DEPARTMENT OF ELECTRICAL & ELECTRONICS ENGINEERING

ACE ENGINEERING COLLEGE
NBA accredited for EEE, CSE, and ECE & NAAC –'A' Grade
(Approved by AICTE and Affiliated to JNTUH, Hyderabad)

COURSE DESCRIPTION

FUNDAMENTALS OF HVDC AND FACTS DEVICES

1. COURSE OVERVIEW:

This subject deals with the importance of HVDC transmission, analysis of HVDC Converters, Harmonics and Filters, Reactive power control and Power factor improvements of the system. It also deals with basic FACTS concepts, static shunt and series compensation and combined compensation techniques.

2. EVALUATION SCHEME:

S.No	Component	Duration	Marks
1	I Mid Examination	80 minutes	20
2	I Assignment	--	05
3	II Mid Examination	80 minutes	20
4	II Assignment	--	05
5	External Examination	3 hours	75

3. COURSE OBJECTIVES:

The course should enable the students to:

I	Summarize the different types of HVDC Transmission systems.
II	Distinguish AC and DC transmission system
III	Examine the control schemes for HVDC transmission systems.
IV	Illustrate the power flow analysis of AC and DC systems.
V	Classify different types of FACTS devices which are used in compensation of reactive power.
VI	Analyze the Static series and combined compensators.

4. COURSE OUTCOMES:

Students, who complete the course, will have demonstrated the ability to do the following:

1	Illustrate the layout of HVDC converter stations.
2	Demonstrate the rectifier and inverter configurations of 12 pulse HVDC converter.
3	Classify different FACTS controllers and their operation.
4	Analyze the power flow in HVDC systems.
5	Describe the converter control characteristics of HVDC systems.
6	Analyze the Harmonics and use of filters to minimize the harmonics.
7	Design AC and DC converters.
8	Summarize different FACTS devices to compensate reactive power.
9	Explain the necessity of Static series and combined compensators.
10	Discuss the principle of operation of unified power flow controller.

SYLLABUS:

UNIT I:

Basic Concept of HVDC Transmission: Comparison of AC-DC transmission systems, application of DC transmission, types of DC links, typical layout of HVDC converter station. HVDC converters, pulse number, analysis of Gratez circuit with and without overlap, converter bridge characteristics, equivalent circuits or rectifier and inverter configurations of twelve pulse converters

UNIT II:

Converter & HVDC system control: Principles of DC Link control, converter control characteristics, system control hierarchy, firing angle control, current and excitation angle control, starting and stopping of DC Link.

UNIT III:

Harmonics, Filters and Reactive power control: Introduction, generation of harmonics, AC and DC Filters, Reactive power Requirements in steady state, sources of reactive power, static VAR systems.

Power flow analysis in AC/DC systems: Modeling of DC/AC converters, controller equations, solutions of AC/DC load flow, simultaneous method, Sequential method.

UNIT IV:

Introduction to FACTS: Flow of power in AC Parallel paths and meshed systems, basic types of FACTS controllers, brief description and definitions of FACTS controllers.

Static shunt compensators: Objectives of shunt compensation, methods of controllable VAR generation, static VAR compensators, SVC and STATCOM, comparison between SVC and STATCOM.

UNIT-V:

Static Compensators: Objectives of Series compensation, Variable impedance type and thyristors switched series capacitors (TCSC), and switching converter type series compensators, static series synchronous compensator (SSSC), power angle characteristics, basic operating control schemes.

Combined Compensators: Introduction, unified power flow controller (UPFC), basic operating principle, independent real and reactive power flow controller, control structure.

TEXT BOOKS:

1. HVDC Transmission systems, S Kamakshaiah, V. Kamaraju, The Mc Graw Hill Companies.

2. Understanding FACTS, Concepts and Technology of Flexible AC Transmission systems, Narain. G. Hingorani, Laszlo Gyugyi, IEEE press, Wiley India.

REFERENCES:

1. HVDC and FACTS Controllers applications of static converters in power systems, Vijay K. sood, Kluwer Accademic Publishers.

2. HVDC Power transmission systems, K R Padiyar, New Age International.

Thyristor Basd Controllers for Electrical Transmission Systems, R. Mohan Mathur, Rajiv K. Varma. Wiley India.

Unit-1

Basic Concept of HVDC Transmission

1.1 Introduction

Electric power transmission was originally developed with direct current. The availability of transformers and the development and improvement of induction motors at the beginning of the 20th century, led to the use of AC transmission. DC Transmission now became practical when long distances were to be covered or where cables were required. Thyristors were applied to DC transmission and solid state valves became a reality. With the fast development of converters (rectifiers and inverters) at higher voltages and larger currents, DC transmission has become a major factor in the planning of the power transmission. In the beginning all HVDC schemes used mercury arc valves, invariably single phase in construction, in contrast to the low voltage polyphase units used for industrial application. About 1960 control electrodes were added to silicon diodes, giving silicon-controlled-rectifiers (SCRs or Thyristors). Today, the highest functional DC voltage for DC transmission is +/- 600kV. D.C transmission is now an integral part of the delivery of electricity in many countries throughout the world.

1.2 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

1.3 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 2 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.

