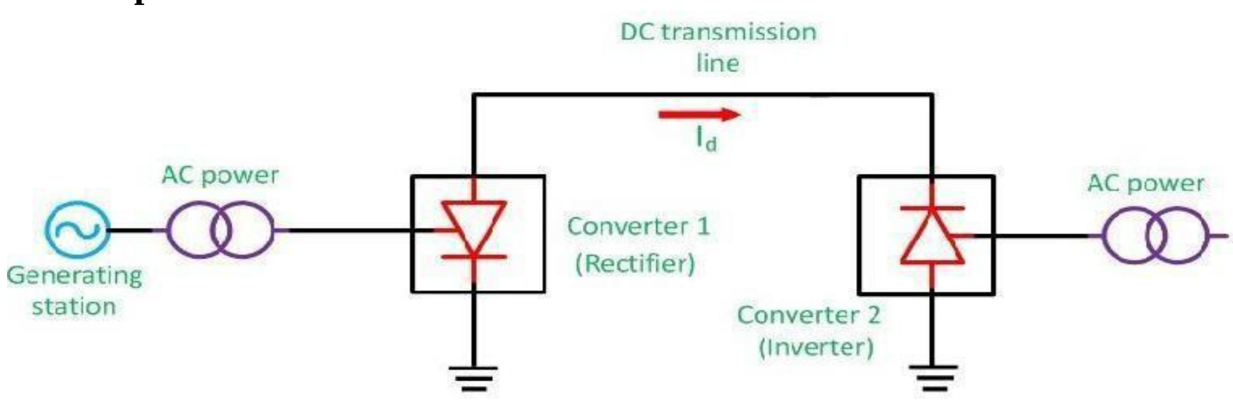


Figure: Relative costs of AC and DC transmission lines vs distance

2.2 Types of HVDC Links

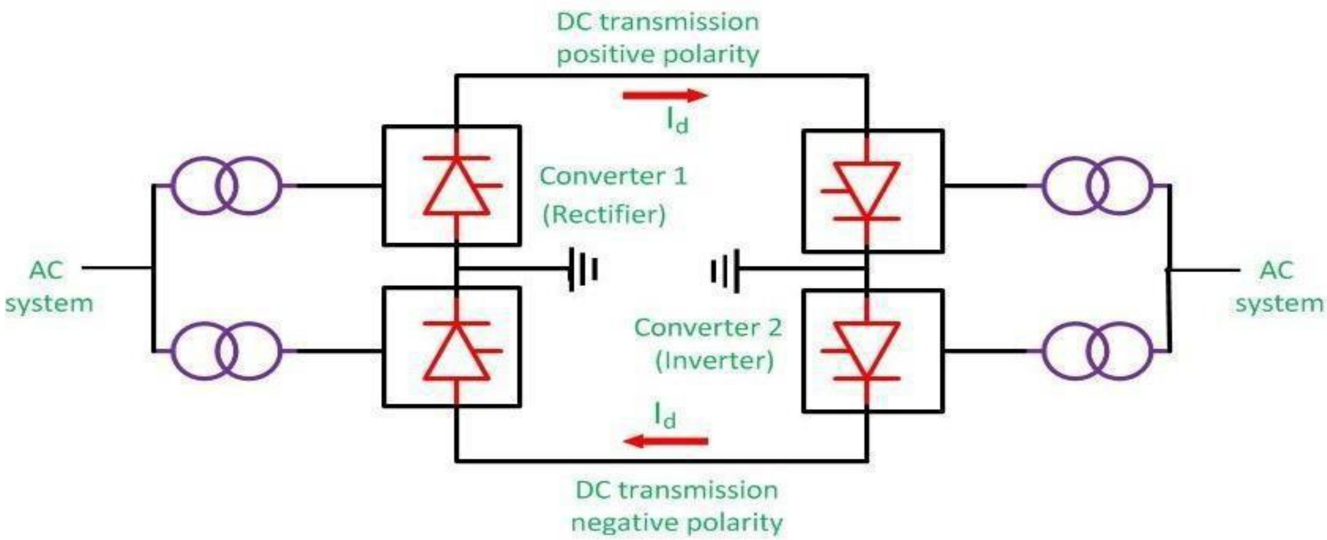
Three types of HVDC Links are considered in HVDC applications which are

1. 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.

2. 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.

3. Homopolar Link:

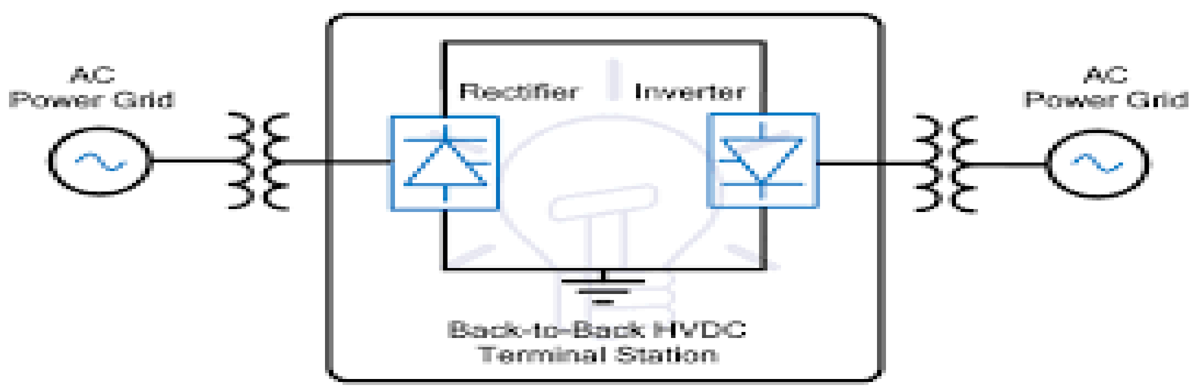
In this type of link as shown in the above figure two conductors having the same polarity (usually negative) can be operated with ground or metallic return.

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.

4. Back-to-Back HVDC Link

It is called back to back system because in electronics and power electronics if two bipolar components are connected in series with opposite polarity then this pair is known as back to back system. Here also rectifier and inverter are identical and connected in series operating on High Voltage DC so this is known as HVDC back to back System**.**

An HVDC back-to-back station can be used to create an asynchronous interconnection between two AC networks. An HVDC Light back-to-back station consists of two converters located in the same building. An HVDC back-to-back station can be used to create an asynchronous interconnection between two AC networks.



Back to Back HVDC System

2.3 Advantages of high voltage DC transmission :

1) Economical transmission of the bulk power

In a conventional transmission line, the distance cannot be more than the breakeven distance. But in the HVDC transmission line, the distance can be more than the breakeven distance.

2) Decrease in the number of conductors

In the HVAC system, the power transmitted in the form of three-phase AC power. Therefore, three or four conductors need as per the type of transmission line.

But in the case of HVDC transmission lines, only two conductors required. Hence, the cost of the conductor decreased.

3) ***Corona***

Corona effect appears in both HVAC and HVDC systems. But, in an HVDC system, the effect of the corona is very less compared to the HVAC system. And there is no disturbance to the nearby communication line.

4) Size of tower

In the HVDC transmission line, phase-phase and phase-ground clearance required is less compared to the HVAC line. Therefore, the height and width of the tower required is less.

The number of conductors required in this system is less. So, the size of the tower is less which results in less cost of the tower.

5) Earth return

For the monopolar HVDC transmission system, earth return can be used. That means, only one conductor required to transmit the power. This is not possible in the HVAC transmission line.

6) Charging current

In the DC transmission line, the capacitance is not produced between two phases or between the phase and ground. Therefore, the charging current is absent in the HVDC system.

7) ***Skin effect***

The current density is uniform throughout the line. Hence, there is no skin effect in the HVDC system.

And it utilizes an entire cross-section area of the conductor. So, the resistance of the line is not increasing and the power loss is less.

8) Reduction in line loss

The line loss reduced due to the absence of the reactive power in the HVDC transmission line. This increases the efficiency of the system.

9) Reduction in size of the conductor

When equal power transmitted for the same distance, less volume of conductor required for the HVDC two-wire system compared to the HVAC three-phase three-wire system.

10) ***<u>Underground cable</u>***

The underground system can be established for the HVDC system because of the absence of the charging current.

In the HVAC system, the distance of underground cables is a constraint. For example, 145 kV line the distance is 60 km, for 245 kV it is 40 km and for 400 kV it is 25 km.

Disadvantages/Limitations

1) Cost of terminal equipment

In the HVDC transmission line, the rectifier used at the sending end and the inverter used at the receiving end. The smoothing filters need at receiving end. The cost of this equipment is very high.

2) DC circuit breaker

The DC circuit breaker is still under development and the cost is high compared to the AC circuit breaker.

3) Additional equipment

This system needs some additional equipment like converter transformer, electrical and mechanical auxiliaries, pole control, valve control, and many more. All this equipment is of high technology and the cost of this equipment is high.

4) Complicated control

The converter used to control the transmission line. But it is difficult to control the converter under certain abnormal conditions.

5) Change the voltage level

In the AC system, with the help of a transformer, the voltage can be easily stepped up and stepped down. Therefore, this system cannot use for low voltage transmission.

6) System failure

There is some abnormal operating condition in which the system may fail to operate.

7) Harmonic filter

In the input side, the AC supply is given to the rectifiers. To mitigate these harmonics, a large amount of filter required. And the cost of this equipment is high.

8) Complicated cooling

The converter used **power electronics switches**. When this is in operation, a very high amount of heat produced in the thyristor.

9) Overload capacity

The converters cannot operate on overload conditions. Therefore, it is not permissible.

10) Multi-terminal network

HVDC transmission line is not suitable for a multi-terminal network.

11) Power loss

The losses occur in the converters and other auxiliaries, which nullify the reduced loss in the line.

HVDC advantages and disadvantages

HVDC links are being used worldwide at power levels of several gigawatts with the use of thyristor valve. So here this article gives information about the advantages and disadvantages of HVDC to know more details about it.

Advantages of high voltage DC transmission :

1. Fault clearance in HVDC is faster, therefore the DC transmission system possesses improved transient stability

2. Size of the conductor in DC transmission can be reduced as there is no skin effect

3. Cost is less as compared to the AC transmission

4. HVDC tower is less costly

5. No requirement of reactive power

6. No system stability problem

7. HVDC require less phase to phase and ground to ground clearance

8. Require less number of conductor for same power transfer

9. Improve line loading capacity

10. To ac system at different frequencies can be interconnected through HVDC transmission lines

11. HVDC is preferred as it requires no charging current

12. Power loss is reduced with DC just because of fewer numbers of lines are required for power transmission

13. HVDC is a more flexible system

Disadvantages of high voltage DC transmission:

1. Expenses inverters with limited overload capacity

2. HVDC is less reliable

3. IN HVDC very accurate and lossless power flows through DC link

4. The disadvantages of HVDC are in conversion, switching, control, maintenance

5. Lower availability than the AC system

6. HVDC is very complicated

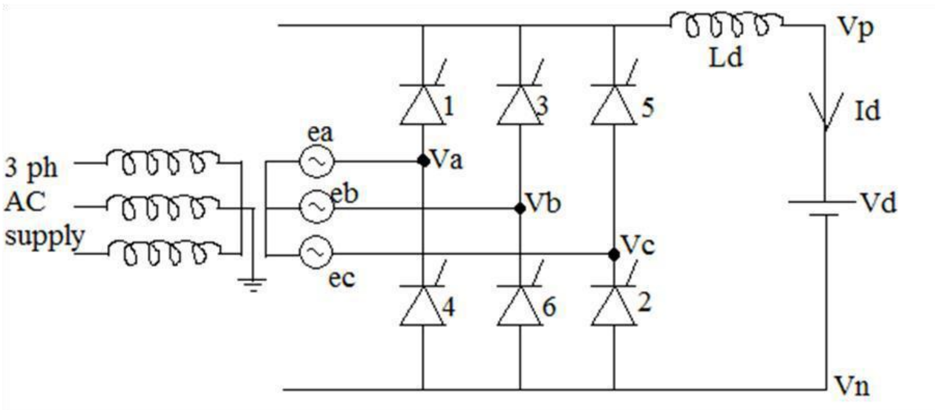
7. The circuit breaker is used in HVDC for circuit breaking, and Inverter and rectifier terminals will generate harmonics which can be reduced by using active filters, which are also very expensive

8. HVDC does not have transformers for changing the voltage levels

9. Heat loss occurs in converters substation

2.4 Analysis of Graetz circuit (6-pulseconverter bridge):

The schematic diagram of a six-pulse Graetz circuit is shown in the fig.



- ❖ This Graetz circuit utilizes the transformer and the converter unit to at most level and it maintains low voltage across the valve when not in conduction.
- ❖ Due to this quality present in Graetz circuit, it dominates all other alternative circuits from being implemented in HVDC converter.
- ❖ The low voltage across the valves is nothing but the peak inverse voltage which the valve should withstand.
- ❖ The six-pulse Graetz circuit consists of 6 valves arranged in bridge type and the converter transformer having tapings on the AC side for voltage control.
- ❖ AC supply is given for the three winding of the converter transformer connected in star withgrounded neutral.
- ❖ The windings on the valve side are either connected in star or delta with ungrounded neutral.
- ❖ The six valves of the circuit are fired in a definite and fixed order and the DC output obtained contains six DC pulses per one cycle of AC voltage wave.

a) **Operation without overlap:**

- ❖ The six pulse converter without over lapping valve construction sequence are 1-2, 2-3, 3-4, 4-5, 5-6,6-1.
- ❖ At any instant two valves are conducting in the bridge. One from the upper group and other from thelower group.
- ❖ Each valve arm conducts for a period of one third of half cycle i.e., 60 degrees.
- ❖ In one full cycle of AC supply there are six pulses in the DC waveform. Hence the bridge is called as sixpulse converter.

For simple analysis following assumptions are much:

i) AC voltage at the converter input is sinusoidal and constant

ii) DC current is constant

iii) Valves are assumed as ideal switches with zero impedance when on(conducting) and with infinite impedance when off(not conducting)

In one full cycle of AC supply we will get 6-pulses in the output. Each pair of the devices will conduct 60 degrees. The dc output voltage waveform repeats every 60 degrees interval.

Therefore for calculation of average output voltages only consider one pulse and multiply with six for one full cycle. In this case each device will fire for 120 deg.

Firing angle delay:

Delay angle is the time required for firing the pulses in a converter for its conduction.

- It is generally expressed in electrical degrees.
- In other words, it is the time between zero crossing of commutation voltage and starting point of forward current conduction.
- The mean value of DC voltage can be reduced by decreasing the conduction duration, which can be achieved by delaying the pulses ie., by increasing the delay angle we can reduce the DC voltage and also the power transmission form one valve to another valve can also be reduced.

- ✓ when $\alpha = 0$, the commutation takes place naturally and the converter acts as a rectifier.
- ✓ when $\alpha > 60$ deg, the voltage with negative spikes appears and the direction of power flow is from AC to DC system without change in magnitude of current.
- ✓ when $\alpha = 90$ deg, the negative and positive portions of the voltage are equal and because of above fact, the DC voltage per cycle is zero. Hence the energy transferred is zero.
- ✓ when $\alpha > 90$ deg, the converter acts as an inverter and the flow of power is from DC system to AC system.

Let valve 3 is fired at an angle of α. the DC output voltage is given by $V_{dc} = V_{do} \cos \alpha$

$$V_d = e_b - e_c = e_{bc}$$
$$e_{bc} = \sqrt{2}V_{LL}Sin\left(\omega t + 60^0\right)$$
$$\therefore V_{dc} = \frac{6}{2\pi}\int_{\alpha}^{\alpha+60^0} e_{bc}.d\,\omega t$$
$$V_{dc} = \frac{3}{\pi}\int_{\alpha}^{\alpha+60^0} \sqrt{2}V_{LL}Sin\left(\omega t + 60^0\right).d\,\omega t$$
$$= \frac{3\sqrt{2}}{\pi}V_{LL}\left(Cos\left(\alpha + 60^0\right) - Cos\left(\alpha + 120^0\right)\right)$$
$$= \frac{3\sqrt{2}}{\pi}V_{LL}Cos\alpha$$
$$= 1.35V_{LL}Cos\alpha$$

From above equation we can say that if firing angle varies, the DC output voltage varies

DC Voltage waveform:

The dc voltage waveform contains a ripple whose frequency is six times the supply frequency. This can be analysed in Fourier series and contains harmonics of the order

h=np

Where p is the pulse number and n is an integer.

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

The r.m.s value of the h^{th} order harmonic in dc voltage is given by

- Although α can vary from 0 to 180 degrees, the full range cannot be utilized. In order to ensure the firing of all the series connected thyristors, it is necessary to provide a minimum limit of α greater than zero, say 5 deg.
- Also in order to allow for the turn off time of a valve, it is necessary to provide an upper limit less than 180 deg.
- The delay angle α is not allowed to go beyond 180-γ where γ is called the extinction angle (sometimes also called the marginal angle).
- The minimum value of the extinction angle is typically 10 deg, although in normal operation as an inverter, it is not allowed to go below 15deg or 18deg.

$$I_p = \frac{2}{\pi}\int_{-\pi/3}^{\pi/3} I_d.\cos\theta.d\theta$$

$$\Rightarrow I_p = \frac{2}{\pi}.I_d \int_{-\pi/3}^{\pi/3} \cos\theta.d\theta$$

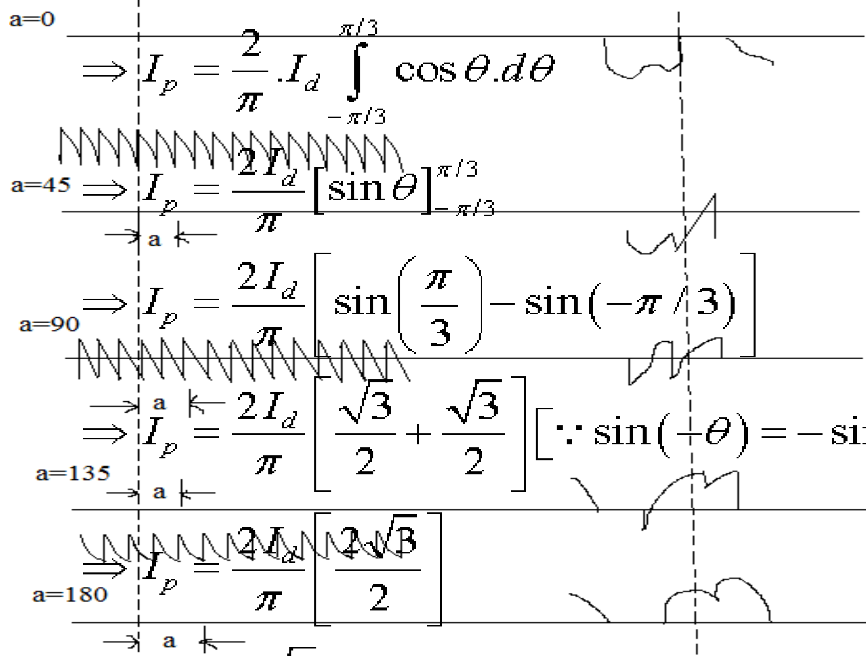
$$\Rightarrow I_p = \frac{2I_d}{\pi}\left[\sin\theta\right]_{-\pi/3}^{\pi/3}$$

$$\Rightarrow I_p = \frac{2I_d}{\pi}\left[\sin\left(\frac{\pi}{3}\right) - \sin(-\pi/3)\right]$$

$$\Rightarrow I_p = \frac{2I_d}{\pi}\left[\frac{\sqrt{3}}{2} + \frac{\sqrt{3}}{2}\right] \left[\because \sin(-\theta) = -\sin\theta\right]$$

$$\Rightarrow I_p = \frac{2I_d}{\pi}\left[\frac{2\sqrt{3}}{2}\right]$$

$$\Rightarrow I_p = \frac{2\sqrt{3}}{\pi}.I_d$$

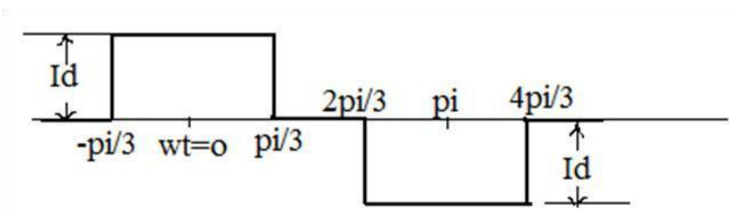


Voltage waveforms

AC current waveform:

It is assumed that the direct current has no ripple (or harmonics) because of the smoothing reactor provided in series with the bridge circuit.

The AC currents flowing through the valve (secondary) and primary windings of the converter transformer contain harmonics.



AC Current waveforms

The waveform of the current in a valve winding is shown in fig.

By Fourier analysis, the peak value of a line current of fundamental frequency component is given by, Now the rms value of line current of fundamental frequency component is given by

$$I_{RMS} = \frac{I_p}{\sqrt{2}}$$

$$\Rightarrow I_{RMS} = \frac{\frac{2\sqrt{3}}{\pi}.I_d}{\sqrt{2}}$$

$$\Rightarrow I_{RMS} = \frac{2\sqrt{3}.I_d}{\sqrt{2}\pi}$$

$$\therefore I_{RMS} = \frac{\sqrt{6}}{\pi}.I_d$$

Generally, the RMS value of nth harmonic is given by,

$$I_n = \frac{I}{n}$$

where I = Fundamental current

n = nth order harmonic.