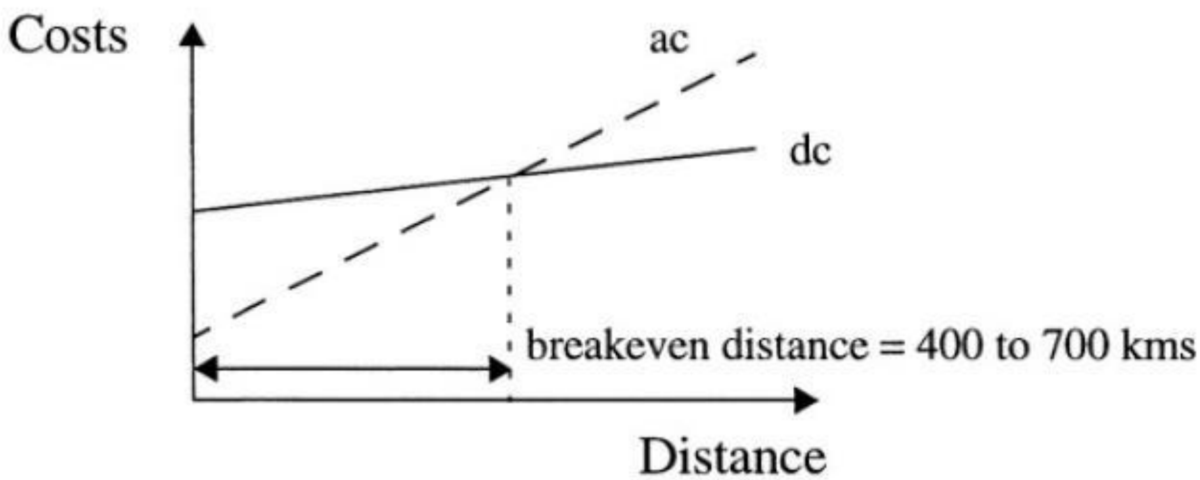


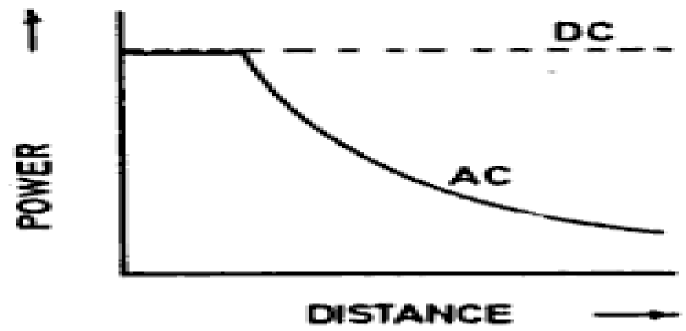
Figure: Relative costs of AC and DC transmission lines vs distance

1.4 Technical Performance:

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

1.5 Stability Limits:

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



Power transfer capability vs. distance

1.6 Voltage Control:

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

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

1.7 Line Compensation:

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

1.8 Problems of AC Interconnection:

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

1. The presence of large power oscillations which can lead to frequent tripping,
2. Increase in fault level, and
3. Transmission of disturbances from one system to the other. 4

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

1.9 Ground Impedance:

In AC transmission, the existence of ground (zero sequence) current cannot be permitted in steady-state due to the high magnitude of ground impedance which will not only affect efficient power transfer, but also result in telephonic interference. The ground impedance is negligible for DC currents and a DC link can operate using one conductor with ground return (monopolar operation).
The ground return is objectionable only when buried metallic structures (such as pipes) are present and are subject to corrosion with DC current flow. While operating in the monopolar mode, the AC network feeding the DC converter station operates with balanced voltages and currents. Hence, single pole operation of dc transmission systems is possible for extended period, while in AC transmission, single phase operation (or any unbalanced operation) is not feasible for more than a second.

1.10 Disadvantages of DC Transmission:

The scope of application of DC transmission is limited by

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

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

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

1.11 Reliability:

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

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

Energy availability:

Energy availability = 100 (1 – equivalent outage time) /Actual time

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

Transient reliability:

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

Transient reliability = 100 X No. of times HVDC systems performed as designed

No. of recordable AC faults

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

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

1.12 Application of DC Transmission

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

(a) Underground or underwater cables:

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

(b) Long distance bulk power transmission:

Bulk power transmission over long distances is an application ideally suited for DC transmission and is more economical than ac transmission whenever the breakeven distance is 6 exceeded. Examples of this type of application abound from the earlier Pacific Intertie to the recent links in China and India. The breakeven distance is being effectively decreased with the reduced costs of new compact converter stations possible due to the recent advances in power electronics.

(c) Stabilization of power flows in integrated power system:

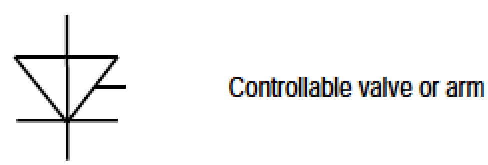
In large interconnected systems, power flow in AC ties (particularly under disturbance conditions) can be uncontrolled and lead to overloads and stability problems thus endangering system security. Strategically placed DC lines can overcome this problem due to the fast controllability of DC power and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

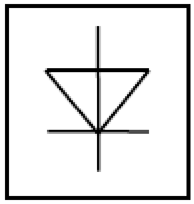
Presently the number of DC lines in a power grid is very small compared to the number of AC lines. This indicates that DC transmission is justified only for specific applications. Although advances in technology and introduction of Multi-Terminal DC (MTDC) systems are expected to increase the scope of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

First, the control and protection of MTDC systems is complex and the inability of voltage transformation in dc networks imposes economic penalties. Second, the advances in power electronics technology have resulted in the improvement of the performance of AC transmissions using FACTS devices, for instance through introduction of static VAR systems, static phase shifters, etc.

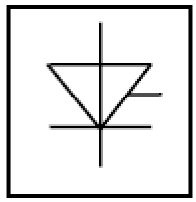
1.13 Types of Valves

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





Non-controllable bridge or valve group

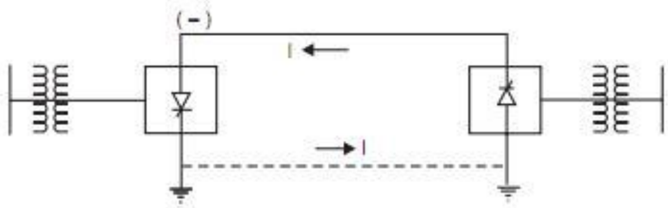


Controllable bridge or valve group

1.14 Types of HVDC Links

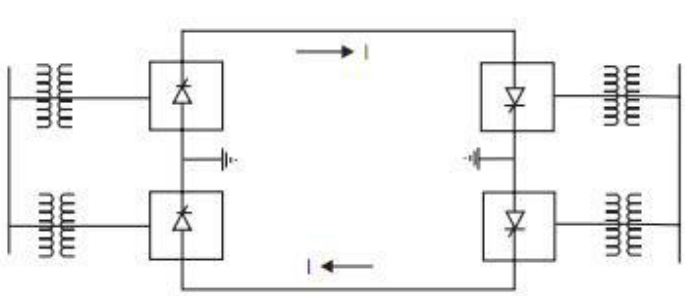
Three types of HVDC Links are considered in HVDC applications which are