The harmonics contained in the current waveform are of the order

given byh = np $\pm$ 1

where n is an integer, p is the pulse number.

For a 6 pulse bridge converter, the order of AC harmonics are 5, 7, 11, 13 and higher order.

They are filtered out by using tuned filters for each one of the first four harmonics and a high pass filter for therest.

The Power Factor:

The AC power supplied to the converter is given by

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

where cosΦ is the power factor.

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

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

$$\frac{\sqrt{6}}{\pi}I_d$$

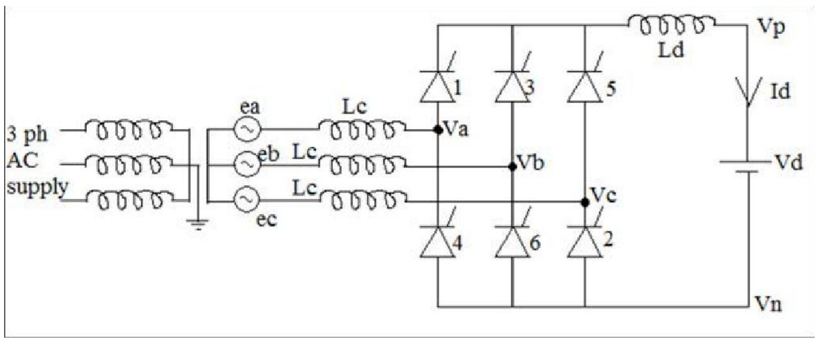
Substituting for Vdc = Vdo Cos α, and I1= , we

obtaincos Φ = cos α

The reactive power requirements are increased as α is increased from 0

When α = 90 deg, the power factor is zero and only reactive power is consumed.

ii) With overlap:



Lc indicates leakage inductance of transformer

Vd, Id = DC voltage and current flowing in the

lineLd = DC side reactance

V1 = voltage across the thyristors

p,n = positive and negative pole on the line

Due to the leakage inductance of the converter transformers and the impedance inthe supply network, the current in a valve cannot change suddenly and thus commutation from one valve to the next cannot be instantaneous.

For example, when valve 3 is fired, the current transformer from valve 1 to valve 3, takes a finite period during which both valves are conducting. This is called overlap and its duration is measured by the overlap (commutation) angle 'μ'.

Commutation delay:

The process of transfer of current from one path to another path with both paths carrying current simultaneously is known overlap.

The time required for commutation or overlapping which is expressed in electrical degrees is done with commutation angle, denoted by μ.

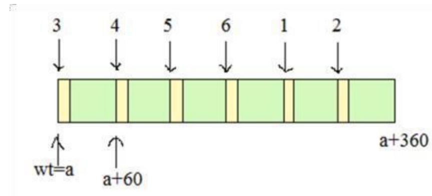
During normal operating conditions the overlap angle is in the range of 0 to 60degrees, in which two (or) three valves are conducting.

However, if the overlap angle is the range of 60 to 120 degrees, then three to four valves are in conducting state which is known as abnormal operation mode.

During commutation period, the current increases from 0 to I_d in the incoming valve and reduce to zero from Id in the outgoing valve.

The commutation process begins with delay angle and ends with extinction angle ie., it starts when $\omega t = \alpha$ and ends when $\omega t = \alpha+\mu = \delta$, where δ is known as an extinction angle.

There are three modes of the converter as follows:



1. Mode-1--- Two and three valve conduction (μ<60 deg)
2. Mode-2--- Three valve conduction (μ=60 deg)
3. Mode-3----Three and four valve conduction (μ>60 deg)

Depending upon the delay angle α, the mode 2 must be just a point on the boundary of modes 1 and 3.

i) Analysis of Two and Three valve conduction mode:

Generally overlap angle will be less than 60 deg, so let us analyse this mode.

Timing diagram

In this mode each interval of the period of supply can be divided into two subintervals. In the first subinterval, three valves are conducting and in the

Let us assume the input voltages

$$e_a = E_m \cos | \omega t + 60^0 |$$
$$e_b = E_m \cos | \omega t - 60^0 |$$
$$e_c = E_m \cos | \omega t - 180^0 |$$

Corresponding line voltages are e_{ac} , e_{ba}, e_{cb}

$$e_{ac} = e_a - e_c$$
$$= E_m \cos(\omega t + 60^0) - E_m \cos(\omega t - 180^0)$$
$$= E_m (\cos(\omega t + 60^0) - \cos(\omega t - 180^0))$$
$$= E_m \left[| \cos \omega t . \frac{1}{2} - \sin \omega t . \frac{\sqrt{3}}{2} + \cos \omega t | \right]$$
$$= E_m \left[\frac{3}{2} \cos \omega t - \frac{\sqrt{3}}{2} \sin \omega t \right]$$
$$= \sqrt{3} E_m \; | \frac{\sqrt{3}}{2} \cos \omega t - \frac{1}{2} \sin \omega t |$$
$$= \sqrt{3} E_m \left[\cos 30^0 \cos \omega t - \frac{1}{2} \sin \omega t \right]$$
$$e_{ac} = \sqrt{3} E_m \cos(\omega t + 30^0)$$

$$e_{ba} = E_m \cos(\omega t - 60^0) - E_m \cos(\omega t + 60^0)$$
$$= E_m((\cos \omega t \cos 60^0 + \sin \omega t \sin 60^0) - (\cos \omega t \cos 60^0 \sin \omega t \sin 60^0))$$
$$= E_m \left[\cos \omega t . \frac{1}{2} + \sin \omega t . \frac{\sqrt{3}}{2} - \cos \omega t . \frac{1}{2} + \sin \omega t . \frac{\sqrt{3}}{2} \right] = \sqrt{3} E_m (\sin \omega t)$$
$$\therefore e_{ba} = \sqrt{3} E_m \sin \omega t$$

second subinterval, twovalves are conducting.

$$e_{cb} = E_m(\cos(\omega t - 180) - \cos(\omega t - 60^0))$$
$$= E_m(\cos \omega t . \cos 180^0 + \sin \omega t \sin 180^0 - \cos \omega t \cos 60^0 - \sin \omega t \sin 60^0)$$
$$= E_m \left[\frac{-3}{2} \cos \omega t - \frac{\sqrt{3}}{2} \sin \omega t \right]$$
$$= \sqrt{3} E_m \left[\frac{-\sqrt{3}}{2} \cos \omega t - \frac{1}{2} \sin \omega t \right]$$
$$\therefore e_{cb} = \sqrt{3} E_m \cos(\omega t + 150^0)$$

$$e_{cb} = E_m(\cos(\omega t - 180) - \cos(\omega t - 60^0))$$

$$= E_m(\cos\omega t.\cos 180^0 + \sin\omega t \sin 180^0 - \cos\omega t \cos 60^0 - \sin\omega t \sin 60^0)$$

$$= E_m\left[\frac{-3}{2}\cos\omega t - \frac{\sqrt{3}}{2}\sin\omega t\right]$$

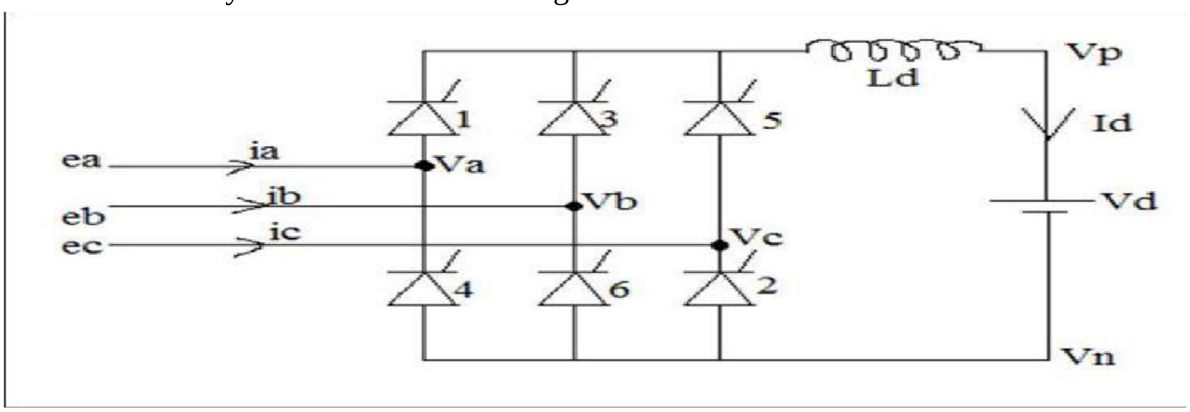
$$= \sqrt{3}E_m\left[\frac{-\sqrt{3}}{2}\cos\omega t - \frac{1}{2}\sin\omega t\right]$$

$$\therefore e_{cb} = \sqrt{3}E_m \cos(\omega t + 150^0)$$

Each valve will conduct for 120 degrees and each pair will conduct for 60 degrees, if there is nooverlap.

Let us consider non-overlap of only valve 1,2 conducting followed by overlap of 3 with 1.Ie., 1,2 and 3 conducting.

When only valve 1 and 2 conducting



$$i_a = -i_c = I_1 = I_2 = I_d$$

$$i_b = I_3 = I_4 = I_5 = I_6 = 0$$

$$V_a = V_p = e_a = E_m \cos(\omega t + 60^0)$$

$$V_b = e_b = E_m \cos(\omega t - 60^0)$$

$$V_c = V_n = e_c = E_m \cos(\omega t - 180^0)$$

$$V_d = V_p - V_n = e_a - e_c = e_{ac} = \sqrt{3}E_m \cos(\omega t + 30^0)$$

$$V_1 = V_2 = 0$$

$$V_3 = e_{ba} = \sqrt{3}E_m \sin\omega t$$

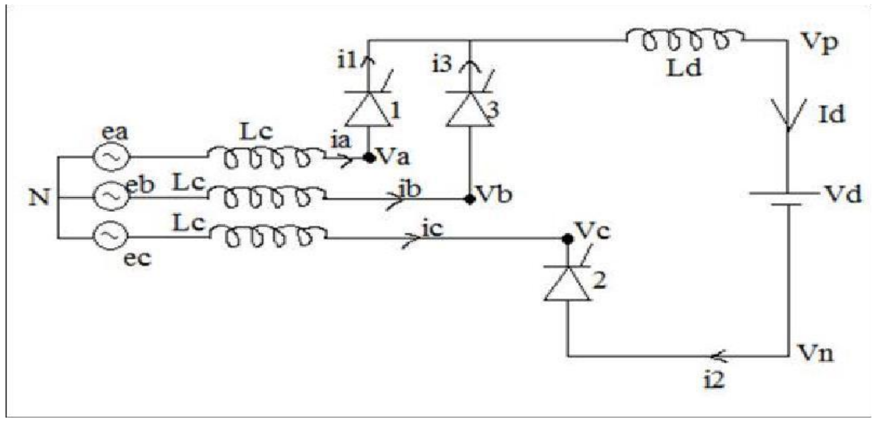
$$V_4 = V_n - V_p = -V_d$$

$$V_5 = V_n - V_p - V_d$$

$$V_6 = e_c - e_b = e_{cb} = \sqrt{3}E_m \cos(\omega t + 150^0)$$

When valve 3 is fired then 3 will overlap with 1 and it will be 3 valve conduction periods ie., 1,2 and 3.

For this period the emanation for the voltage and current are different and thus canbe obtained as follows



:

Consider that valve 3 is ignited at angle 'α' and for overlap angle both 1 and 3 conduct together.

The duration of overlap 1 and 3 will conduct top with 2 at the bottom as shown in the fig.

Just at the beginning, $\omega t = \alpha$

At $\omega t = \alpha$

$$i_1 = I_d$$
$$i_3 = 0$$

When the overlap ends at an angle $(\alpha+\mu)$

At $\omega t = (\alpha+\mu)$ $\quad i_1 = 0$

$$i_3 = I_d$$

The angle $(\alpha+\mu)$ is called extinction angle During overlap a loop is formed as N-3-1-NFor this loop,

$$e_b - e_a = L_c \frac{di_3}{dt} - L_c \frac{di_1}{dt}$$

$$\sqrt{3}E_m \sin \omega t = L_c \frac{di_3}{dt} - L_c \frac{di_1}{dt}$$

Assuming the dc current either i1 alone conduct, i3 alone when 3 alone conducts should be equal to IdSo both 1 and 3 conduct overlap

$$i_1 + i_3 = I_d$$

$$i_1 = I_d - i_3$$

So

$$\sqrt{3}E_m \sin \omega t = L_c \frac{di_3}{dt} - L_c \frac{di}{dt}(i_d - i_3)$$

$$\sqrt{3}E_m \sin \omega t = 2L_c \frac{di_3}{dt}$$

$$\sqrt{3}E_m \int \sin \omega t . dt = 2L_c \int di_3$$

$$\sqrt{3}E_m \int_{\alpha/\omega}^{t} \sin \omega t . dt = 2L_c \int_{\alpha/\omega}^{t} di_3$$

$$\frac{\sqrt{3}E_m}{2L_c . \omega}(-\cos \omega t)_{\alpha/\omega}^{t} = i_3$$

$$i_3 = \frac{\sqrt{3}E_m}{2L_c . \omega}(\cos \alpha - \cos \omega t) = I_d - i_1$$

At $\omega t = (\alpha+\mu)$;

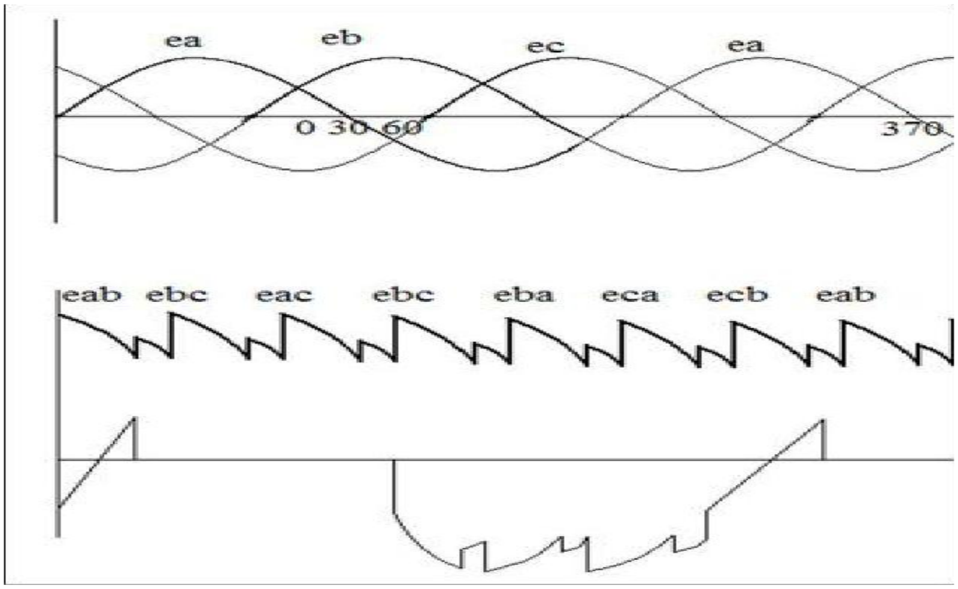
$$i_3 = I_d$$

$$\therefore I_d = \frac{\sqrt{3}E_m}{2\omega L_c}(\cos\alpha - \cos(\alpha+\mu))$$

$$\therefore I_d = I_{s2}(\cos\alpha - \cos(\alpha+\mu))$$

$$i_3 = I_d - i_1 = \frac{\sqrt{3}E_m}{2\omega L_c}(\cos\alpha - \cos\omega t)$$

$$I_{s2} = \frac{\sqrt{3}E_m}{2\omega L_c}$$



DC voltage and valve voltage waveforms for rectifier when α=15 deg,

μ = 15 deg, δ = 30 deg

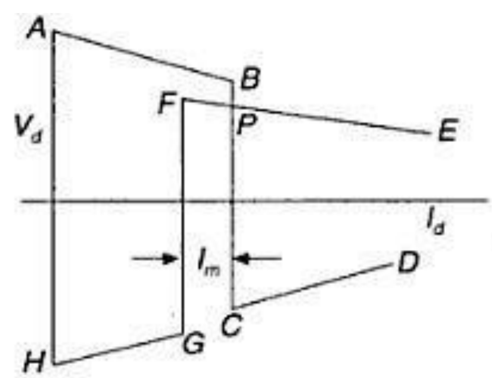
2.5 Converter Control Characteristics

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.

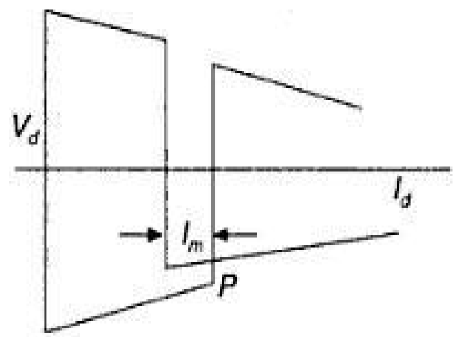


Controllers characteristics.

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 toR_{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.

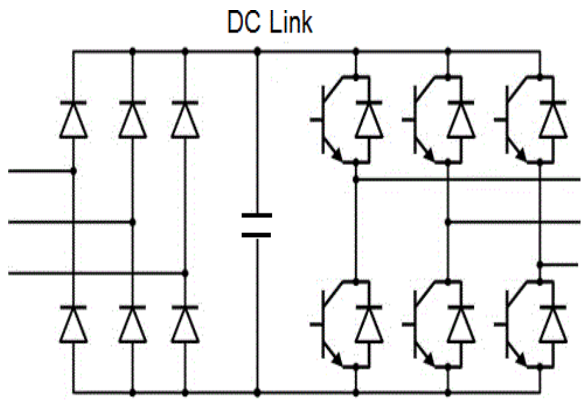
2.6 Equivalent circuit of HVDC Link:

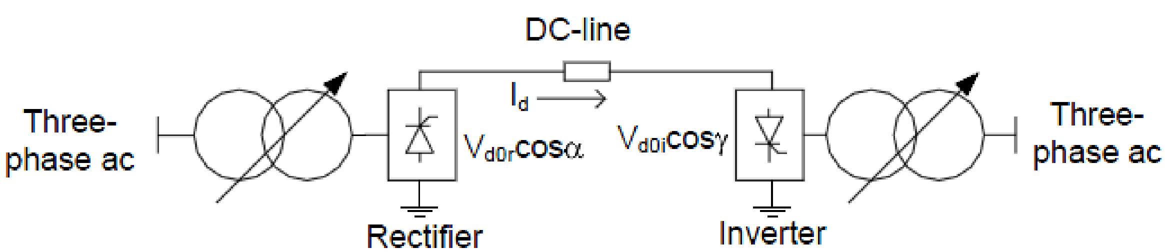
The major advantage of a HVDC link is rapid controllability of transmitted power through the control of firing angles of the converters. Modern converter controls are not only fast, but also very reliable and they are used for protection against line and converter faults.

A DC link is a connection which connects a rectifier and an inverter. These links are found in converter circuits and in VFD circuits. The AC supply of a specific frequency is converted into DC. This DC, in turn, is converted into AC voltage.

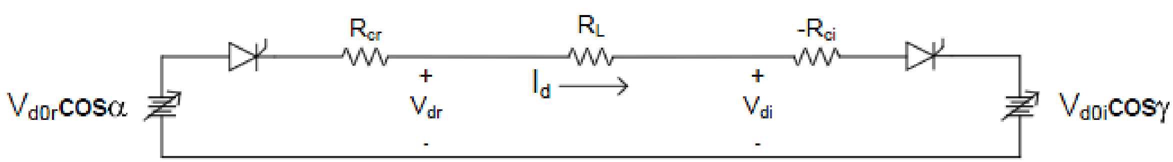
The DC link is the connection between these two circuits. The DC link usually has a capacitor known as the DC link Capacitor. This capacitor is connected in parallel between the positive and the negative conductors.

The DC capacitor helps prevent the transients from the load side from going back to the distributor side. It also serves to smoothen the pulses in the rectified DC.





(a)



(b)

Applications of HVDC transmission:

- Undersea and underground cables
- AC network interconnections
- Interconnecting Asynchronous system

Connecting remote generation

Some energy sources, such as hydro and solar power, are often located hundreds or thousands kilometers away from the load centers. HVDC will reliably deliver electricity generated from mountain tops, deserts and seas across vast distances with low losses.

Interconnecting grids

Connecting ac grids is done for stabilization purposes and to allow energy trading. During some specific circumstances, the connection has to be done using HVDC, for example when the grids have different frequencies or when the connection has to go long distances over water and ac cables cannot be used because of the high losses.

Connecting offshore wind

Wind parks are often placed far out at sea, because the wind conditions are more advantageous there. If the distance to the grid on land exceeds a certain stretch, the only possible solution is HVDC - due to the technology's low losses.

Power from shore

Traditionally, oil and gas platforms use local generation to supply the electricity needed to run the drilling equipment and for the daily need of often hundreds of persons working on the platform. If the power is instead supplied from shore, viaan hvdc link, costs go down, emissions are lower and the working conditions on the platform are improved.