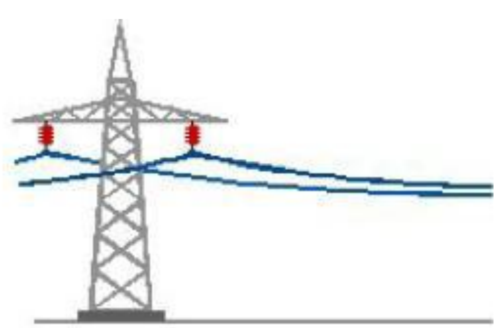
Monopolar Link:



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

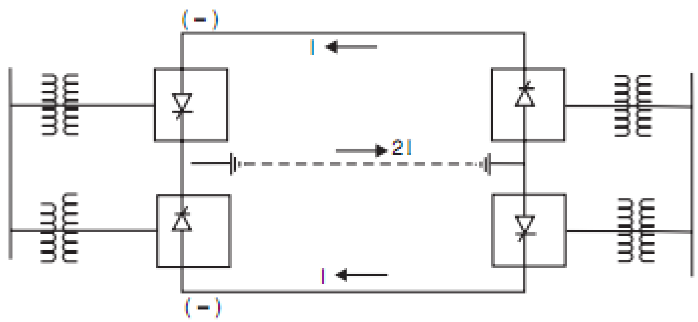
Bipolar Link:





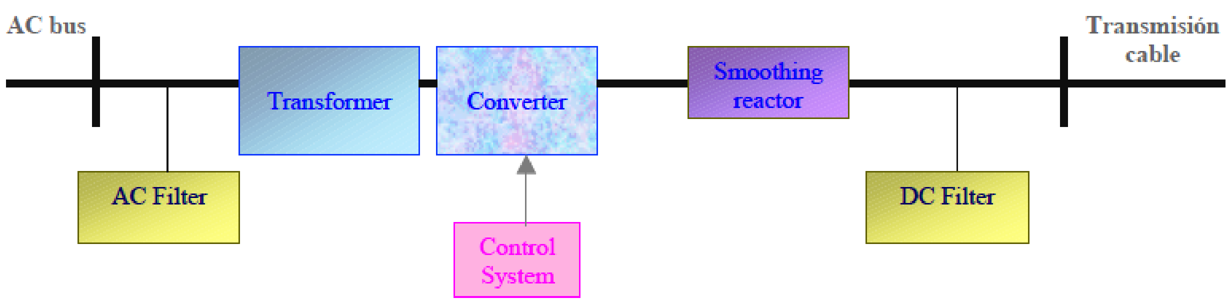
A bipolar link as shown in the above figure has two conductors, one positive and the other negative. Each terminal has two sets of converters of equal rating, in series on the DC side. The junction between the two sets of converters is grounded at one or both ends by the use of a short electrode line.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

Homopolar Link:



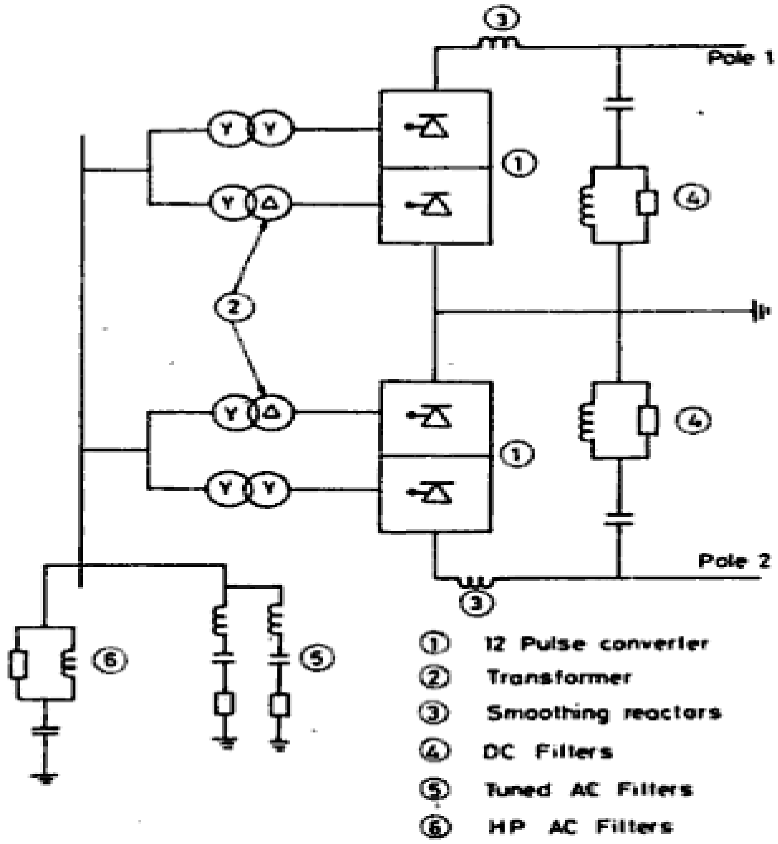
In this type of link as shown in the above figure two conductors having the same polarity (usually negative) can be operated with ground or metallic return. Due to the undesirability of operating a DC link with ground return, bipolar links are mostly used. A homopolar link has the advantage of reduced insulation costs, but the disadvantages of earth return outweigh the advantages.

1.15 HVDC Converter Station

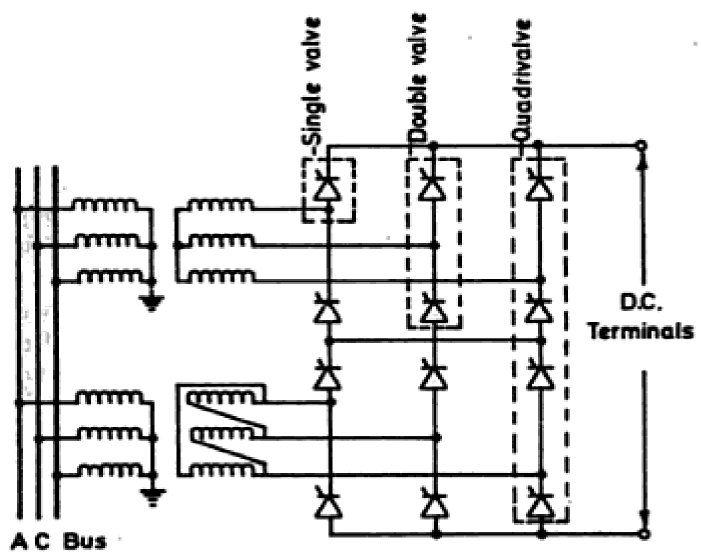


The major components of a HVDC transmission system are converter stations where conversions from AC to DC (Rectifier station) and from DC to AC (Inverter station) are performed. A point to point transmission requires two converter stations. The role of rectifier and inverter stations can be reversed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

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



Converter Unit:



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

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

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

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

Converter Transformer:

The converter transformer has three different configurations-

(i) three phase, two winding,

(ii) single phase, three winding and

(iii)single phase, two winding

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

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

Filters:

There are three types of filters used which are

1. AC Filters:

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

2. DC Filters:

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

3. High Frequency (RF/PLC) Filters:

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

1.16 Reactive power source:

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

1.17 Smoothing Reactor:

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

1.18 DC Switchgear:

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

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

1.19 Modern Trends in DC Transmission

To overcome the losses and faults in AC transmission, HVDC transmission is preferred. 12

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

Power semiconductors and valves:

The IGBTs or GTOs employed required huge amount of current to turn it ON which was a big problem. GTOs are available at 2500V and 2100A. As the disadvantage of GTOs is the large gate current needed to turn them OFF, so MCT which can be switched OFF by a small current is preferred as valves. The power rating of thyristors is also increased by better cooling methods. Deionized water cooling has now become a standard and results in reduced losses in cooling.

Converter Control:

The development of micro-computer based converter control equipment has made possible to design systems with completely redundant converter control with automatic transfer between systems in the case of a problem. The micro-computer based control also has the flexibility to implement adaptive control algorithms or even the use of expert systems for fault diagnosis and protection.

DC Breakers:

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

Conversion of existing AC lines:

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

Operation with weak AC systems:

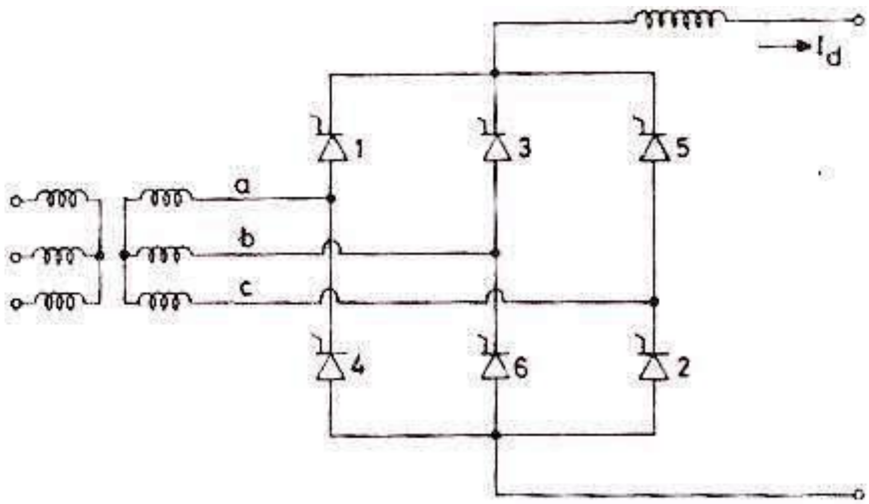
The strength of AC systems connected to the terminals of a DC link is measured in terms of Short Circuit Ratio (SCR) which is defined as SCR = Short circuit level at the converter bus

Rated DC Power If SCR is less than 3, the AC system is said to be weak. The conventional constant extinction angle control may not be suitable for weak AC systems. 13

Constant reactive current control or AC voltage control may overcome some of the problems of weak AC systems. The power modulation techniques used to improve dynamic stability of power systems will have to be modified in the presence of weak AC systems.