Dc links in ac grids

HVDC links within an ac grid can be successfully utilized to strengthen the entire transmission grid, especially under demanding load conditions and during system disturbances. Transmission capacity will improve and bottlenecks be dissolved.

City-center in feed

HVDC systems are ideal for feeding electricity into densely populated urban centers. Because it is possible to use land cables, the transmission is invisible, thus avoiding the opposition and uncertain approval of overhead lines.

Connecting remote loads

Islands and remotely located mines often have the disadvantage of a weak surrounding ac grid. Feeding power into the grid with an HVDC link, improves the stability and even prevents black-outs.

2.7 Part A-2 Marks Questions and Answers

1. What are the types of DC link?(Remembering)

1. Monopolar link
2. Bipolar link
3. Homopolar link

2. Write the advantages and disadvantages of HVDC Transmission Advantages

1.Full control over power transmitted

2.The ability to enhance transient and dynamic stability in associated AC networks

3.Fast control to limit fault current in DC lines

4.Reduced transmission lines

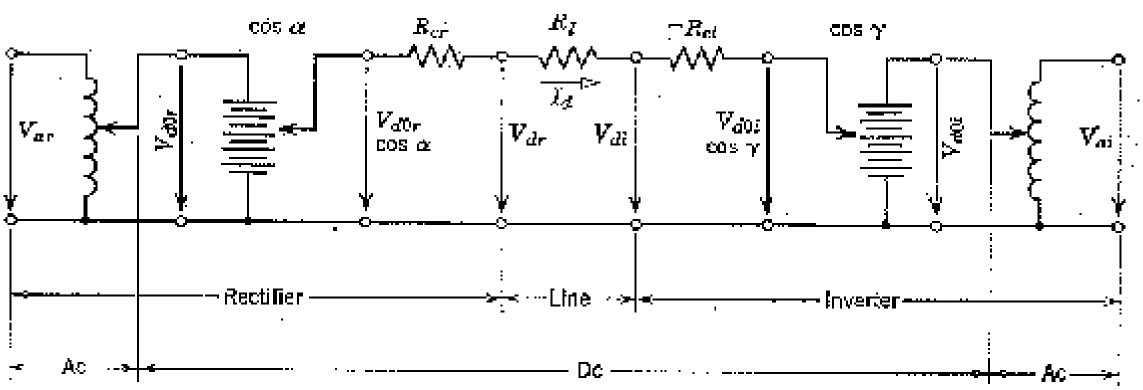
UNIT – III

HIGH VOLTAGE DC TRANSMISSION – II

Syllabus: 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.

3.1 Basic means of control:

OVERALL EQUIVALENT CIRCUIT OF HVDC SYSTEM



From the overall equivalent circuit of HVDC system

$$I_d = \frac{V_d \;\; c \;\; \alpha - V_d \;\; c \;\; (\beta/\gamma)}{R_C + R_L \pm R_C}$$

The DC voltage and current in the DC link can be controlled by controlling rectifier voltagesand inverter voltages using two methods

- **GRID CONTROL**
- **MANUAL CONTROL**

- **GRID CONTROL:** It is done by varying ignition angle of the valves. It is rapid orinstantaneous control

- **MANUAL CONTROL:** It is done changing the taps ratio of the converter transformer. It is slow and done in steps
  Power reversal can be done by changing the polarity of the DC voltage at both ends

BASIS FOR SELECTION OF THE CONTROL:

- Prevention of large fluctuating current due to variations of AC voltages
- Maintaining the DC voltage near to its rated
- Maintaining the power factor at the sending and receiving end as high as possible
- Prevention of various faults in the valves

What is the Need for power factor high?

- To keep the rated power in the converter as high as possible wrt givenvoltage, current, voltage ratings of the transformer and the valves.
- To reduce the stress on the valve.
- To minimize the losses and the current ratings of the equipment in the AC system to which the converter is connected.
- To minimize the voltage drops as the load increases.
- To minimize the reactive power supplied to the converter

3.1.1 DESIRED FEATURES OF THE CONTROLLER:

- Control system should not be sensitive to normal variations in voltage and frequency of the AC supply system.
- Control should be fast reliable and easy to implement.
- There should be continuous operating range of full Rectification to full Inversion.
- Control should be such that it should require less reactive power.
- Under at steady state conditions the valves should be fired symmetrically.
- Control should be such that it must control the maximum current in the DC link and limit the fluctuations of the current.
- Power should be controlled independently and smoothly which can be doneby controlling the current or voltage or both.
- Control should be such that it can be used for protection of the line and the converter

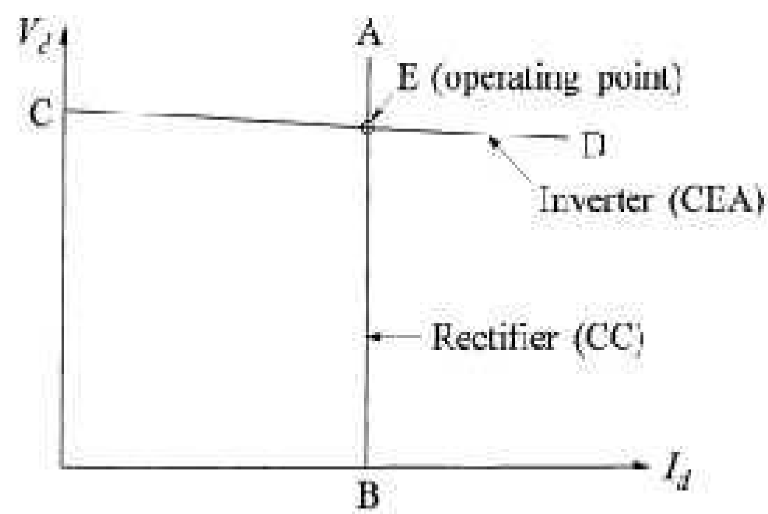
3.2.1 CHARACTERISTICS OF THE HVDC SYSTEM:

In order to satisfy basic requirements for better voltage regulation and current regulation it is always be advisable to assign these parameters for the converters. Under normal operations **Rectifier** will take care of the **current** and the **Inverter** will take care ofthe **voltage**.

Rectifier - Constant Current Control (CC)

Inverter - Constant Extinction Angle Control (CEA)

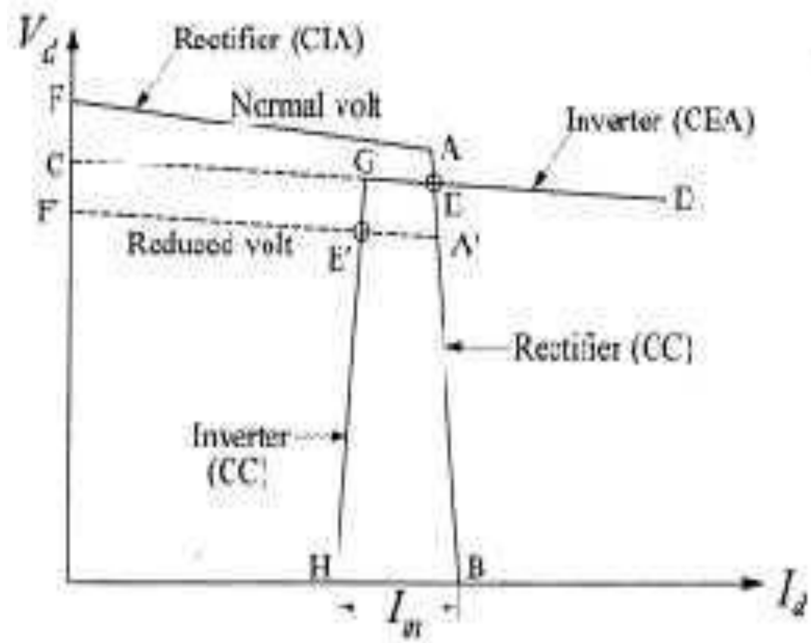
IDEAL CHARACTERISTICS: Rectifier will take care of current so it is a line parallel to Y axis. As Inverter equation with gama is negative slope. The point where rectifier current control and inverter voltage control coincide there exist a operating point which is the power order of the HVDC link



The rectifier characteristics can be shifted horizontally by adjusting the current command or current order. If the measured current is less than the command the regulator advances the firing by decreasing α.

The inverter characteristics can be raised or lowered by means of the transformer tap changer. When the tap is moved the CEA regulator quickly restores the desired gama. As a result the DC current changes which is then quickly restored by current regulator of the rectifier.

ACTUAL CHARACTERISTICS:



- The rectifier maintains constant current in the DC link by changing α however α cannot be less than α_{min}. Once α_{min} . is hit no further increase in voltage is possible. This is called Constant Ignition Angle Control(CIA)

- In practice as current controller will have a proportional controller it has high negative slope due to finite gain of the controller

CONSTANT VOLTAGE	CONSTANT CURRENT
Voltage is constant	Current is constant
Current is varied to change power	Voltage is varied to change power
Loads and power sources are connected in parallel in order to turnoff a load or a source respective branch is opened	Loads and power sources are connected in series in order to turn off a load or source it should be bypassed
AC transmission and DC Distribution	Street lighting in DC
DC system the fault current can be greater limited by circuit resistance	Short circuit current is ideally limited by load current and it is twice of the rated current and Accidental open circuits give rise to huge voltages
Power loss is α (power transmitted)^2	Power loss is α full load value

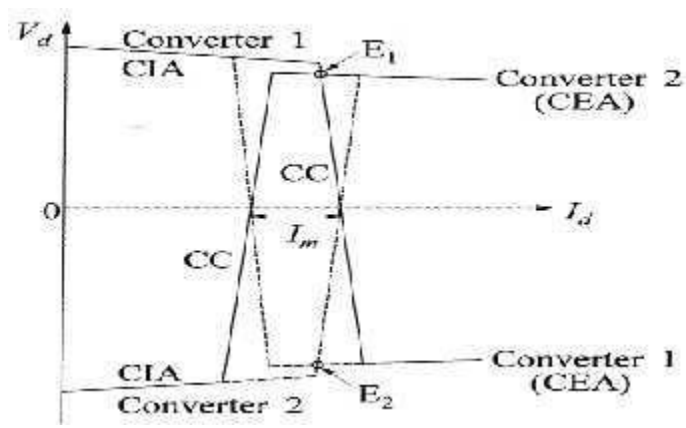
3.2.2 Constant Current Control (CC)

In a d.c. link it is common practice to operate the link at constant current rather than at constant voltage. [Of course, constant current means that current is held nearly constant and not exactly constant]. In constant current control, the power is varied by varying the voltage. There is an allowed range of current settings within which the current varies.

3.2.3 CONSTANT EXTINCTION ANGLE CONTROL:

Maximum **utilization** of an inverter's capacity and minimum consumption of reactive power demands an accurate constant extinction angle control. ... The control is extended to cover the converter operation over its full range from a minimum permissible angle of delay to the minimum permissible extinction angle

3.2.4 COMBINED RECTIFIER AND INVERTER CHARACTERISTICS:



Power reversal can be done by changing the current settings of the converter and inverter which is shown in the dotted line above

3.3 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 senda 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)**

3.3.1 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.

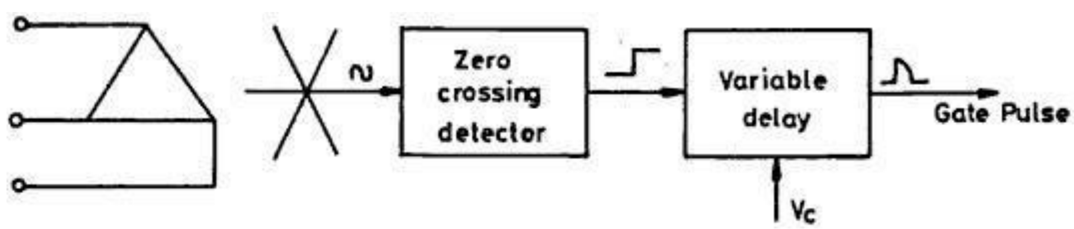
There are two ways in which this can be achieved

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

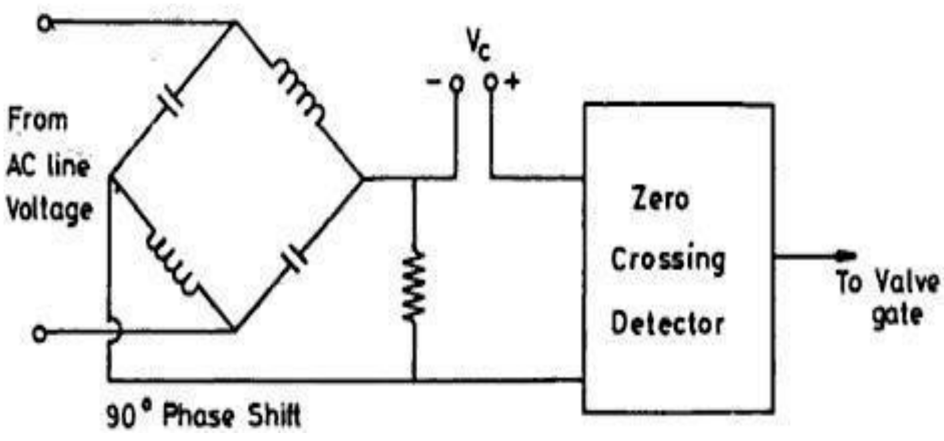
voltage corresponds to $\alpha = 0^o$ for that valve.



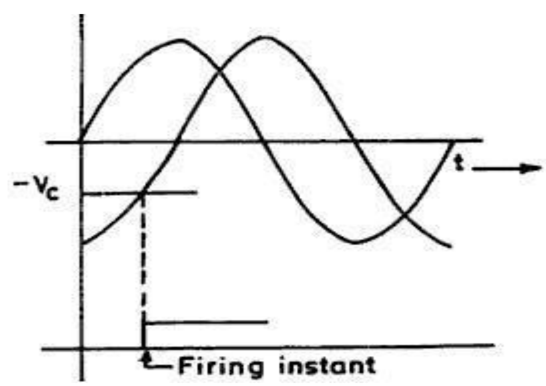
The delays are produced by independent delay circuits and controlled by a common control voltage V derived from the current controllers.

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 theparticular 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 .

ADVANTAGES OF IPC:

- The output voltage will be high

DISADVANTAGES OF IPC:

- Harmonic instability with less SCR.
- Non characteristics harmonics introduction in the system.
- Parallel resonance with filter impedance and system impedance

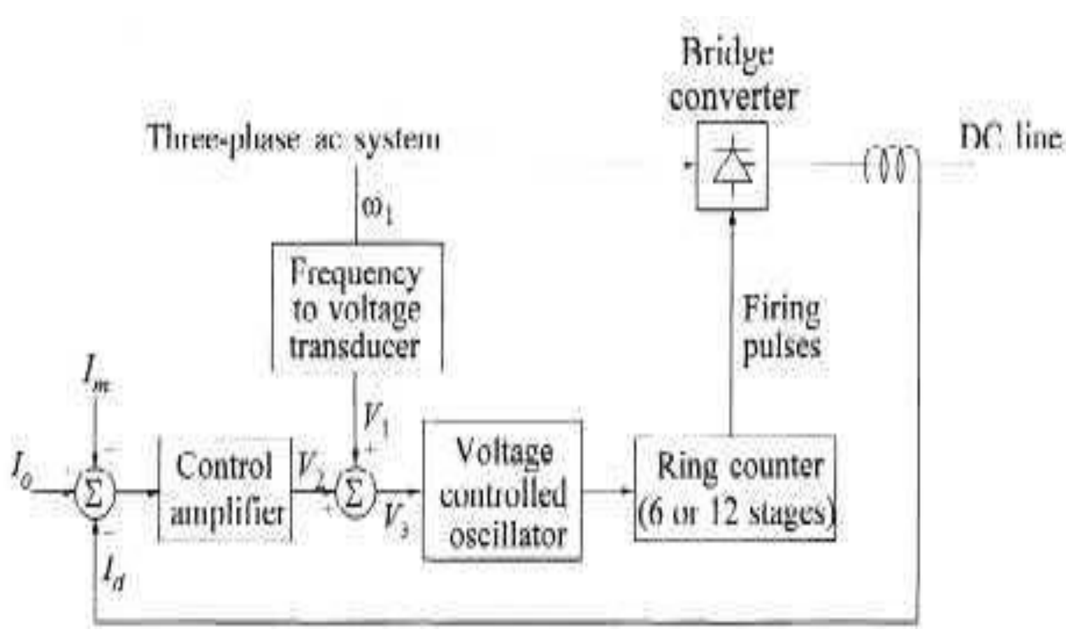
3.3.2 Equidistant Pulse Control (EPC)

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 arethree variations of the EPC scheme

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

1.Pulse Frequency Control (PFC):

- The basic components of the system are Voltage Controlled Oscillator (VCO) and a ring counter. The VCO delivers pulses at a frequency directly proportional to the input control voltage.
- The train of pulses is fed to a ring counter which has six or twelve stages.
- One stage is on at a time with the pulse train output of the VCO changing the on stage of the ring counter.
- As each stage turns on it produces a short output pulse once per cycle.
- Over one cycle a complete set of 6 or 12 output pulses are produced by the ring counter at equal intervals.
- These pulses are transferred to the firing pulse generator to the appropriate valves of the converter bridge



- Under steady state conditions V2=0 and the voltage V1 is proportional to the AC line frequency ω1.
- This generates pulses at the line frequency and constant firing delay angles α.
- If there is a change in the current order , margin settings or line frequency., a change in V3 occurs which in turn results in change in the frequency of the firing pulses.
- A change in the firing delay angle results from the time integral of the differences between the line and firing pulse frequencies.
- It is apparent that this equidistant pulse control firing scheme is based on pulse frequency control.

2. Pulse Period Control:

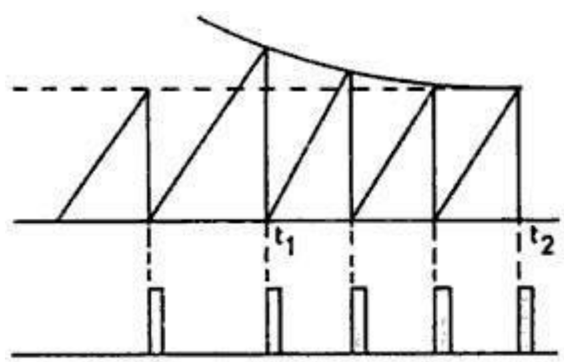
In this scheme a step change in control signals causes a spacing of the only pulse to change these results in a shift of phase only.

ADVANTAGES:

- Equal delay for all the devices.
- Non characteristics harmonics are not introduced

DISADVANTAGES:

- Less DC output voltage than IPC



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

3. 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.

(iii) Limits can also be incorporated into PFC or pulse period control system.

Drawbacks of EPC Scheme

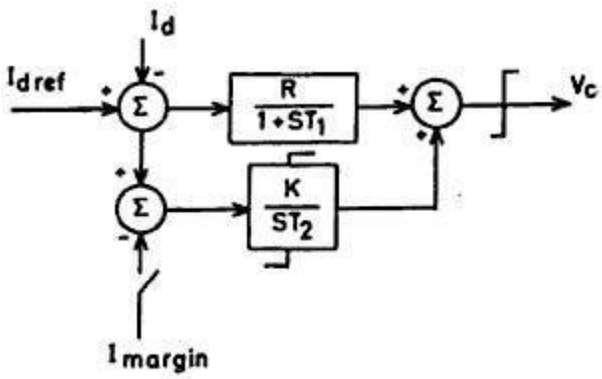
EPC Scheme has replaced IPC Scheme in modern HVDC projects; it has certain limitations which are

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 oscillationswhen 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.

3.4 Tap changer control:

In High **voltage DC converter transformer** is the main component which is used in HVDC transmission. Tap changer is an essential part of any power transformer for obtaining various turns ratios to get different voltage levels. Conventional mechanical tap changers are commonly employed for this purpose.

High voltage DC transmission is gaining more and more importance due to various advantages over high voltage AC transmission. High voltage DC converter transformer is the main component which is used in HVDC transmission. Tap changer is an essential part of any power transformer for obtaining various turns ratios to get different voltage levels.

Conventional mechanical tap changers are commonly employed for this purpose. Mechanical tap changers require continuous maintenance when tap changers require frequent operation. The tap changers in high voltage DC converter transformer is such an application where frequent operation of tap changer is needed

The main purpose of tap changer in LCC-HVDC converter trasformers is **to operate the converter bridge nearby the nominal (rated) firing /extintion angle, independently from the ac-side voltage and from the dc-side current**

3.5 Starting and Stopping of DC Link

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.

Power Reversal in HVDC links:

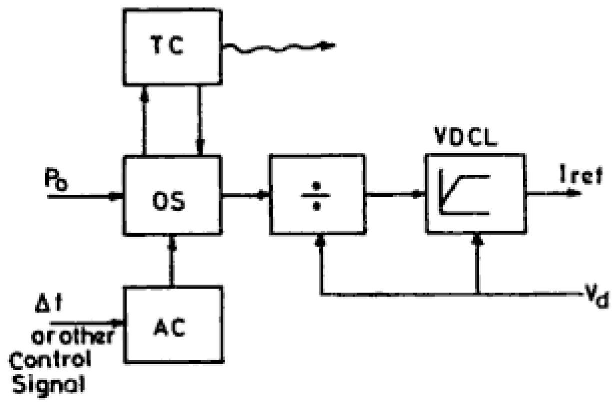
In contrast to line-commutated HVDC converters, voltage-source converters maintain a constant polarity of DC voltage and power reversal is achieved instead by reversing the direction of current. This makes voltage-source converters much easier to connect into a Multi-terminal HVDC system or "DC Grid".