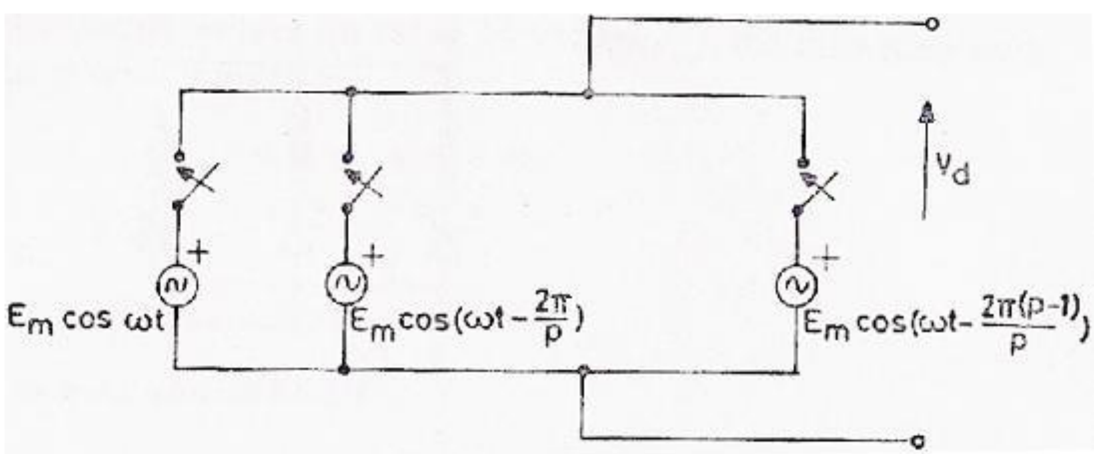
1.21 Six Pulse Converters

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



Pulse Number

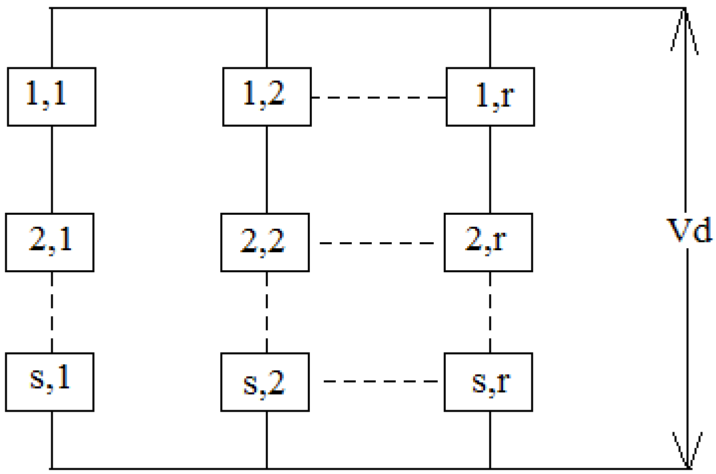
The pulse number of a converter is defined as the number of pulsations (cycles of ripple) of direct voltage per cycle of alternating voltage. The conversion from AC to DC involves switching sequentially different sinusoidal voltages onto the DC circuit.



A valve can be treated as a controllable switch which can be turned ON at any instant, provided the voltage across it is positive. The output voltage V_d of the converter consists of a DC component and a ripple whose frequency is determined by the pulse number

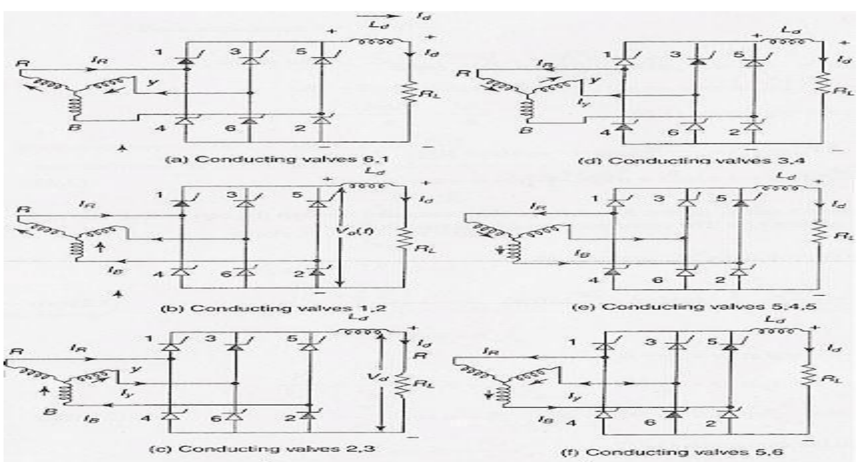
Choice of Converter Configuration

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



A converter configuration can be defined by the basic commutation group and the number of such groups connected in series and parallel. If there are 'q' valves in a basic commutation group and r of those are connected in parallel and s of them in series then,

$p = q\,r\,s$



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

1.22 Analysis of Graetz Circuit without overlap:

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

The following assumptions are made to simplify the analysis

a. The DC current is constant.

b. The valves are modeled as ideal switches with zero impedance when ON and with infinite impedance when OFF.

c. The AC voltages at the converter bus are sinusoidal and remain constant.

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

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

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

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

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

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

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

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

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

DC Voltage Waveform:

The DC voltage waveform contains a ripple whose fundamental frequency is six times the supply frequency. This can analyzed in Fourier series and contains harmonics of the order

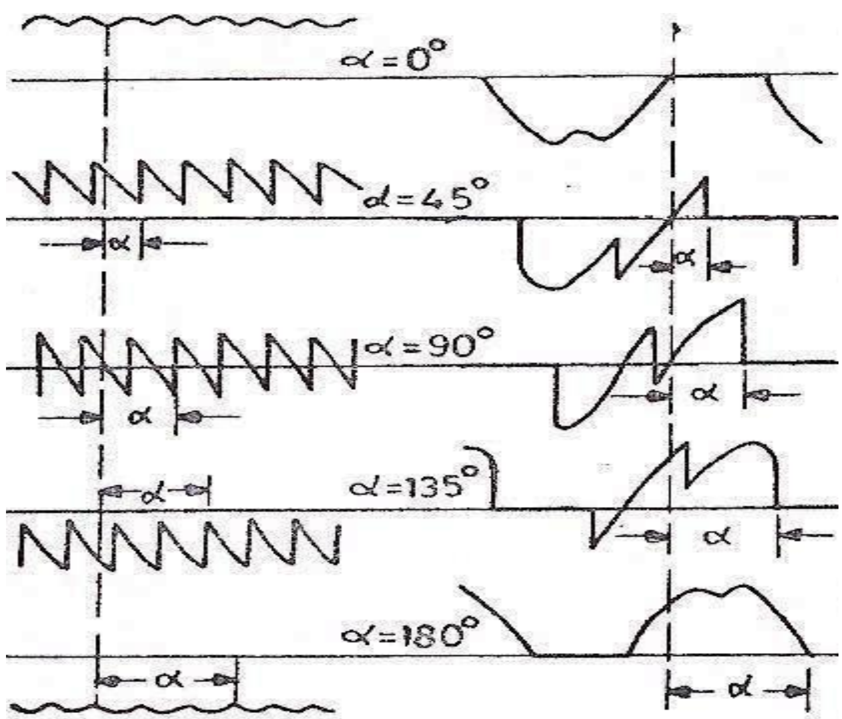
h = np

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

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

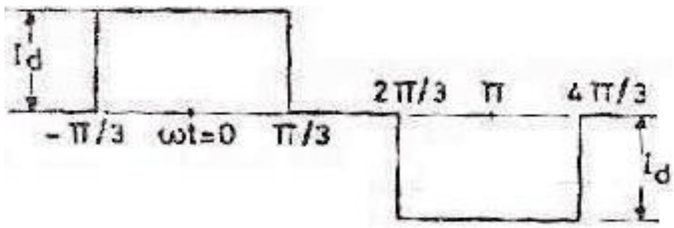
$$V_h = V_{do} \frac{\sqrt{2}}{h^2 - 1} [1 + (h^2 + 1)\sin^2\alpha]^{1/2}$$