Power reversal in the LCC link can be achieved by **reversing LCCs' DC polarity through changing their control modes**

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

UNIT – IV

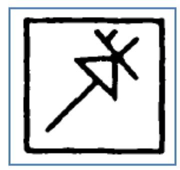
FLEXIBLE AC TRANSMISSION SYSTEMS-I

Syllabus: 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.

4.1 BASIC TYPES OF FACTS CONTROLLERS:

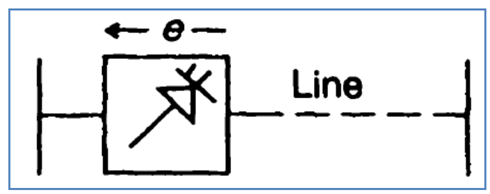
In general, FACTS Controllers can be divided into four categories:

- Series Controllers
- Shunt Controllers
- Combined series-series Controllers
- Combined series-shunt Controllers



the general symbol for a FACTS Controller: a thyristor arrow inside a box.

Series Controllers:

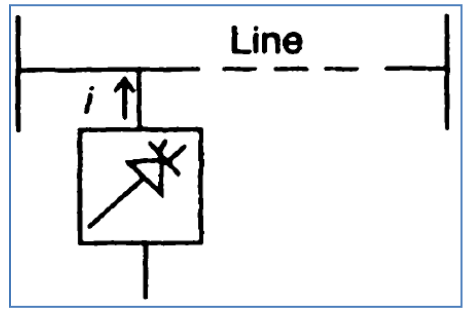


The series Controller is a variable impedance type component, such as capacitor, reactor, etc., or power electronics based variable source of main frequency, sub synchronous and harmonic frequencies (or a combination) to serve the desired need.

- All series Controllers inject voltage in series with the line.
- Even variable impedance multiplied by the current flow through it, represents an injected series voltage in the line.
- As long as the voltage is in phase quadrature with the line current, the series Controller only supplies or consumes variable reactive power. Any other phase relationship will involve handling of real power as well.

Shunt Controllers:

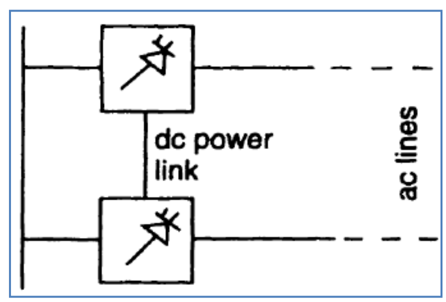
As in the case of series Controllers, the shunt Controllers may be variable impedance, variable source, or a combination of these.



- All shunt Controllers 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 only supplies or consumes variable reactive power. Any other phase relationship will involve handling of real power as well.

Combined series-series Controllers:

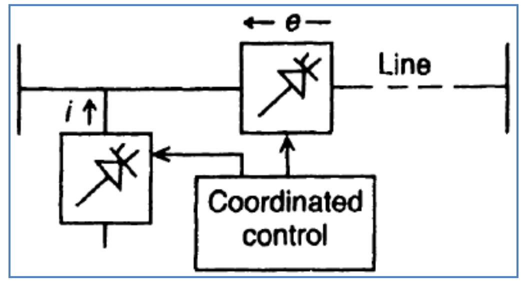
These are combination of separate series controllers, which are controlled in a coordinated manner, in a multiline transmission system. Or it could be a unified Controller,



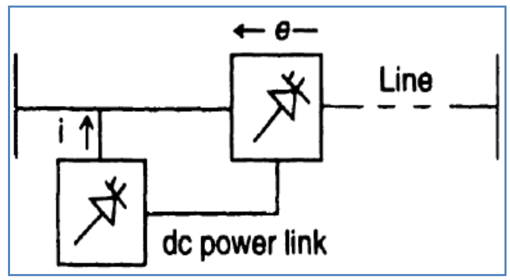
- Series Controllers provide independent series reactive compensation for each line but also transfer real power among the lines via the power link.
- The real power transfer capability of the unified series-series Controller, referred to as Interline Power Flow Controller, makes it possible to balance both the real and reactive power flow in the lines and thereby maximize the utilization of the transmission system.
- The term "unified" here means that the de terminals of all Controller converters are all connected together for real power transfer.

Combined series-shunt Controllers:

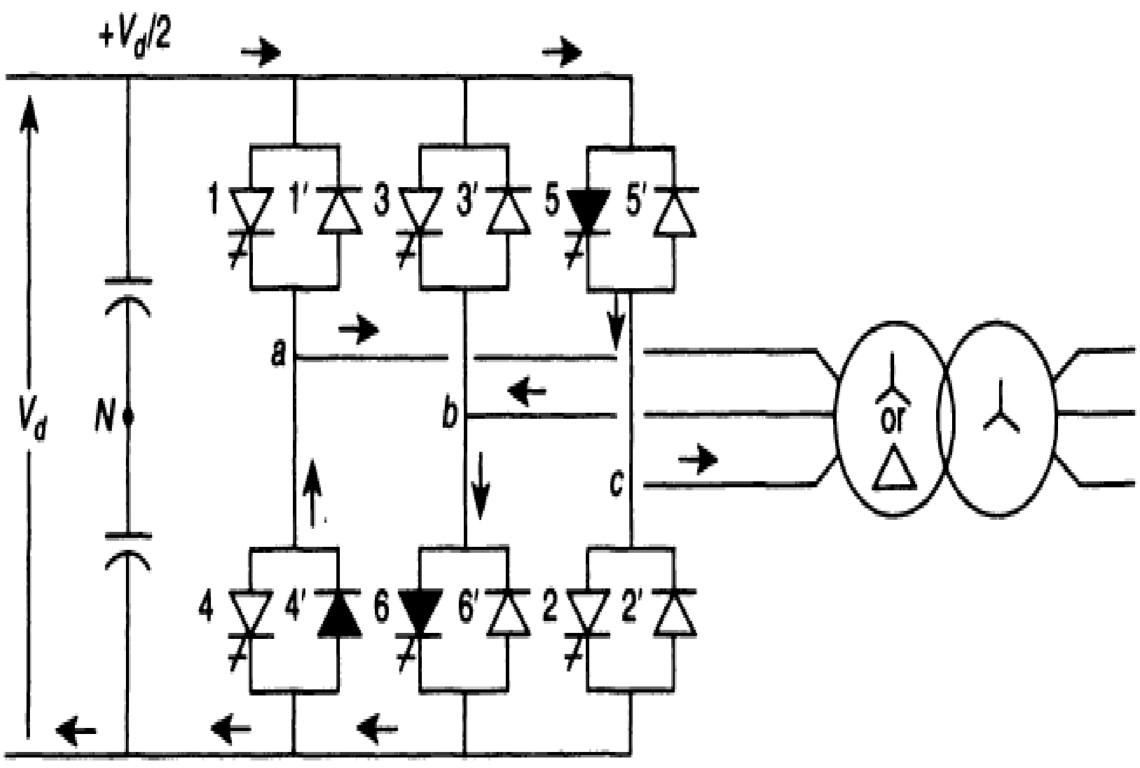
These are combination of separate shunt and series Controllers, which are controlled in a coordinated manner or a Unified Power Flow Controller with series and shunt elements.

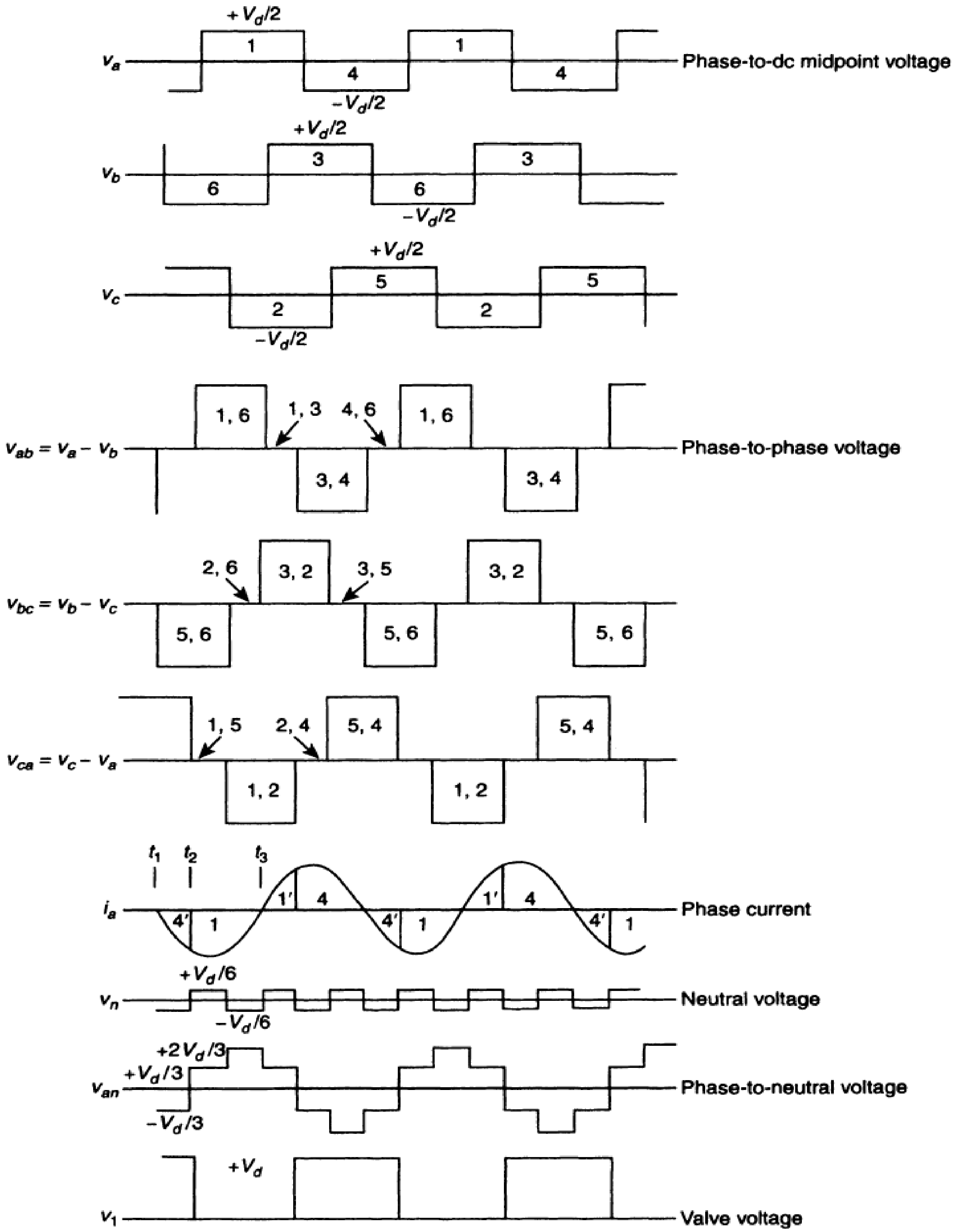


- Combined shunt and series Controllers inject current into the system with the shunt part of the Controller and voltage in series in the line with the series part of the Controller.
- When the shunt and series Controllers are unified, there can be a real power exchange between the series and shunt Controllers via the power link.



4.2 Operation of 6-pulse converter




$+V_d/2$
v_a
1
4
$-V_d/2$
Phase-to-dc midpoint voltage
v_b
3
6
v_c
5
2
$v_{ab} = v_a - v_b$
1, 6
1, 3
4, 6
3, 4
Phase-to-phase voltage
$v_{bc} = v_b - v_c$
2, 6
3, 2
3, 5
5, 6
$v_{ca} = v_c - v_a$
1, 5
2, 4
5, 4
1, 2
t_1
t_2
t_3
i_a
4'
1'
Phase current
$+V_d/6$
v_n
$-V_d/6$
Neutral voltage
$+2V_d/3$
$+V_d/3$
v_{an}
$-V_d/3$
Phase-to-neutral voltage
$+V_d$
v_1
Valve voltage

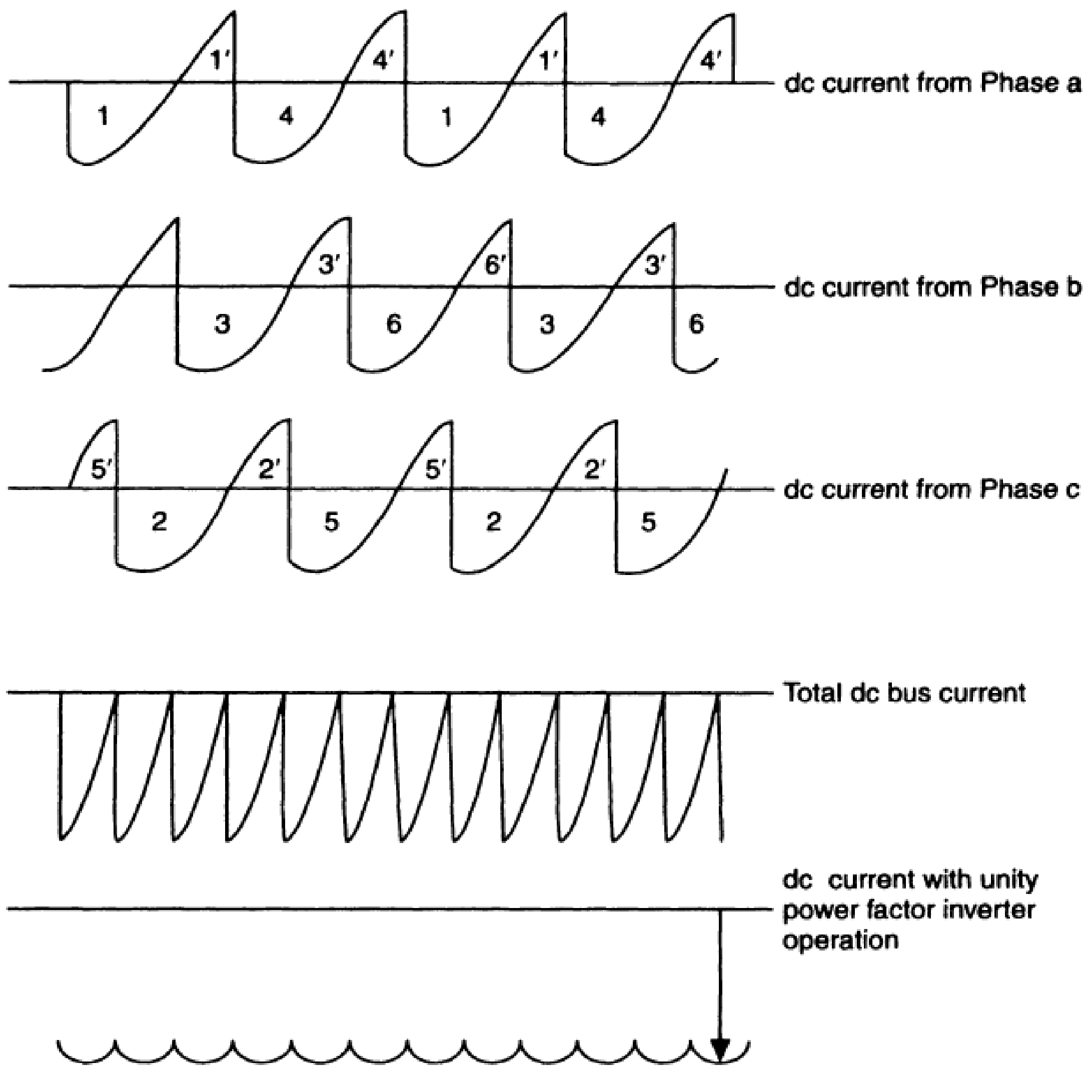


Fig a shows 3-Φ full wave bridge converter with 6 valves. The designated order of 1 to 6 represents sequence of valve conduction with time.

It consists of 3-Φ legs and operation 120^0 apart. The 3-Φ legs operates in square wave mode. The phase voltages of this supply designated as a V_A,V_B & V_C as shown in figure. These three square wave forms are the voltages of AC buses, A,B & C w.r.t hypothetical DC capacitor midpoint' N'.

The 3-Φ legs have their firing 120^0 apart w.r.t each other in a 6 pulse operation converter. Phase leg 3-6 switches 120^0 after phase leg 1-4 and 5-

2 switches 120^0 after phase leg 3-6. Thu completing the cycle as shown in figure.

Figure b shows phase to phase voltages V_{AB},V_{BC} & V_{CA} where $V_{AB} = V_A - V_B$, $V_{BC} = V_B - V_C$ & $V_{CA} = V_C - V_A$.

S.No	**Conducting Angle**	**Conducting Phase**	**Conducting Devices**
1	$0\text{-}60^0$	A	1& 6
2	$60^0\text{-}120^0$	A	1&2
3	$120^0\text{-}180^0$	B	3&2
4	$180^0\text{-}240^0$	B	3&4
5	$240^0\text{-}300^0$	C	5&4
6	$300^0\text{-}360^0$	C	5&6

4.3 TRANSFORMER CONNECTION FOR 12-PULSE OPERATION:

The harmonics content of the phase to phase voltage and phase to neutral voltage are 30º out of phase. If this phase shift is corrected, then the phase to neutral voltage (Van) other than that of the harmonics order $12n\pm1$ would be in phase opposition to those of the phase to phase voltage (Vab) and with $1/\sqrt{3}$ times the amplitude.

The arrangement shown below 5^{th},7^{th} 17^{th} & 19^{th} and so on harmonics voltages are cancelled out an two fundamental voltages are add up as shown in wave form the combine unit becomes 12 pulse converter.

The two converters can also connected in series on dc side for a 12 pulse converter of twice dc voltages as shown in fig c . increase in pulse number will decreases the harmonic content.

Note: for 12 pulse converter harmonics of order 6th ,18th and so on are cancelled out and only 12 pulse harmonics such as 12th ,24th and so on entire dc bus

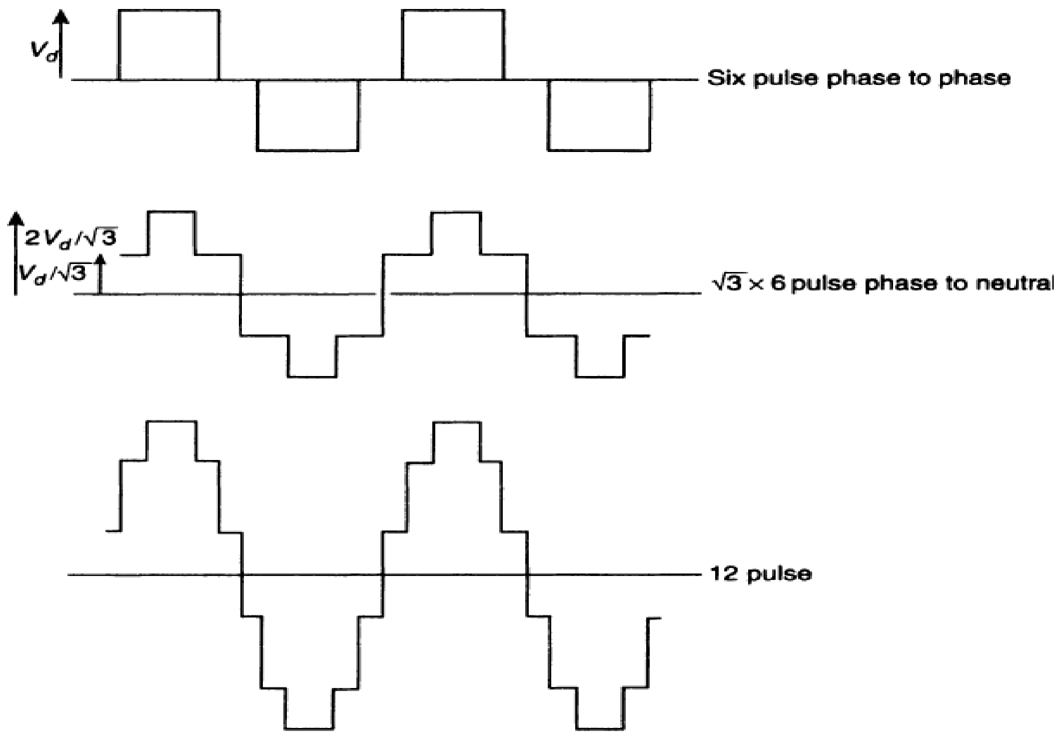


Fig: a) 12 pulse wave from two six pulse waveforms

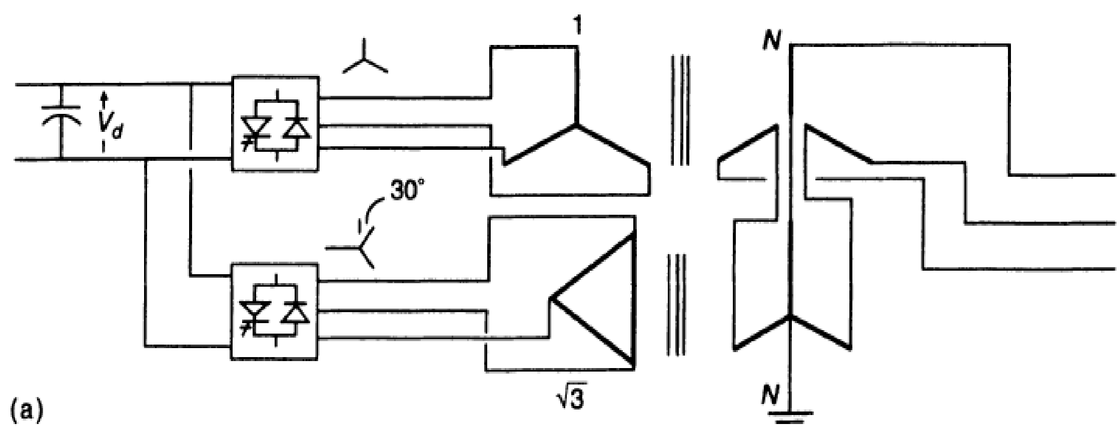


Fig: b) 12- pulse converter with wye and delta connected secondary's

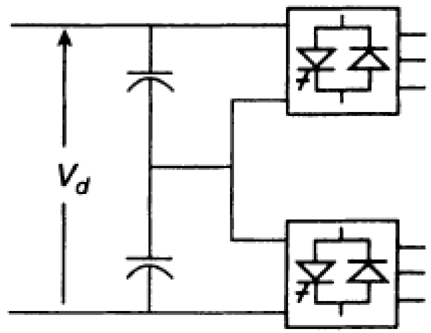


Fig: c) 12 pulse converter with two series connected six pulse convertes

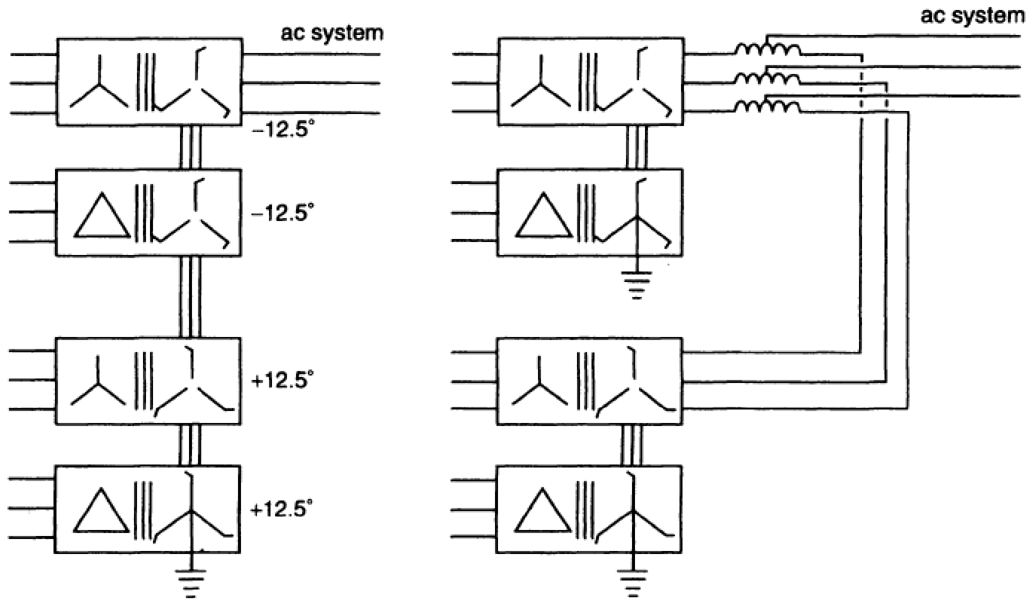
Fig (b): shows the two wave forms Van and Vab, adjusted for the transformer ratio and one of them phase displaced by 30º. These two wave forms are then added to give the third wave form, which is a 12-pulse wave form, closer to being a sine wave than each of the six-phase wave form.

In the arrangement of Fig (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 secondary 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 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: $In/ I1 = 100/ (XT * n^2)$ Percent Where I1 is the nominal fundamental current, n is the relevant harmonic number, and XT is the per unit transformer impedance of each transformer at the fundamental frequency. For example, if XT 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.

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

Two 12-pulse converters phase shifted by 15º from each other can provide a 24-pulse converter, with much lower harmonics on both A.C. and D.C. sides. It"s A.C. out put voltage would have 24n±1 order of harmonics i.e. 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 15º phase shift windings on the two transformers of one of the two 12-pulse converters. Another approach is to provide phase shift windings for (+7.5º) phase shift on the two transformers of one 12-pulse converter and (-7.5º) on the two transformers of the other 12-pulse converter, as shown in Fig2.6 (a), the later 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 secondary, and the other two with delta-connected secondary.



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 worthwhile 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.

4.5 Methods of controllable VAR generators

There are two basic types of VAR generator as they listed as follows

1. **Variable impedance type VAR generators**

   Examples: TCR, TSR, TSC, FC- TCR and SVC

2. **Variable voltage or current source type VAR generators**

   Examples: STATCOM

1. TCR(Thyristor controlled reactor):

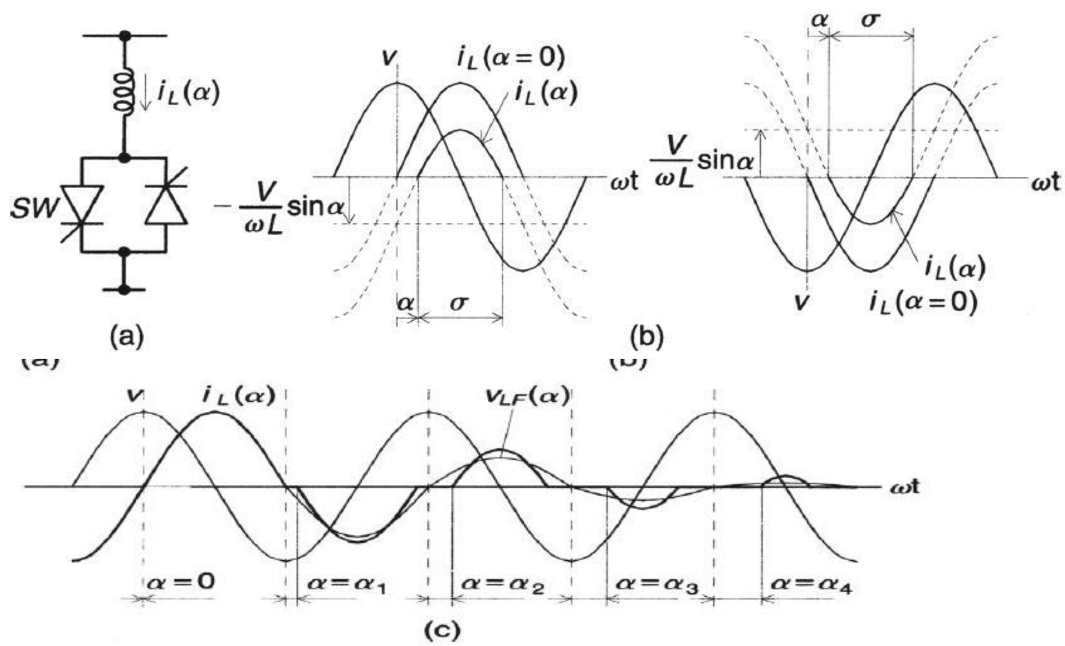


Figure: a) Basic thyristor controlled reactor b) firing angle delay control c) operating waveforms

Description: An elementary single phase thyristor controlled reactors as shown figure, it consists of fixed (usually air cored) reactor of inductance L and bidirectional valve or switch SW. Currently available thyristors block voltage up to 4000volts to 9000volts and conduct current up to 3000ampers to 6000 amperes. In practical valve many thyristors, usually 10 to 20 thyristors are connected in series to meet the required voltage blocking voltage levels at a given power rating.

Operation:

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 dosed) 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 fur the positive and negative current half cycles in fig. (b). Where applied voltage u and the reactor current $i_L(\alpha)$ at zero delay angle and at arbitrary a 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 $\alpha(0 \leq \alpha \leq 90^0)$ with respect to the crest of the voltage, The current in the reactor can be expressed with u(t)= V cos ωt as follows:

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

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

In practice, the maximum magnitude of the applied voltage and that of the corresponding current will be limited by the rating s 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.

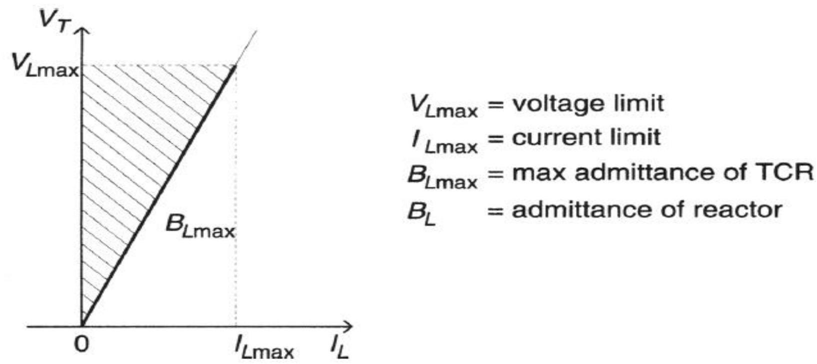


Figure: Operating V-I characteristics of TCR

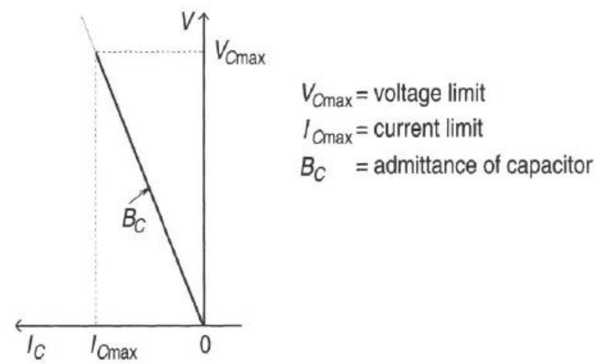
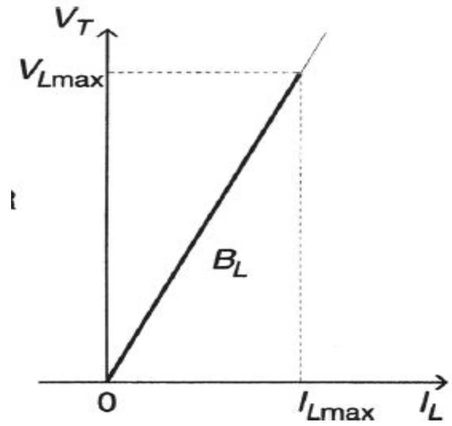


Figure: Operating V-I characteristics of TSC

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 b e employed, which would increase in a step-like manner the capacitive admittance.

2. Thyristor Switched Reactor (TSR):

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 reacti ve current in it will be proportional to the applied voltage as shown in fig.



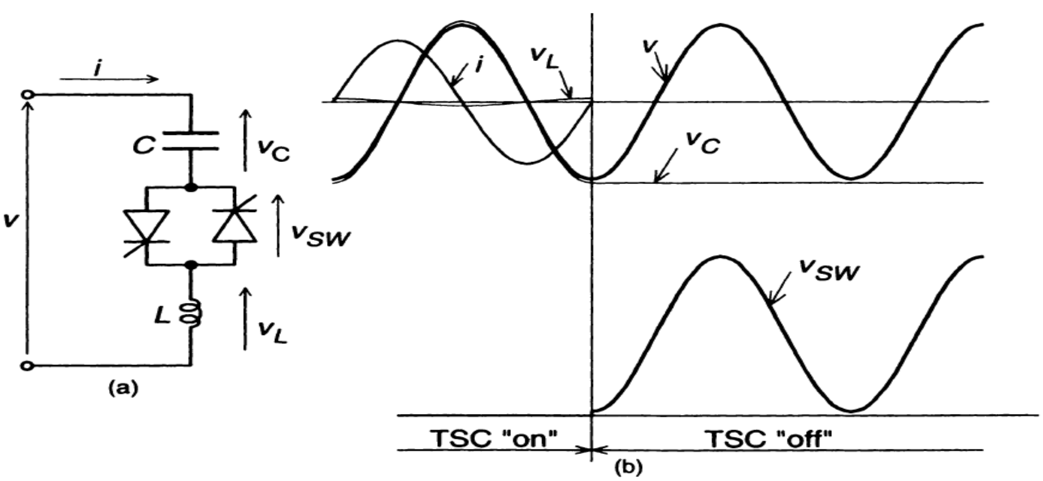
3.

4. **Figure: Operating V-I characteristics of TSR**

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

3. **Thyristor Switched Capacitor (TSC):**

A 1-Φ Thyristor Switched Capacitor is shown in figure



It consists of a capacitor, a bi-directional thyristors valve, and a relatively small surge current limiting reactor. This reactor is needed primarily a) To limit the surge current in the thyristors valve under abnormal operating conditions b) 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=V sin ωt, the current in the branch is given by

$$i(\omega t) = V \frac{n^2}{n^2 - 1} \omega C \cos \omega t$$ Where $$n = \frac{1}{\sqrt{\omega^2 LC}} = \sqrt{\frac{X_C}{X_L}}$$

The amplitude of voltage across capacitor is given as

$$V_C = \frac{n^2}{n^2 - 1} V$$

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 A.C system The current in the TSC branch varies linearly with the applied voltage according to the admittance of the capacitor as illustrate d by the V-I plot in the following fig.

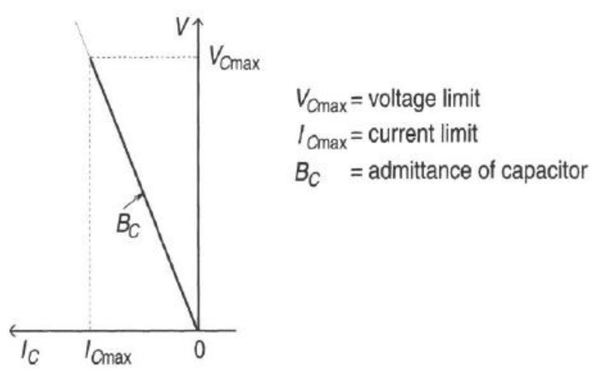


Figure: Operating V-I characteristics of TSC

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 b e employed, which would increase in a step-like manner the capacitive admittance.

4. Fixed Capacitor- Thyristor Controlled Reactor (FC-TCR): A basic VAR generator arrangement using fixed capacitor with a thyristor controlled reactor is shown in figure. The current in the reactor is varied by the method of firing angle delay control. The fixed capacitor usually substituted in practice fully or partially by filter network that it has the necessary capacitive impedance at the fundamental frequency to generate required reactive power.

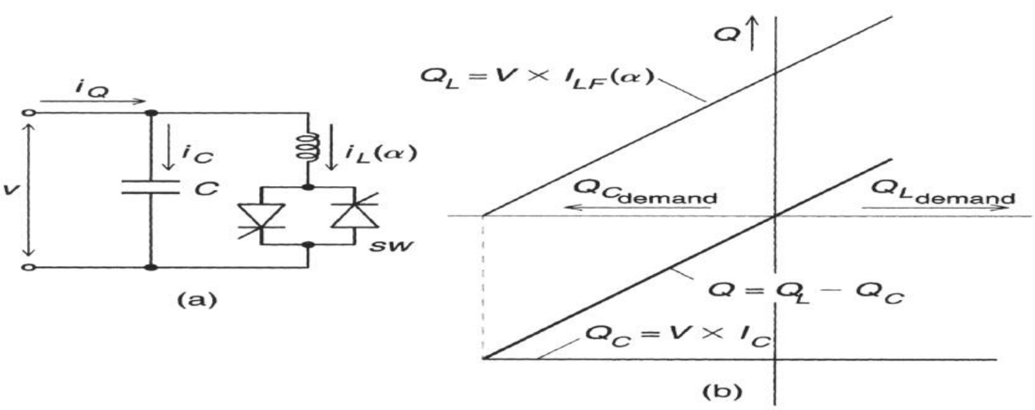


Figure: a) Basic FC-TCR b) VAR demand versus VAR output characteristics

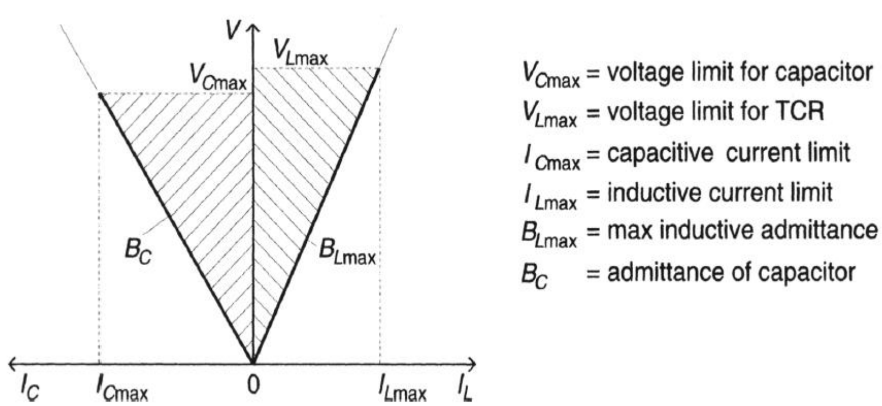


Figure: Operating V-I characteristics of FC-TCR

5.Static VAR Compensator (SVC):

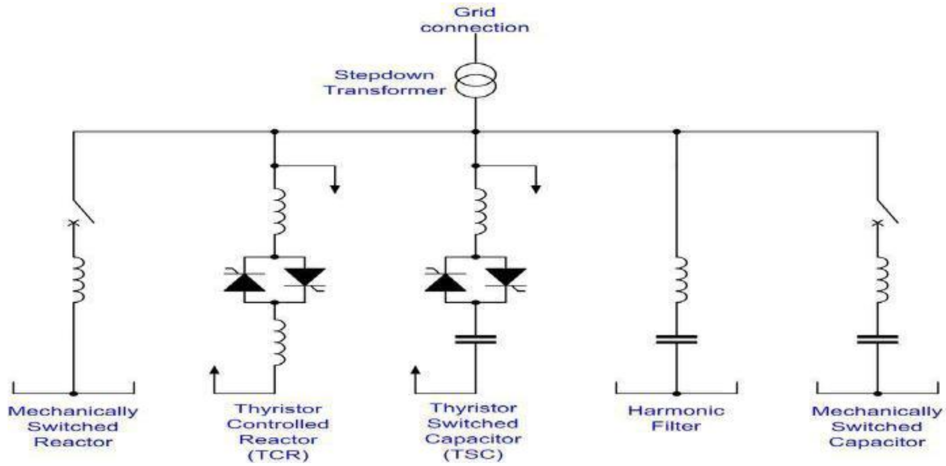
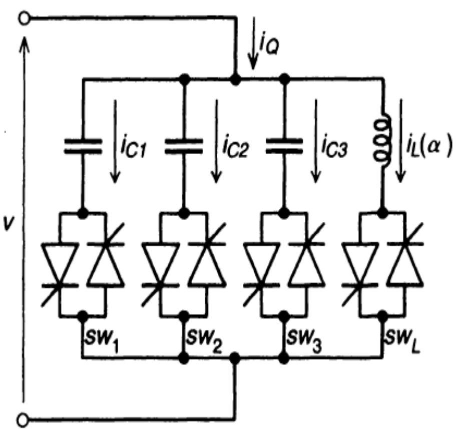


Figure: Basic Structure of SVC



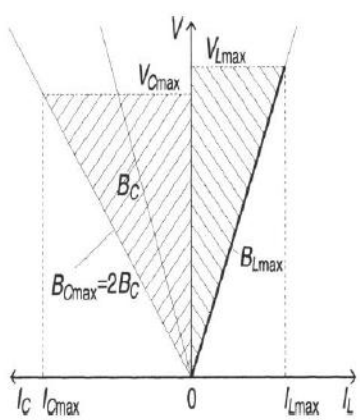


Figure: Advanced Structure of SVC **Figure: A Operating V-I characteristics of SVC**

Static VAR generators: In general it is not possible to control or regulate real power in the transmission system directly and hence we are preferring the control of reactive power by using the VAR generators, There are basically two types of VAR generators such as 1. SVC 2. STATCOM.

An SVC consists of mechanically switched reactor, TCR ,harmonic filter, mechanically switched capacitors and n numbers of TSC's. SVC is used in a power system to increase the power transmission capacity with given network.

Basic Operation

The static var compensator regulates the voltage by controlling the amount of reactive power absorbed from or injected into the power system. For example, it generates reactive power by switching capacitor banks when the system voltage is low or loads are inductive. Consequently, the reactive power demand of the lagging load is supplied by the SVC – relieving the distributing lines from delivering it. Thus, the voltage drop decreases and the voltage at the load terminals shall improve.

Likewise, the static var compensator absorbs reactive power when the system voltage is high or loads are capacitive. In this case, the SVC uses the reactors to consume the VARs from the system, thereby lowering the system voltage.

From the operating V-I characteristics of SVC we can say the with the operation of TCR we can obtain controllable inductive reactances as represented in first quadrant, similarly with the operation TSC we can obtain controllable capacitive reactances as represented in second quadrant

Applications and Benefits

Static VAR compensators are primarily used to mitigate voltage fluctuations, as well as the resulting flicker since the 1970s. Nowadays, large industries, particularly the steel-making plants typically apply SVCs for flicker compensation in electric arc furnace installations.