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



AC Current Waveform:

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



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

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

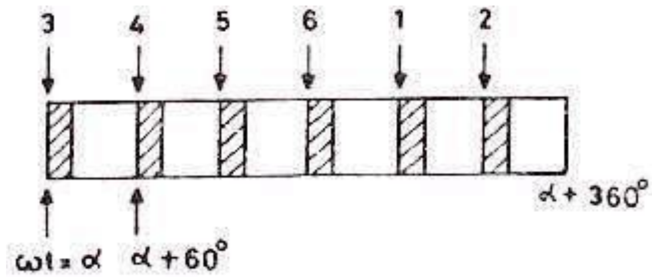
where as the rms value of the current is

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

Analysis of Graetz Circuit with overlap

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

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



There are three modes of the converter which are

i) Mode 1 – Two and three valve conduction ($\mu<60^{o}$)

ii) Mode 2 – Three valve conduction ($\mu=60^{o}$)

iii) Mode 3 – Three and four valve conduction ($\mu>60^{o}$)

i)Analysis of Two and Three Valve Conduction Mode:

The equivalent circuit for three valve conduction is shown below.

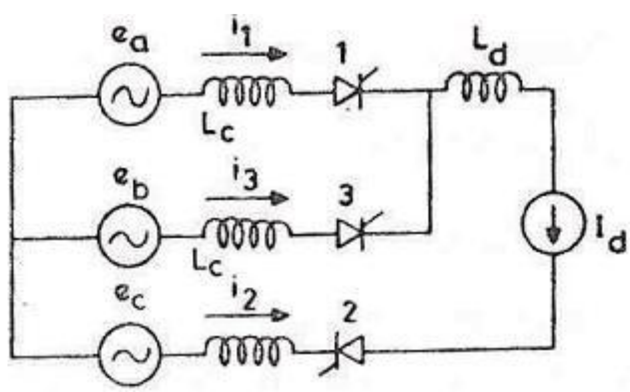
For this circuit,

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

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

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

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



Since, $i_1 = I_d - i_3$

We get,

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

Solving the above equation, we get

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

Where,

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

At $\omega t=\alpha+\mu$, $i_s = I_d$. This gives $I_d = I_s[\cos\alpha - \cos(\alpha+\mu)]$

The average direct voltage can be obtained as

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

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

1.22 Converter Bridge Characteristics

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

1) First mode: Two and three valve conduction mode ($\mu < 60^o$)
2) Second mode: Three valve conduction mode only for $\alpha < 30^o$ ($\mu = 60^o$)
3) Third mode: Three and four valve conduction mode $\alpha \ge 30^o$ ($60^o \le \mu \le 120^o$)

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

The DC voltage continues to decrease until it reaches zero.

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

For Modes 1 and 3, we have

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

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

The voltage and current characteristics are linear with different slopes

For mode 2, $\mu = 60^\circ$, μ is constant, so the characteristics are elliptical

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

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

B) Inverter:

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

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

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

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

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

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

Mode 1

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

The characteristics are linear defined by

$V_{d|} = \cos\gamma_o - I_{d|}$

1(b) $60_o < \beta < 90_o$ for

$\mu = 60_o - \xi_o = 60_o - \gamma_o =$ constant

The characteristics are elliptical.

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

$60_o - \xi_o \leq \mu \leq 60_o$

The characteristics in this case are line and defined by

$V_{d|} = \cos(\gamma_o + 30_o) - I_d$

Mode 2

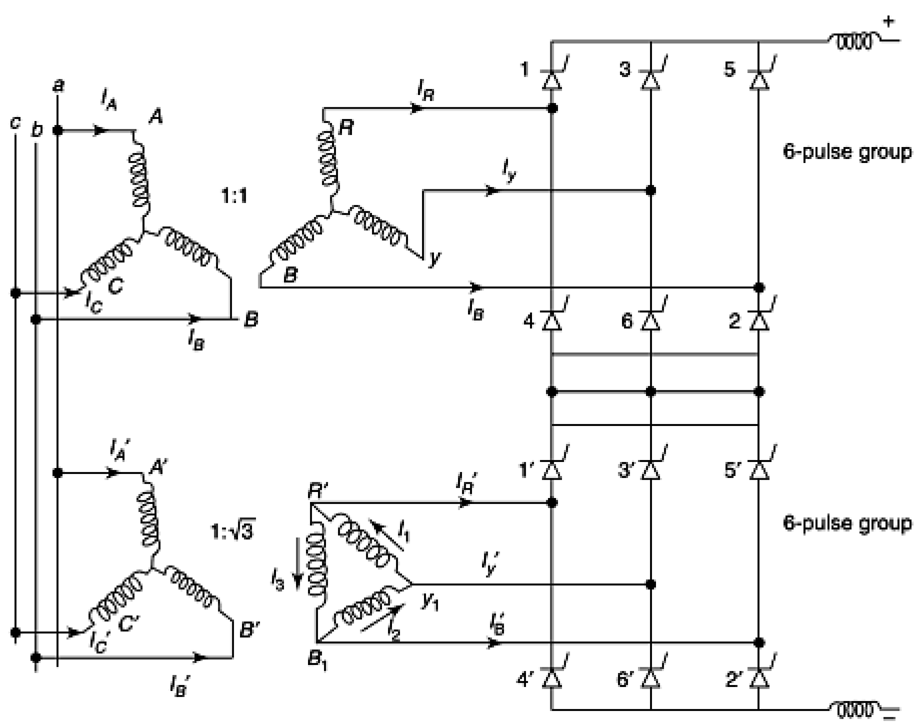
For $\mu > 60_o$ corresponding to $\beta > 90_o + \gamma_o$

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

$V_{d|} = \sqrt{3}\cos\gamma_o - 3I_{d|}$

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

Characteristics of a twelve pulse converter



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

Mode 1: 4 and 5 valve conduction

$0 < \mu < 30_o$

Mode 2: 5 and 6 valve conduction

$30_o < \mu < 60_o$

Mode 3: 6 valve conduction

$0 < \alpha < 30_o$, $\mu = 60_o$

Mode 4: 6 and 7 valve conduction

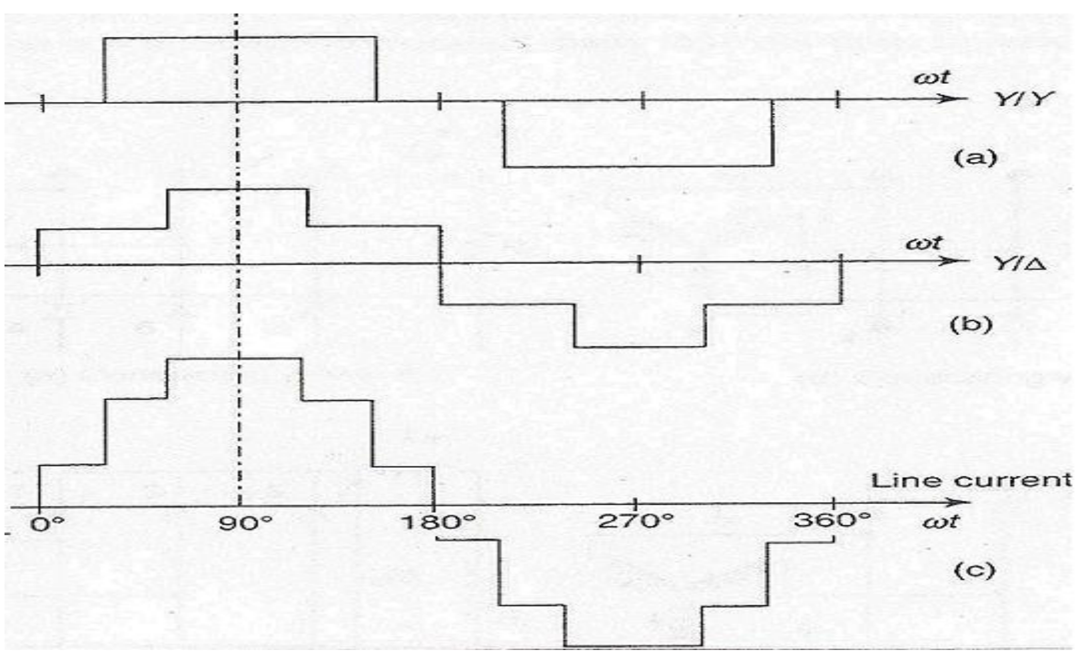
$60_o < \mu < 90_o$

Mode 5: 7 and 8 valve conduction

$90_o < \mu < 120_o$

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

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



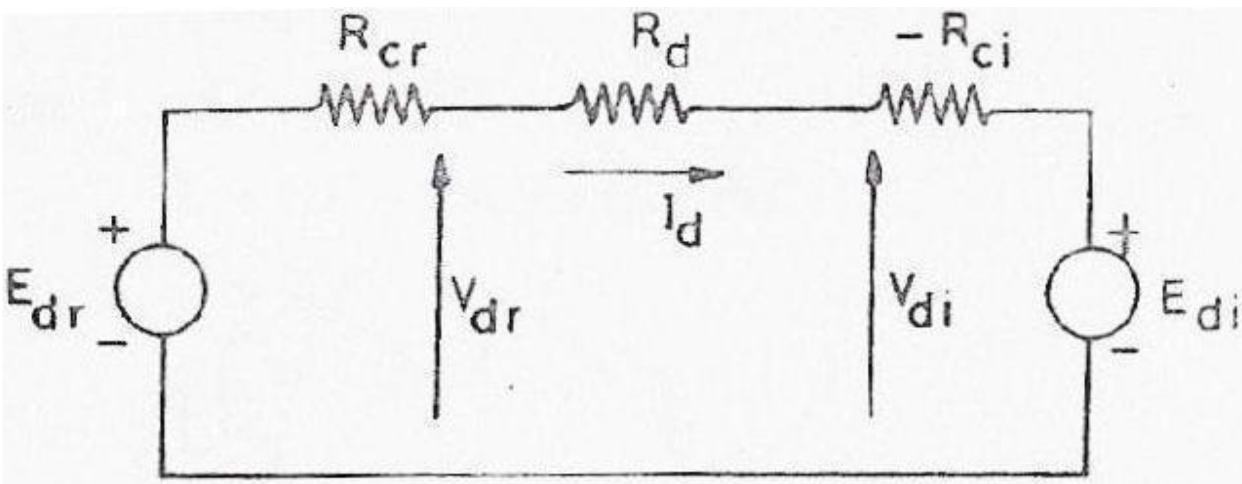
UNIT-II:

CONTROL OF HVDC CONVERTER SYSTEMS

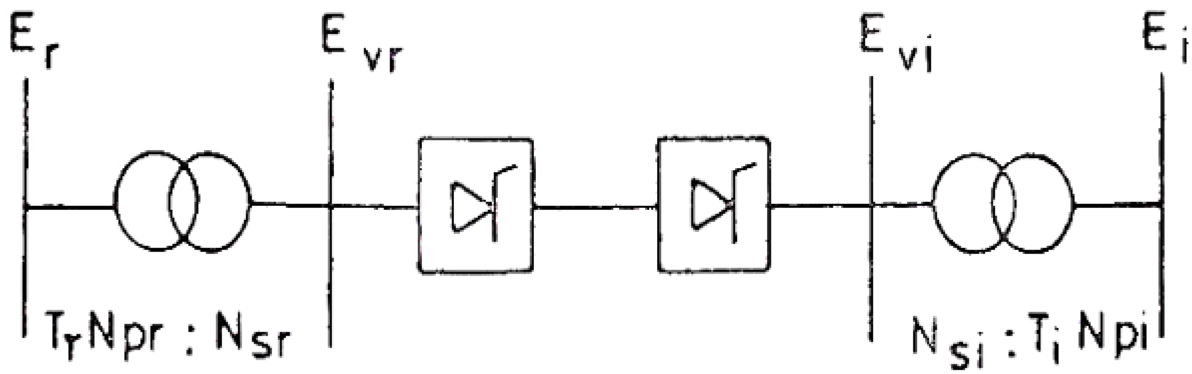
The major advantage of a HVDC link is rapid controllability of transmitted power through the control of firing angles of the converters. Modern converter controls are not only fast, but also very reliable and they are used for protection against line and converter faults.