In addition, static var compensators are installed at suitable points in the electric power system to augment its transfer capability by improving voltage stability, while keeping a smooth voltage profile under different system conditions. SVCs can also mitigate active power oscillations through voltage amplitude modulation. Moreover, as an automated impedance matching device, they have the added benefit of bringing the system power factor close to unity.

Furthermore, other benefits of static var compensators include:

- Maximized power compensation
- Near-instantaneous response to system voltage variations
- Increased customer's economic benefits
- Eliminate harmonics and reduce voltage distortion with appropriate shunt filters
- Load balancing on three-phase systems

STATCOM: it stands for Static Synchronous Compensator or Static Synchronous condenser(STATCON) It is basically regulating device use in A.C transmission system to control the reactive and it is also a voltage converter. STATCOM is an example for switching converter type FACT devices and it not a variable impedance type FACT device.The main function of STATCOM is to generate 3-Φ voltages with controllable magnitude and phase angles.

In general STATCOM can be implemented with the help of 6-pulse voltage source converter which consists of GTO's. Based on the principle of operation 3-Φ voltage source converter it will act as a both rectifier as well as inverter, if the generated voltages at the 3-Φ converter will be more than the bus bar voltage then converter will operates in leading conditions i.e it will acts as a TSC and corresponding V-I characteristics are represented in second quadrant as represented in V-I characteristics as shown in figure during this period voltage is positive and current is negative.

Similarly if the generated voltages at the 3-Φ converter will be less than the bus bar voltage then converter will operates in lagging conditions i.e it will acts as a TCR and corresponding V-I characteristics are represented in first quadrant as represented in V-I characteristics as shown in figure during this period both voltage and current is positive .

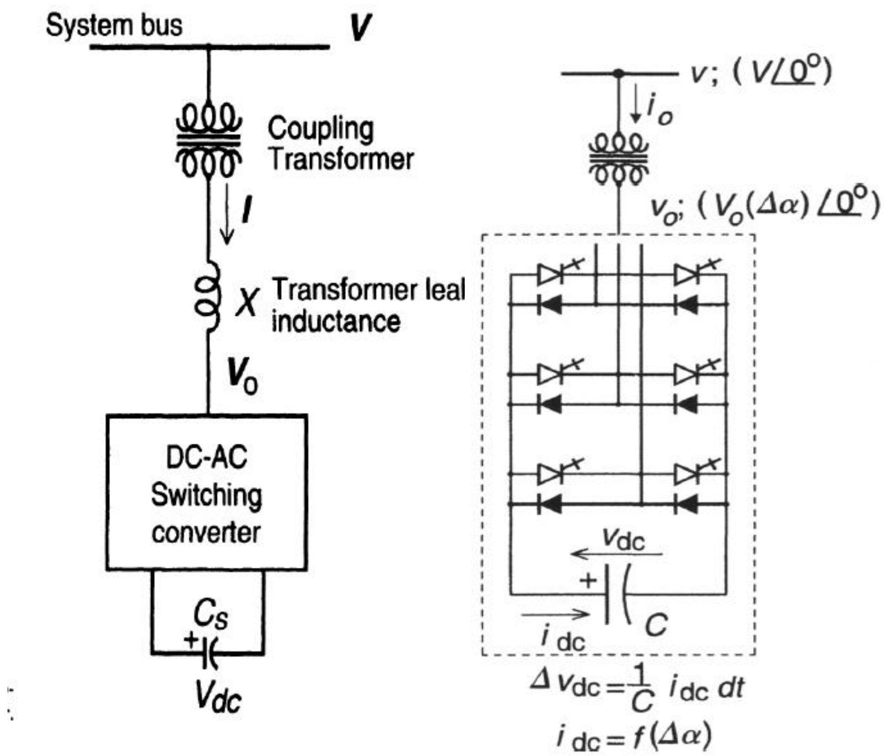
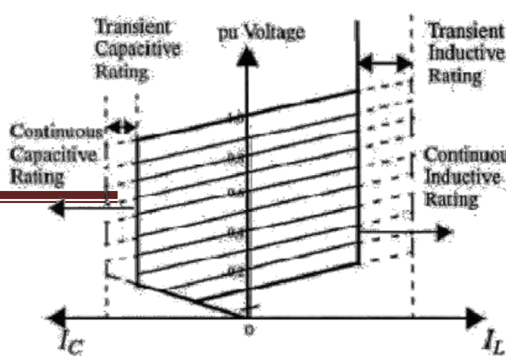


Figure: a) Conventional Representation of STATCOM b) GTO based STATCOM



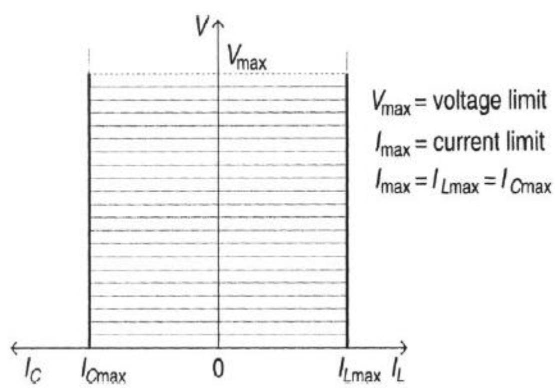


Figure: Operating V-I characteristics of STATCOM

Note: As compared to SVC, STATCOM has better voltage profile and hence better power transfer capability.

Design

A STATCOM is composed of the following components:

A. Voltage-Source Converter (VSC)

The voltage-source converter transforms the DC input voltage to an AC output voltage. Two of the most common VSC types are described below.

1. Square-wave Inverters using Gate Turn-Off Thyristors

Generally, four three-level inverters are utilized to make a 48-step voltage waveform. Subsequently, it controls reactive power flow by changing the DC capacitor input voltage, simply because the fundamental component of the converter output voltage is proportional to the DC voltage.

2. PWM Inverters using Insulated Gate Bipolar Transistors (IGBT)

It uses Pulse-Width Modulation (PWM) technique to create a sinusoidal waveform from a DC voltage source with a typical chopping frequency of a few kHz. In contrast to the GTO-based type, the IGBT-based VSC utilizes a fixed DC voltage and varies its output AC voltage by changing the modulation index of the PWM modulator.

B. DC Capacitor

This component provides the DC voltage for the inverter.

C. Inductive Reactance (X)

It connects the inverter output to the power system. This is usually the leakage inductance of a coupling transformer.

D. Harmonic Filters

Mitigate harmonics and other high frequency components due to the inverters.

STATCOM Operation

Basic Principle of Operation

In the case of two AC sources, which have the same frequency and are connected through a series reactance, the power flows will be:

- Active or Real Power flows from the leading source to the lagging source.
- Reactive Power flows from the higher to the lower voltage magnitude source.

Consequently, the phase angle difference between the sources decides the active power flow, while the voltage magnitude difference between the sources determines the reactive power flow. Based on this principle, a STATCOM can be used to regulate the reactive power flow by changing the output voltage of the voltage-source converter with respect to the system voltage

Applications

STATCOMs are typically applied in long distance transmission systems, power substations and heavy industries where voltage stability is the primary concern.

In addition, static synchronous compensators are installed in select points in the power system to perform the following:

- Voltage support and control
- Voltage fluctuation and flicker mitigation
- Unsymmetrical load balancing
- Power factor correction
- Active harmonics cancellation
- Improve transient stability of the power system

STATCOM versus SVC

The STATCOM has the ability to provide more capacitive reactive power during faults, or when the system voltage drops abnormally,

S.No	SVC	STATCOM
1.	It act as a variable impedance type VAR generator	It act as a voltage source type VAR generator
2.	Sensitive to transmission system harmonic resonance	Insensitive to transmission system harmonic resonance
3.	Has a smaller dynamic voltage	Has a larger dynamic range
4.	Higher generation of harmonics	Lower generation of harmonics

compared to ordinary static var compensator. This is because the maximum capacitive reactive power generated by a STATCOM decreases linearly with system voltage, while that of the SVC is proportional to the square of the voltage.

5.	Somewhat slower response	Faster response and better performance during transients
6.	Mostly capacitive region of operation	Both inductive and capacitive regions of operation is possible
7.	Has difficulty operating with a very weak A.C. system	Can maintain a stable voltage even with a very weak A.C. system
8.	Cost is moderate	Cost is low

4.6 VARIABLE IMPEDANCE TYPE SERIES COMPENSATORS

Variable impedance type series compensators are composed of thyristor-switched/controlled capacitors or thyristor-controlled reactors with capacitors.

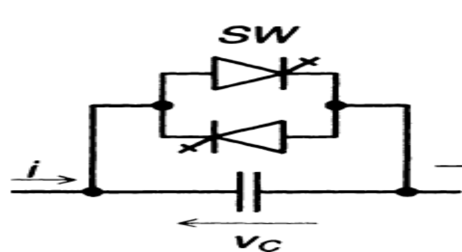
(i) GTO Thyristor –Controlled Series Capacitor(GCSC)

(ii) Thyristor –Switched Series Capacitor (TSSC)

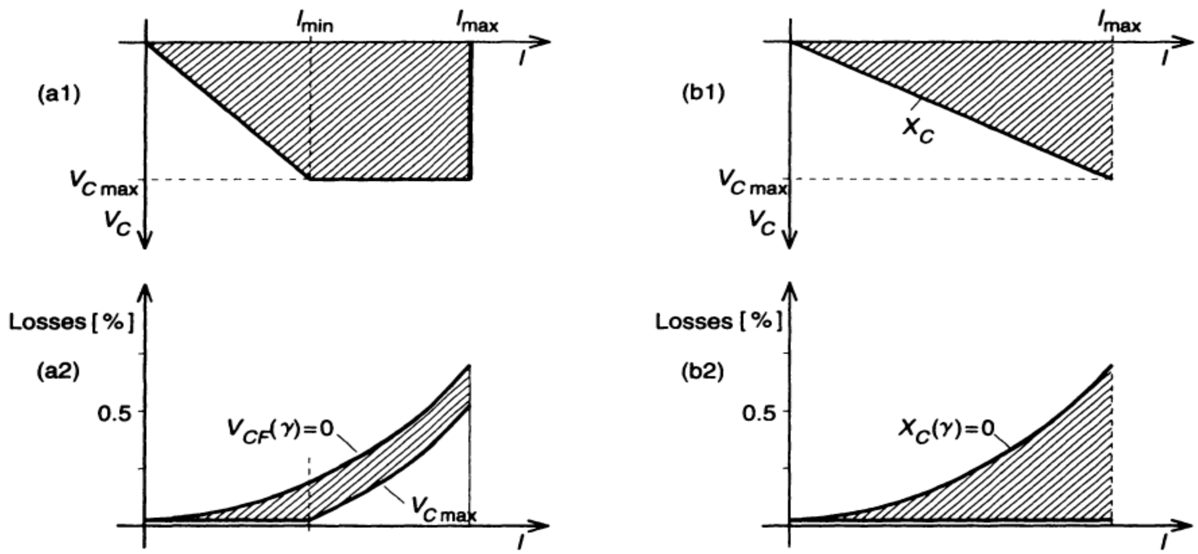
(iii)Thyristor Controlled Series Capacitor (TCSC)

1. GTO Thyristor Controlled Series Capacitor (GCSC)

A GCSC consists of a fixed capacitor in parallel with a GTO Thyristor as in figure which 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.



Attainable *V-I* (compensating voltage vs. line current) characteristics of the GCSC when operated in voltage control (a1) and reactance control (b1) modes, and the associated loss vs. line current characteristics (a2 and b2, respectively).

2. Thyristor Switched Series Capacitor (TSSC)

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

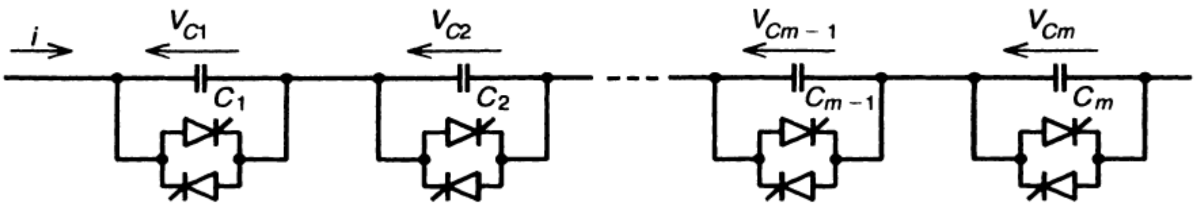


Figure: Basic Thyristor Switched Series Capacitor Scheme

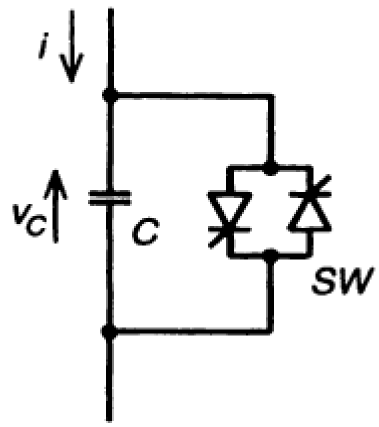
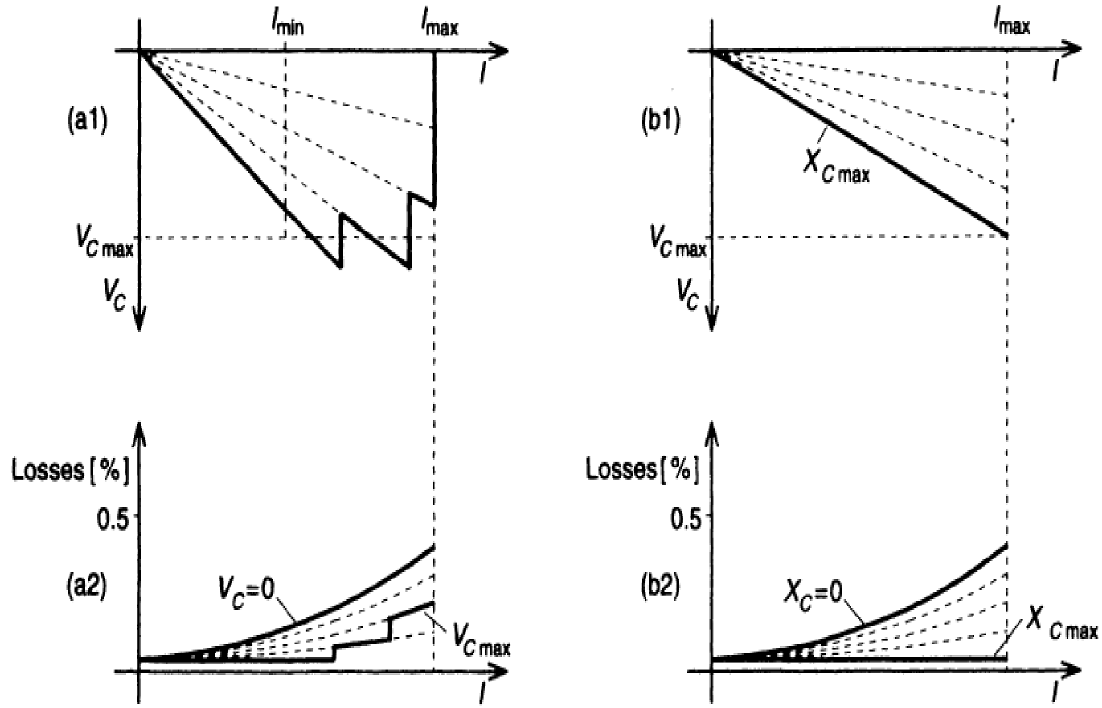


Figure: Thyristor Switched Series Capacitor

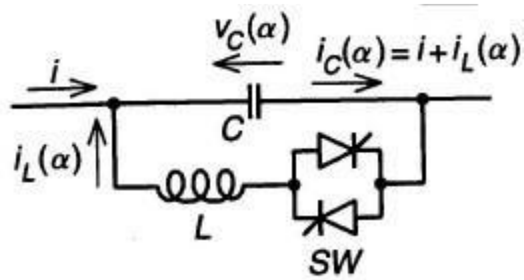
In TSSC, the amount of series compensation is controlled in a step- like manner by increasing or decreasing the number of series capacitors inserted into the line. The thyristor turns off when the line current crosses the zero point. As a result, capacitors can only be inserted or deleted from the string 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.



Attainable *V-I* (compensating voltage vs. line current) characteristics of the TSSC when operated in voltage control (a1) and reactance control (b1) modes, and the associated loss vs. line current characteristics (a2 and b2, respectively).

3. Thyristor Controlled Series Capacitor (TCSC): It consists of series compensating capacitor shunted by a Thyristor controlled reactor as shown in fig.

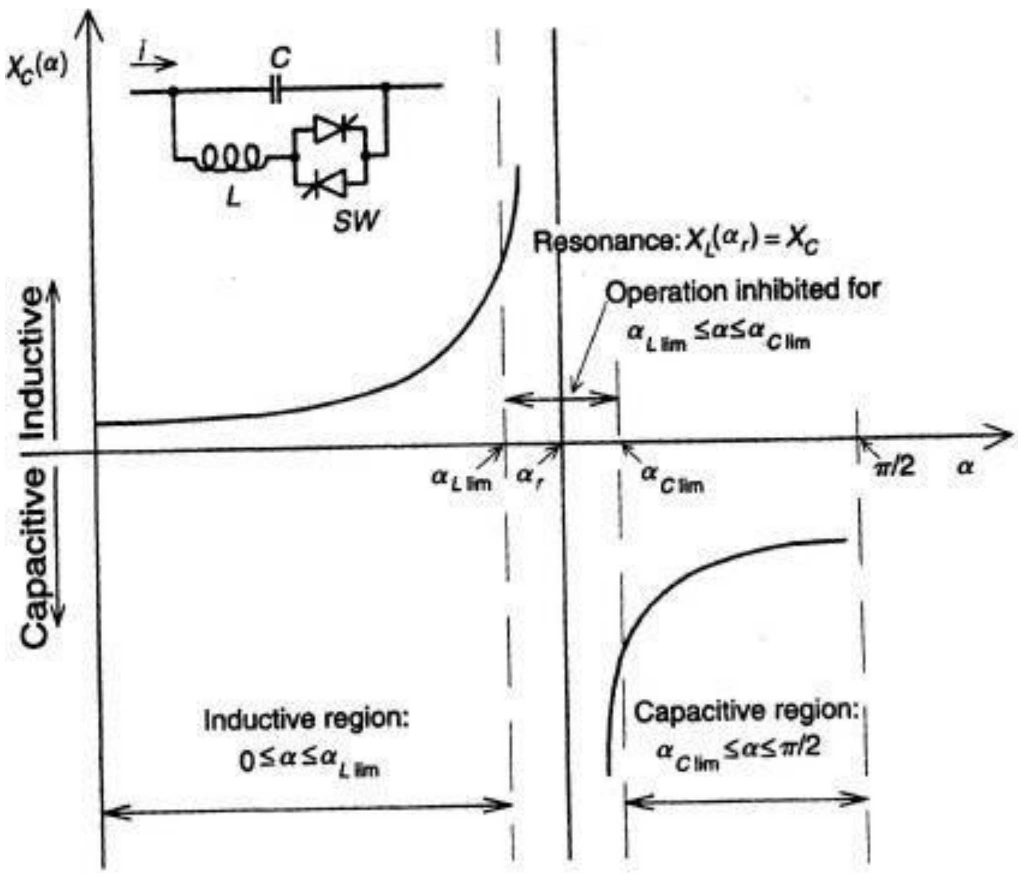


TCSC is connected in series with the line and allows changing of impedance of transmission path and thus affecting the power flows. With the help of TCSC, control is fast and efficient.

Change of impedance of TCSC is achieved by changing thyristor controlled inductive reactance of inductors connected in parallel to the capacitor. The magnitude of inductive reactance is determined by angle(ɑ) of switching thyristor. The magnitude of current through reactor changes from maximum to zero by switching thyristors.

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 $a_{Clim} \le a \le n/2$, where the TCSC is in capacitive mode. The other range of operation is $0 \le a \le a_{Llim}$, where the TCSC is in inductive mode. TCSC can be operated in impedance compensation mode or voltage compensation mode.

Fig. shows impedance Vs. delay angle (ɑ) characteristic of the TCSC.



Under normal operating conditions, TCSC can operate in modes of operation namely, blocked mode, bypass mode, capacitive and inductive mode.

4.7 SWITCHING CONVERTER TYPE SERIES COMPENSATORS

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.

The static Synchronous Series Compensator (SSSC) will fall into switching converter type series compensator. 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 90º.

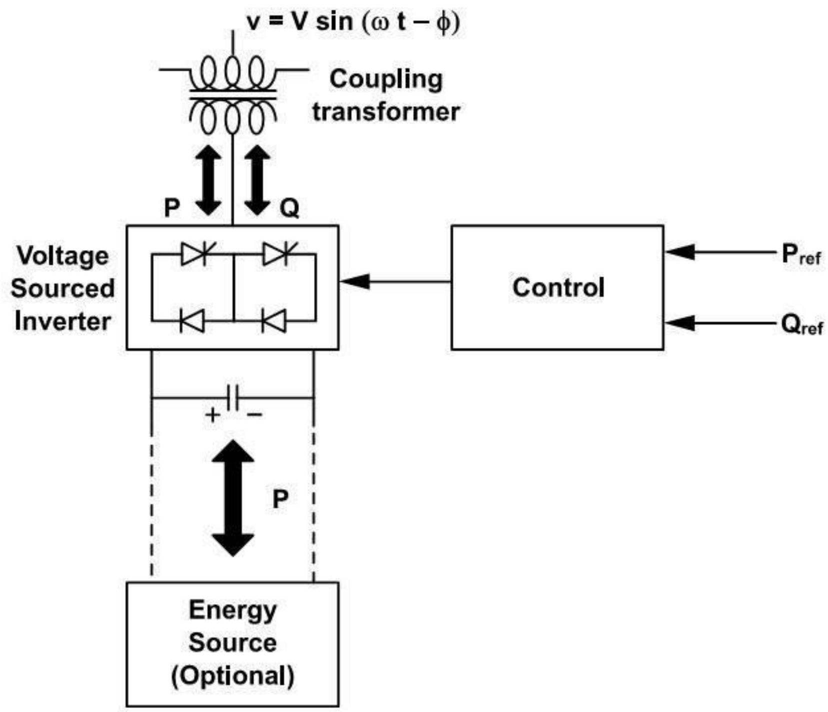


Figure: Schematic diagram of SSSC

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 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.

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.

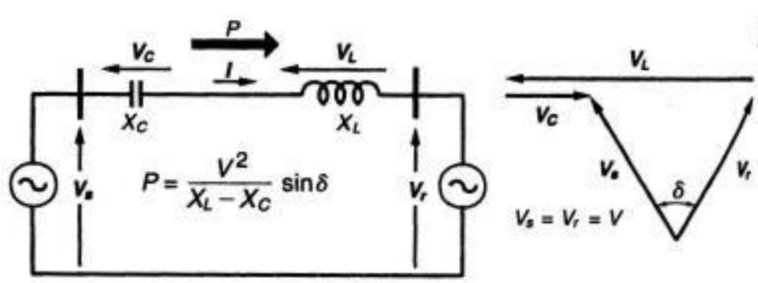


Figure : Simplified diagram of series compensation with the Phasor diagram.

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 (4.1) and the transmitted power verses transmitted angle as a function of the degree of series compensation is shown in Figure.

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

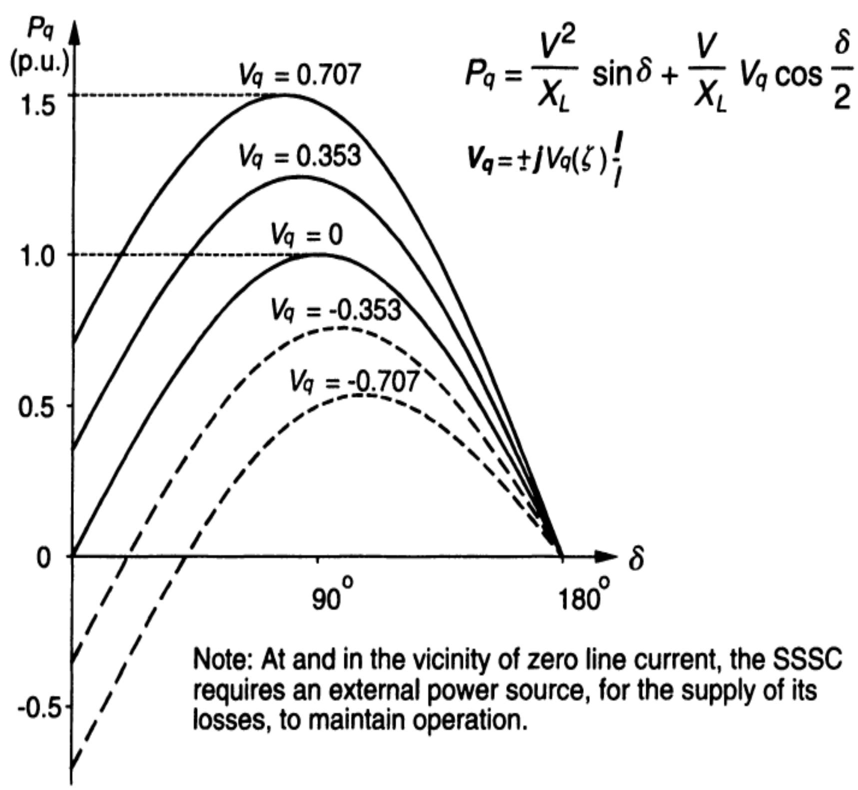


Figure : Transmitted power verses transmitted angle as a function of series compensation

Fig. shows relation between normalized power P versus δ plots of a series capacitor compensated two- machine system as a parametric function of the degree of series compensation.

Comparison of corresponding plots that the series capacitor increases the transmitted power by a fixed percentage of that transmitted by the uncompensated line at a given δ and by contract SSSC can increase by a fixed fraction of the maximum power transmittable by the uncompensated line, independent of δ in the range of $0 \le \delta \le 90$.

Part A-2 Marks Questions and Answers

1. **What is the necessity of compensation?**

The reactive power through the system can significantly improve the performance / parameters of the power system as follows

Voltage profile

Power angle characteristics

Stability margin

Damping to power oscillations

2. What are the objectives of line compensation?

To increase the power transmission capacity of the line

To keep the voltage profile of the line along its length within acceptable bounds to ensure the quality of supply to the connected customer as well as to minimize the line insulation costs.

3. Explain the objectives of FACTS controllers in the power system network.

Better the control of power flow (Real and Reactive) in transmission lines.

Limits SC current

Increase the load ability of the system

Increase dynamic and transient stability of power system

Load compensation

Power quality improvement

4. **Define the term Static VAR compensator.**

The SVC is a shunt device of FACTS group using power electronics to control power flow and improve transient stability on power grids. The SVC regulates voltage at its terminals by controlling the amount of reactive power injected into or absorbed from the power system.

5. Define the term FACTS.

Flexible AC Transmission System

Alternating current transmission system incorporating power electronics based and other static controllers to enhance controllability and increase power transfer capability.

10 Marks questions

1. What are the basic types of FACTS controllers? Explain each one in detail.

2. (a) What are the objectives of shunt compensation?

   (b) Explain the control scheme and characteristics of Static VAR generators, SVC and STATCOM, for the control of terminal voltage in proportion to their line current.

3.(a) Explain the midpoint voltage regulation for line segmentation of shunt compensator.

   (b) Explain the working principle and V-I characteristics of STATCOM.

4. With a neat sketch, explain working of STATCOM with its characteristics.

5. With a neat sketch, explain working of SVC with its characteristics.

UNIT-V

FLEXIBLE AC TRANSMISSION SYSTEMS-II

Syllabus:

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

---

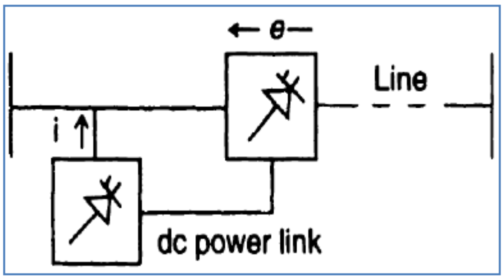
Introduction: In the previous discussion, separate shunt and series controllers are acted individually to control the one of the three line parameters (Voltage, Impedance and angle) with control the power transfer in line. Any controller capability lies in generating reactive power and exchange real power.

Controllers such as SVC, TCSC using reactive elements with conventional thyristors unable to exchange real power with ac system (ignore losses) and only provides reactive power compensation.

STATCOM and SSSC implemented by voltage source converter operated as synchronous voltage source provide voltage control and power flow control respectively.

Combined series-shunt Controllers:

In Principle combines shunt and series controllers inject current into the system with shunt part of the controller and voltage in series with line with the series part of the controller. When the shunt and series controllers are unified(Connected back to back) there can be real power exchange between the series and shunt controllers via dc power link. Such controller is called Unified Power Flow Controller(UPFC).



Operating Principle of UPFC:

UPFC is one of the FACTS devices that uses power semiconductor switches, which can control simultaneously or selectively all the parameters such as terminal voltage, line impedance , phase angle which determines the power transfer. This unique quality has given the name as **'UNIFIED'.**

UPFC consists of a series compensator (SSSC) and shunt compensator(STATCOM) coupled via common dc-link . So the UPFC uses two voltage source Converters sharing a common dc storage capacitor and connected to the power system through coupling transformer.

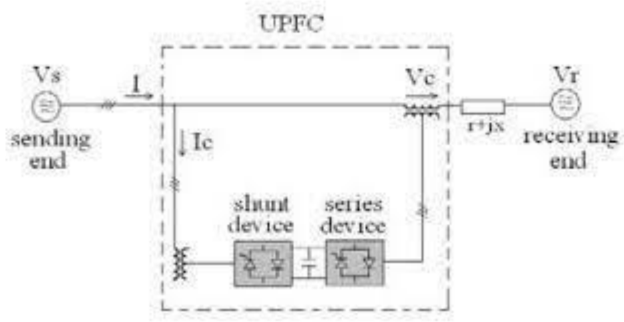


Figure: Basic functional Scheme of UPFC

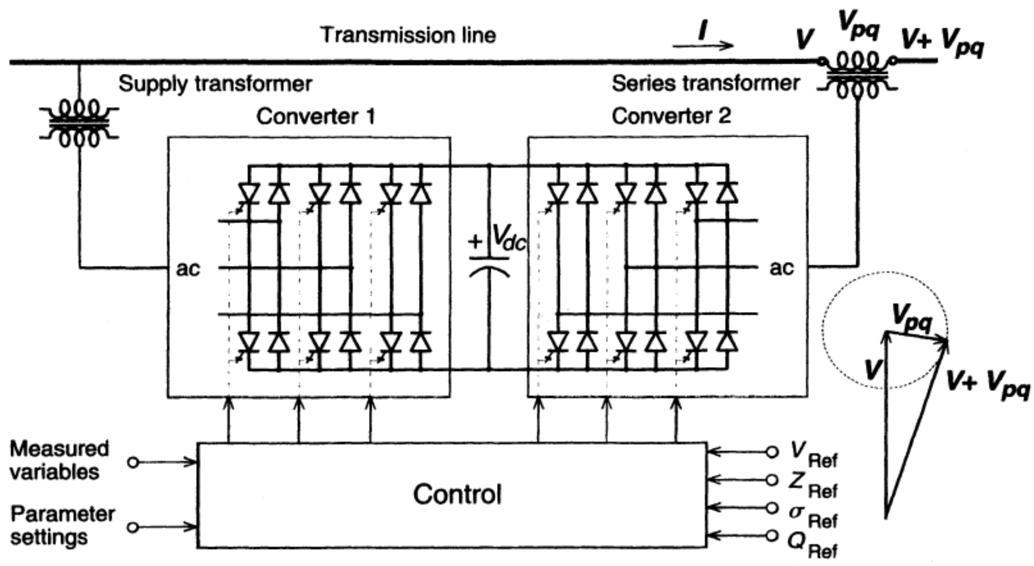


Figure: Implementation of the UPFC by two back-to-back voltage-sourced converters.

The series compensator injects a symmetrical three phase voltage system of controllable magnitude and phase angle in series with the line to control active and reactive power flown on the transmission line. On the other hand, shunt controller is used to supply reactive power required for the power system network, as well as to regulate the DC voltage.

On the other hand the shunt controller also draws active power from the system and transmitted to the dc terminals, thereby through series controller back to the system.

In general reactive power compensation is provided by each controller individually and active power can be transmitted in either direction.

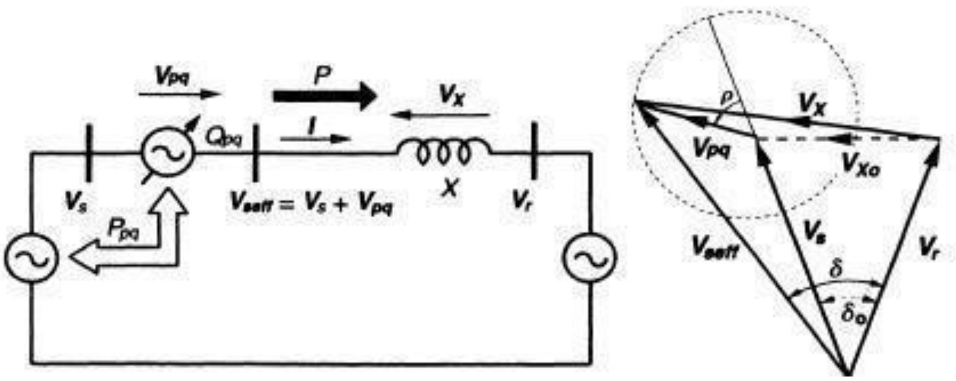


Fig: Conceptual representation of UPFC in two machine model system

In the two bus elementary circuit as shown above , the UPFC is represented as synchronous ac voltage source(SVS) at system frequency by Phasor ‘Vpq’ with controllable magnitude Vpq and angle in series with the line.

SVS exchanges both active and reactive with transmission system. Active power exchange is provided by one of the bus. Active power flows through dc power line either direction.

Applications:

1. Control of power flow 2. Reactive Power compensation 3. Power oscillation damping 4. Improve power system stability.

Independent Real and Reactive Power Flow Control

The figure below show the single phase elementary two bus system with injection of voltage Phasor 'Vpq'

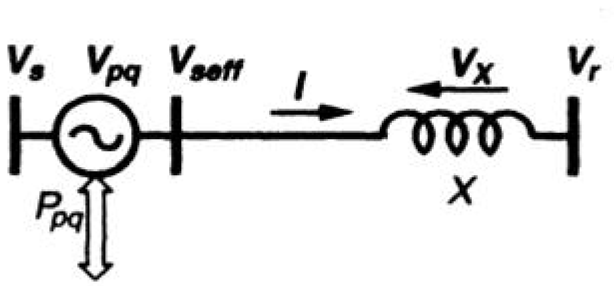


Fig: Elementary two bus system.

With 'Vpq=0'

In order to investigate the capability of the UPFC to control real and reactive power flow in the transmission line Let it first be assumed that the injected voltage Vpq = 0 . With this the system becomes elementary two bus system with all parameters is restored to original as shown below. The normalized active power and reactive power flows describe a circle of centre(0,-1) and radius 1.0 and in the Qr-P plane.

$$P_0(\delta) = \{V^2/X\} \sin \delta = \sin \delta,$$

$$Q_0(\delta) = Q_{0s}(\delta) = -Q_{0r}(\delta) = \{V^2/X\}\{1-\cos \delta\} = 1-\cos \delta,$$

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

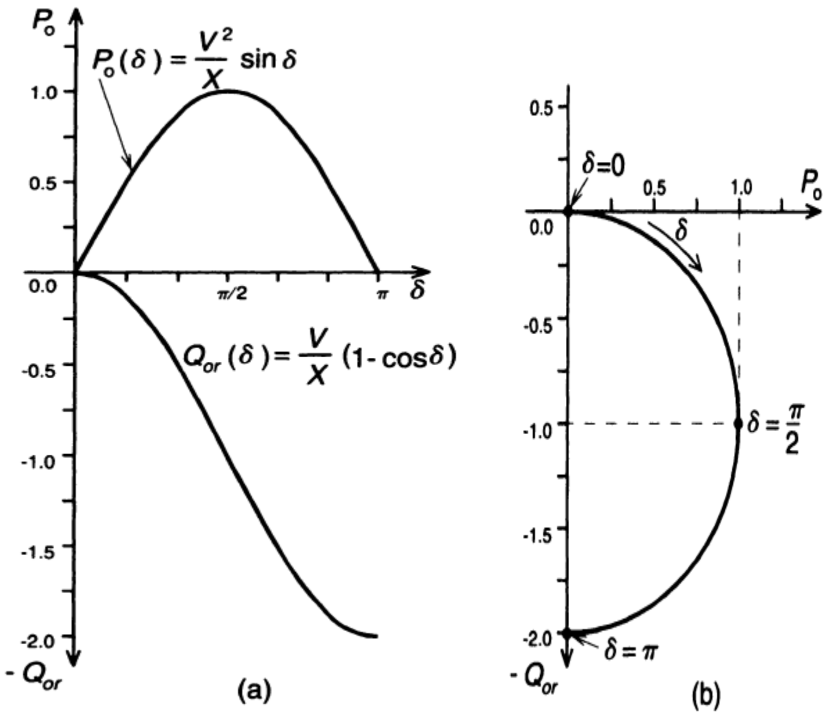


Fig: a) Transmittable real power *Po*and receiving-end reactive power dem and *Qor* vs. transmission angle of a two-machine system

b) the corresponding *Qor* vs. *Po* loci

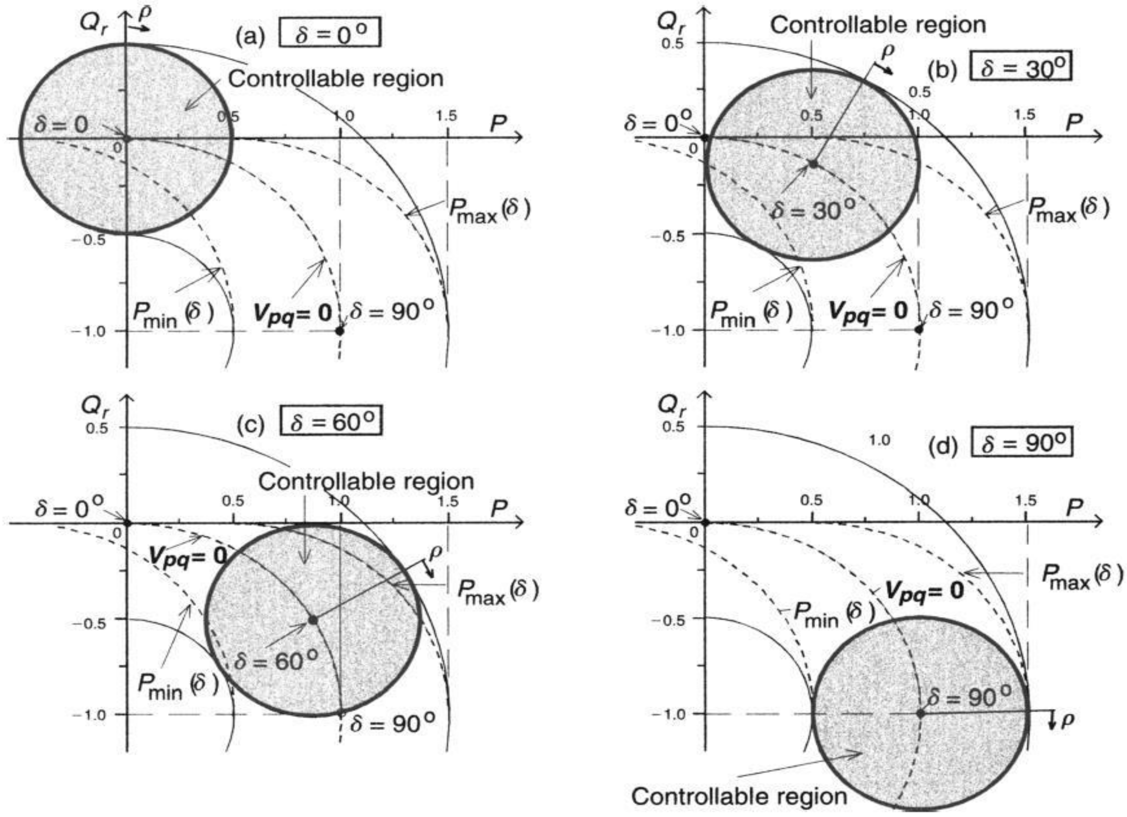
With 'Vpq#0'

Now the active and reactive power are the functions of Vpq magnitude $(0 \leq \rho \leq 2\pi)$ and phase angle δ. the boundary of the controllable region is obtained by complete rotation of Phasor Vpq with its max value around 2π radians. The region becomes circular with centre and radius as per the equation shown below

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

The control regions are shown for specified values of V= 1.0 pu Vpq(max) = 0.5 pu, X= 1.0 pu with various δ angles as shown below.

The area within the circles define all P&Q values obtainable by controlling magnitude Vpq and ' p' of the Phasor Vpq that can be obtained with given UPFC. In general at any angle of 'δ' , P & Q can be controlled independently within boundary



Control Structure of UPFC:

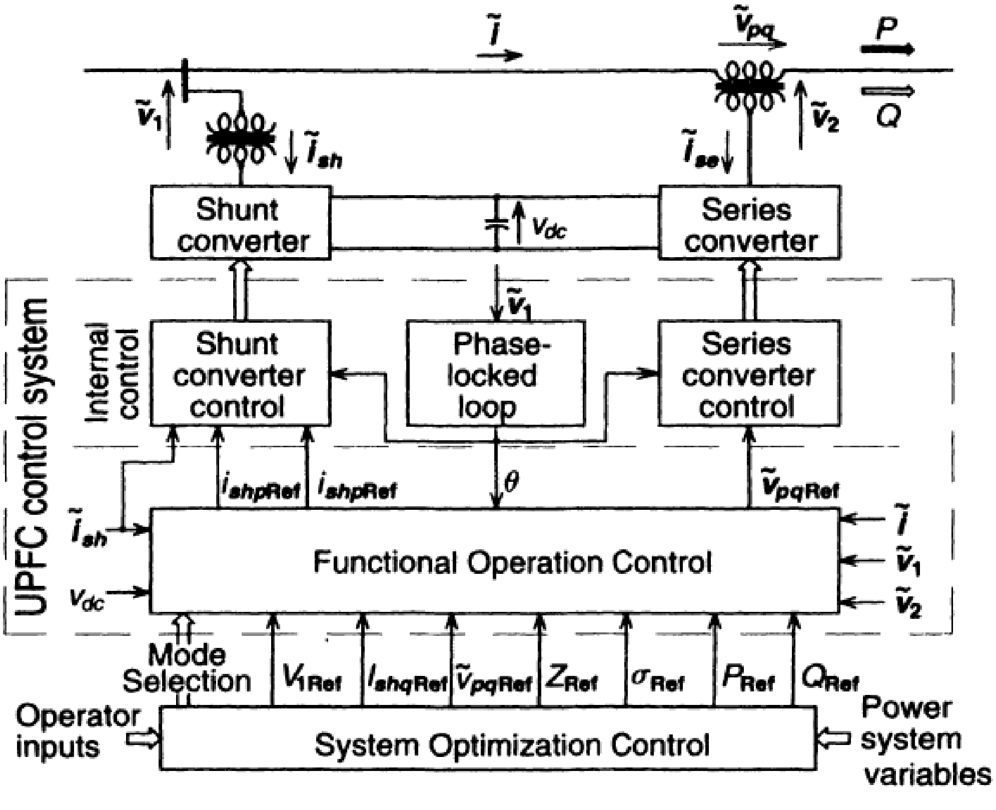


Figure: Overall UPFC control structure

The injected voltage Phasor with arbitrary magnitude and phase angle in series with line as a vector that represents a set of 3 instantaneous phase voltages, currents By suitable electronic controls, UPFC can cause the series injected voltage vector to vary continuous with magnitude and phase angles as desired.

Thus it provides a suitable operating point within possible P & Q on the line. The vectors v, i can move around a fixed point in the plane that makes circle loci.

The controls scheme is divided into two parts.

1. Internal Control Scheme (converter control) :

1.It operates the two converters so as to produce the desired series injected voltage and also to draw the desired shunt reactive current.

2. Internal control provides the gating signals to converter valves. So that converter output voltages are produced as per internal reference signals ip(ref), iq(ref) Vpq(ref).

3. series converter works directly and independently as per the demand to inject voltage in series.

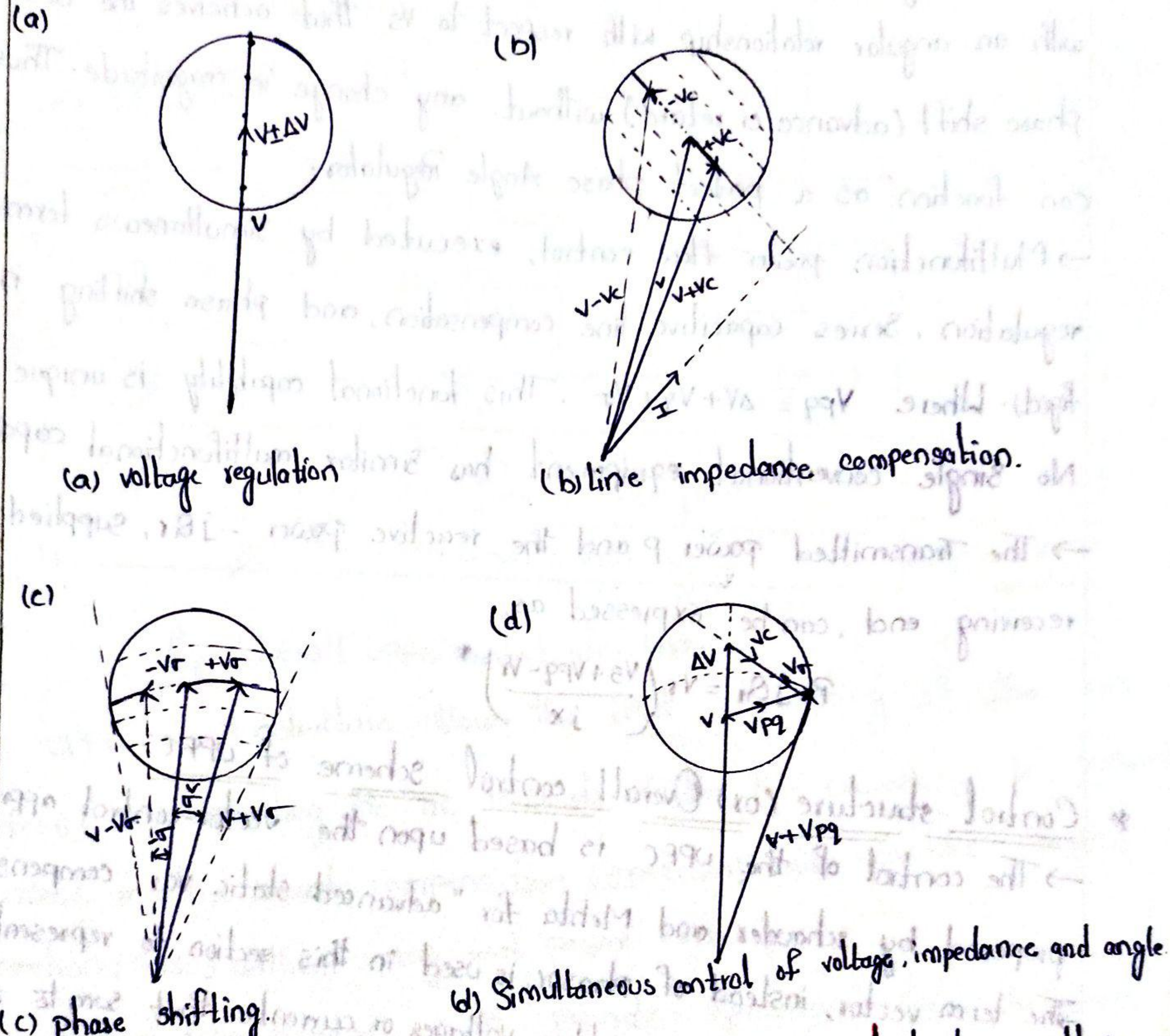
4.Shunt converter operates under a closed loop current structure there by shunt real and reactive components are independently controlled.

2. External control(functional operating control):

1. In this control mode, compensation demand which is represented by various reference inputs can be set manually by operator or by automatic optimization control to meet requirements of transmission system.

* Conventional Transmission Control capabilities:

→ The power Transfer capability in a Transmission line is controlled by varying impedence, voltage and phase angle.



(a) voltage regulation (b) Line impedance compensation.

(c) phase shifting. (d) Simultaneous control of voltage, impedance and angle

→ voltage regulation with continously variable in-phase/anti-phase voltage injection is shown in figure(a) for voltage increments $V_{pq} = \pm\Delta V (P=0)$. This is functionally similar to that obtainable with a Transformer tap changer having infinitely small steps.

→ Series reactive compensation is shown in fig b where $V_{pq} = V_q$ is injected in quadrature with line current I. Functionally this is similar to series capacitive and inductive line compensation attained by the SSSC. The injected series compensating voltage can be kept constant, if desired, independent of line current variation, or can be varied in proportion with the line current to imitate the compensation obtained with a series capacitor or reactor.

→ phase angle regulation (phase shift) is shown in fig(c) where $V_{pq} = V_\sigma$ is injected with an angular relationship with respect to V_s that acheives the desired σ phase shift (advance or retard) without any change in magnitude. Thus, the UPFC can function as a perfect phase Angle Regulator.

→ Multifunction power flow control, executed by simultaneous terminal voltage regulation, Series capacitive line compensation, and phase shifting is shown in fig(d). Where $V_{pq} = \Delta V + V_q + V_\sigma$. This functional capability is unique to the UPFC. No single conventional equipment has similar multifunctional capability.

→ The Transmitted power P and the reactive power $-jQ_r$, supplied by the receiving end, can be expressed as,

$$P - jQ_r = V_r \left(\frac{V_s + V_{pq} - V_r}{jX} \right)^*$$

Control structure (or) Overall control scheme of UPFC:-

→ The control of the UPFC is based upon the vector-control approach proposed by schauder and Mehta for "advanced static var compensators" in 199 The term vector, instead of phasor, is used in this section to represent a set of three instantaneous phase variables, voltages or currents that sum to zero. The symbols $\bar{v}$ and $\bar{i}$ are used for voltage and current vectors.

→ The UPFC Control system may, in the previously established manner, be divided functionally into internal (or converter) control and functional operation control. The internal controls provide gating signals to the converter values so that the converter output voltages will properly respond to the internal reference variables i_{pref}, i_{qref}, and $\bar{v}_{pqref}$.

→ The external or functional operation control defines the functional operating mode of the UPFC and is responsible for generating the internal references, $\bar{V}_{pqref}$ and i_{qref}, for the series and shunt compensation to meet the demands of Transmission system.

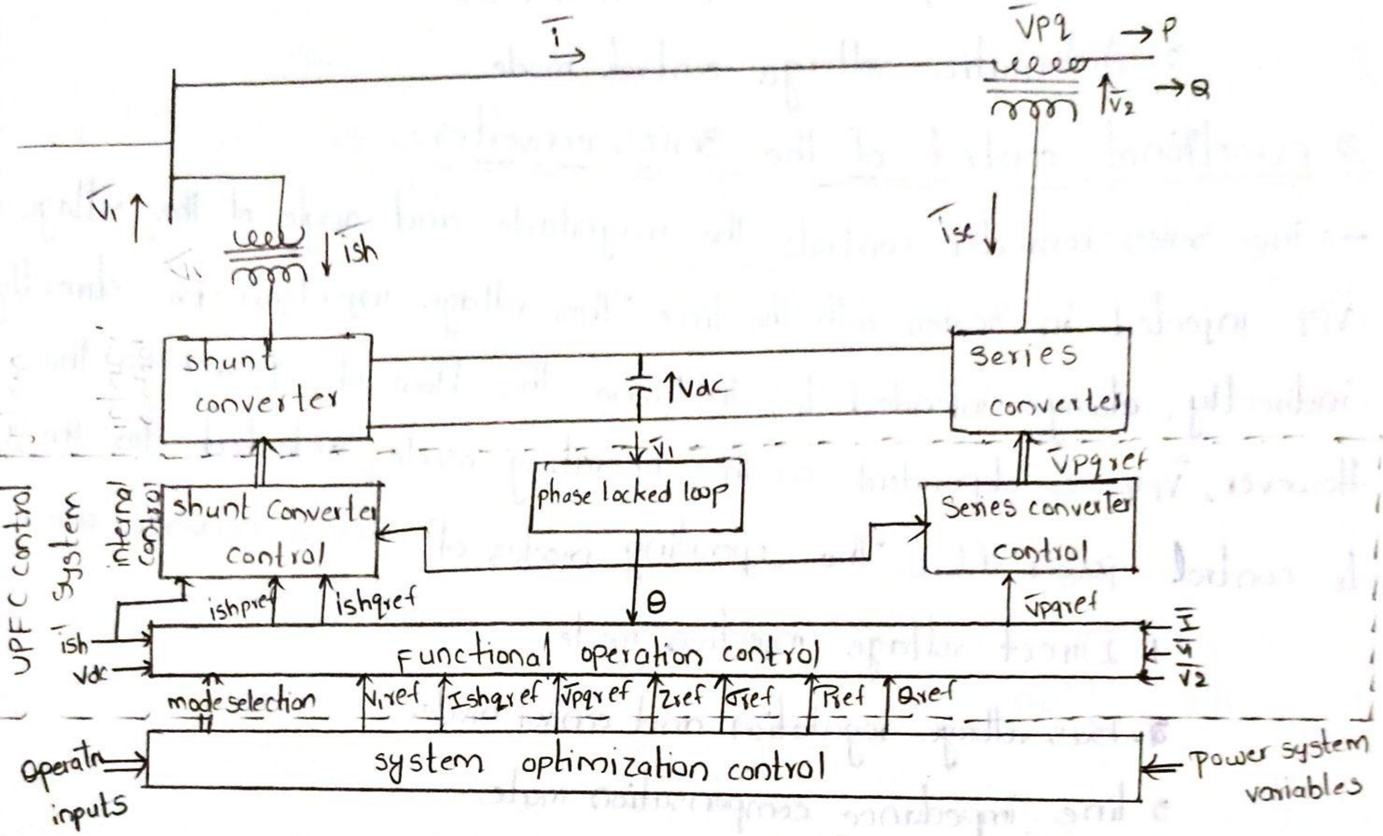


Fig: Overall UPFC control structure.

→ The UPFC circuit structure allows the total decoupling of the two Converters (i.e., Seperating the dc terminals of the two converters) to provide independent reactive shunt compensation (STATCOM) and reactive series Compensation (SSSC) without any real power exchange.

→ phase locked loop purpose is to provide synchronization between Transmission parameters and converter parameter.

→ mode selection means selection of voltage, impedence, phase angle to control the power flow through system optimization control.

1. Functional control of the shunt Converter:

→ The shunt converter is operated so as to draw a controlled current, $\bar{i}_{sh}$, from the line. One component i_{shp}, is automatically determined by the requirement to balance the real power of series converter. The other current component, i_{shq}, is reactive & can be set to any desired reference level (inductive or capacitive) within the capability of the converter. The control Modes of shunt converter are:-

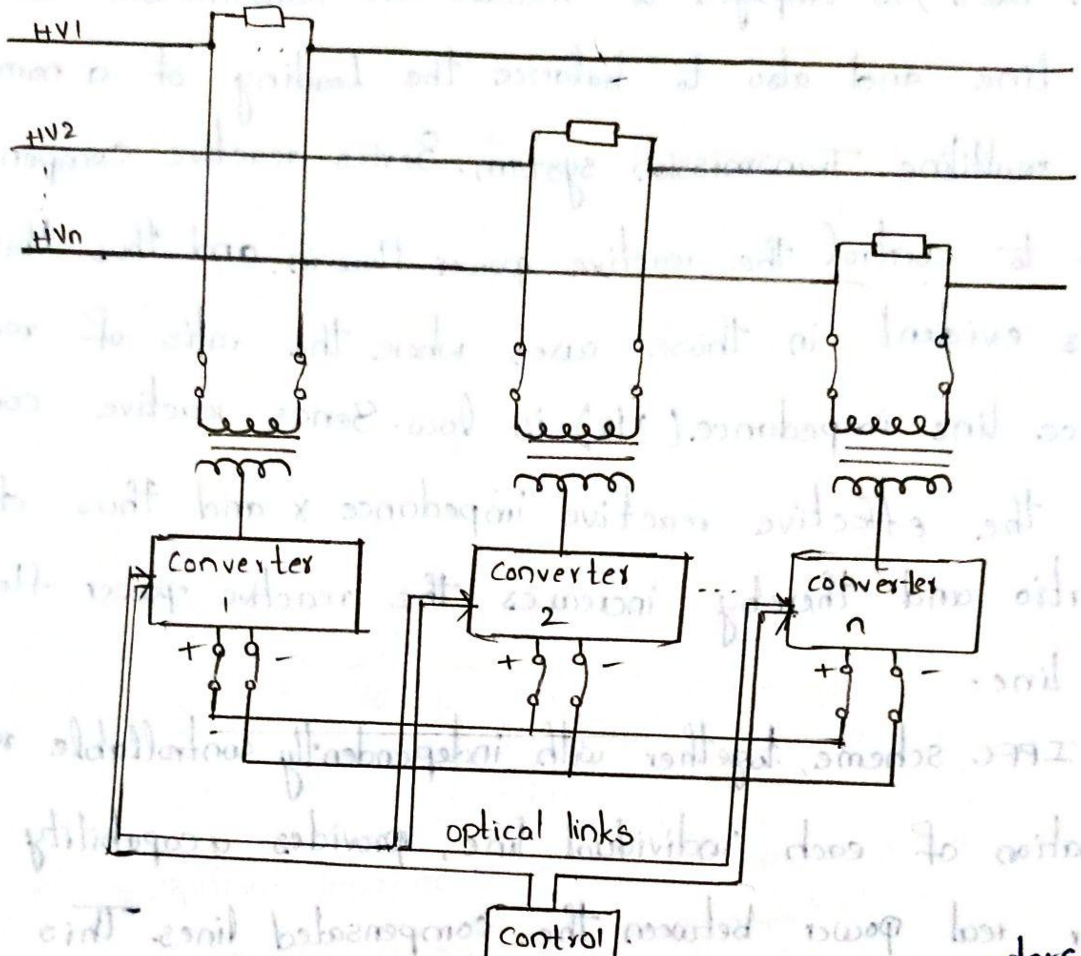
1. Reactive power (VAR) control mode.
2. Automatic voltage control mode.

2. Functional control of the series converter:

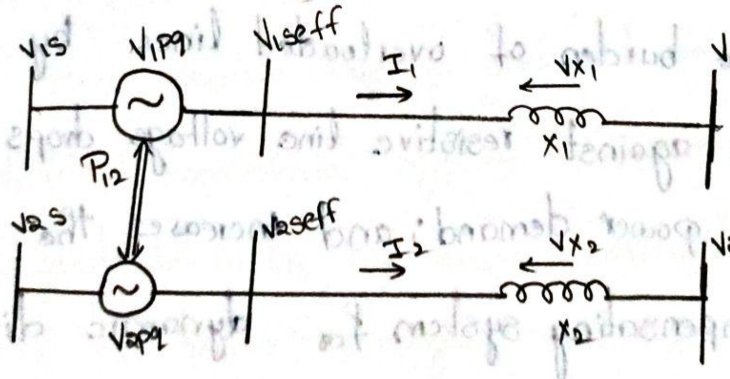
→ The series converter controls the magnitude and angle of the voltage vector $\bar{V}_{pq}$ injected in series with the line. This voltage injection is, directly or indirectly, always intended to influence the flow of power on the line. However, $\bar{V}_{pq}$ is dependent on the operating mode selected for the UPFC to control power flow. The operating modes of series converter are:-

1. Direct voltage injection mode.
2. Bus voltage regulation and control mode.
3. line impedance compensation mode.
4. phase angle regulation mode.
5. Automatic power flow control mode.

* Basic Operating principles and characteristics of IPFC:-



fig(a): Interline power flow controller comprising n converters.



fig(b): Basic two-converter Interline power flow controller scheme.

1. IPFC:-

→ The UPFC concept provides a powerful tool for the cost-effective utilization of individual Transmission lines by facilitating the independent control of both the real and reactive power flow, and thus the maximization of real power transfer at minimum losses, in the line.

→ The IPFC, proposed by Gyugi with sen and schauder in 1998.

addresses the problem of compensating a number of Transmission lines at a given substation. the series capacitive compensation(fixed thyristor-controlled or SSSC based) is employed to increase the Transmittable real power over a given line and also to balance the Loading of a normally encountered multiline Transmission system. Series reactive Compensators are unable to control the reactive power flow in, and thus this problem becomes evident in those cases where the ratio of reactive to resistance line impedance(X/R) is low. Series reactive compensation reduce the effective reactive impedance x and thus decreases the X/R ratio and thereby increases the reactive power flow and losses in the line.

→ The IPFC scheme, together with independently controllable reactive series Compensation of each individual line, provides a capability to directly Transfer real power between the compensated lines. This capability makes it possible to: equalize both real and reactive power flow between the lines; reduce the burden of overloaded lines by real power Transfer; compensate against resistive line voltage drops and the Corresponding reactive power demand; and increases the effectiveness of the overall compensating system for dynamic disturbances.

→ In other words, the IPFC can potentially provide a highly effective scheme for power Transmission management at a multiline substation.

2. <u>Basic operating principle(fig a & fig b)</u>:-

→ IPFC employs a number of dc-to-ac converters each providing series compensation for a different line. In otherwords, the IPFC

Comprises a number of static synchronous series compensators. In IPFC, the compensating converters are linked together at their dc terminals. In addition to providing series reactive compensation, any converter can be controlled to supply real power to the common dc link from its own transmission line. Thus overall surplus power can be available from the under utilized lines which then can be used by other lines for real power compensation. 5

→ Consider IPFC consists of two back-to-back dc-to-ac converters, each compensating a transmission line by series voltage injection. This is shown in fig(b), where two synchronous voltage sources, with phasors V_{1pq} and V_{2pq}, in series with transmission lines 1 & 2, represent the two back-to-back dc-to-ac converters. The common dc link is represented by a bidirectional link for real power exchange between the two voltage sources.

→ For clarity, all the sending-end and receiving-end voltages are assumed to be constant with fixed amplitudes, $V_{1s} = V_{1r} = V_{2s} = V_{2r} = 1.0$ pu., & with fixed angles (constant with) resulting in identical transmission angles $\delta_1 = \delta_2 (= 30°)$ for two systems. The two line impedences, & rating of the two compensating voltages sources, are also assumed to be identical i.e., $V_{1pqmax} = V_{2pqmax}$ & $X_1 = X_2 = 0.5$ p.u. Note that the two lines are assumed to be independent and not in any phase relationship with each other.