2.1 Principles of DC Link Control

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



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



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

$$E_{dr} = (3\sqrt{2}/\pi)\, n_b\, E_{vr} \cos\alpha_r$$
$$E_{di} = (3\sqrt{2}/\pi)\, n_b\, E_{vi} \cos\gamma_i$$

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

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

where E_r and E_i are the AC (line to line) voltages of the converter buses on the rectifier and inverter side. T_r and T_i are the OFF-nominal tap ratios on the rectifier and inverter side.
Combining equations (1), (2) and (3),

$$E_{dr} = (A_r\, E_r\, /T_r) \cos\alpha_r$$
$$E_{di} = (A_i\, E_i\, /T_i) \cos\gamma_i$$

where A_r and A_i are constants.
The steady-state current I_d in the DC link is obtained as

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

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

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

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

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

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

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

1) At low DC voltages, the current required is excessive to maintain the required level of power. This can be counterproductive because of the excessive requirements of the reactive power, which depresses voltage further.

2) The constant power characteristic contributes to negative damping and degrades dynamic stability.

2.2 Converter Control Characteristics

Basic Characteristics:

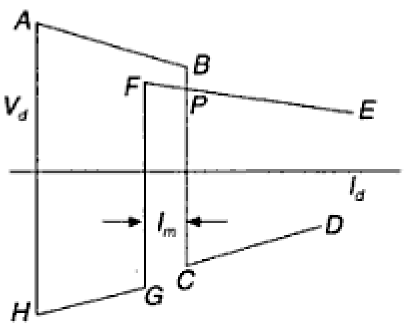
The intersection of the two characteristics (point A) determines the mode of operation-Station I operating as rectifier with constant current control and station II operating at constant (minimum) extinction angle.

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

1) CC at rectifier and CEA at inverter (operating point A) which is the normal mode of operation.

2) With slight dip in the AC voltage, the point of intersection drifts to C which implies minimum α at rectifier and minimum γ at the inverter.

3) With lower AC voltage at the rectifier, the mode of operation shifts to point B which implies CC at the inverter with minimum α at the rectifier.

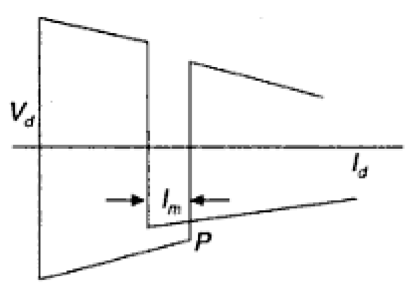


Controllers characteristics.

Types of Station Control Characteristics

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

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



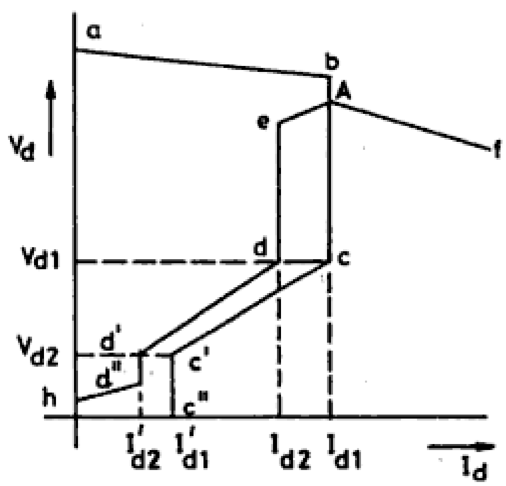
Power reversal controllers characteristics

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

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

Voltage Dependent Current Limit:

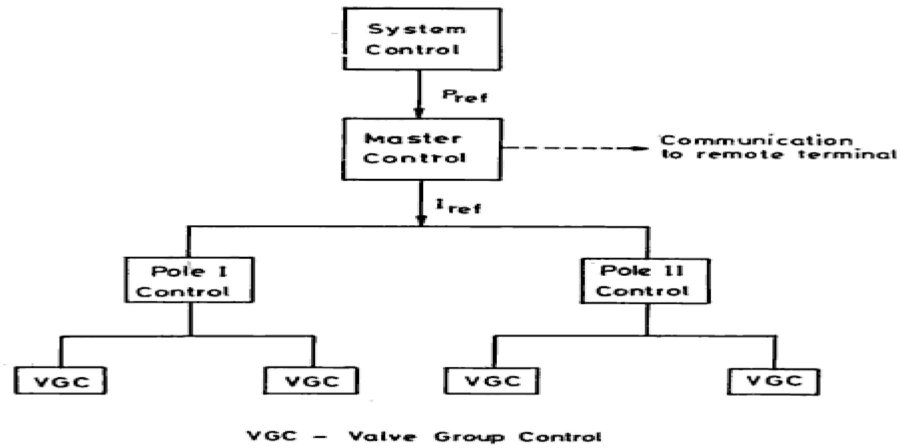
The low voltage in the DC link is mainly due to the faults in the AC system on the rectifier or inverter side. The low AC voltage due to faults on the inverter side can result in 33 persistent commutation failure because of the increase of the overlap angle. In such cases, it is necessary to reduce the DC current in the link until the conditions that led to the reduced DC voltage are relieved. Also the reduction of current relieves those valves in the inverter which are overstressed due to continuous current flow in them.



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

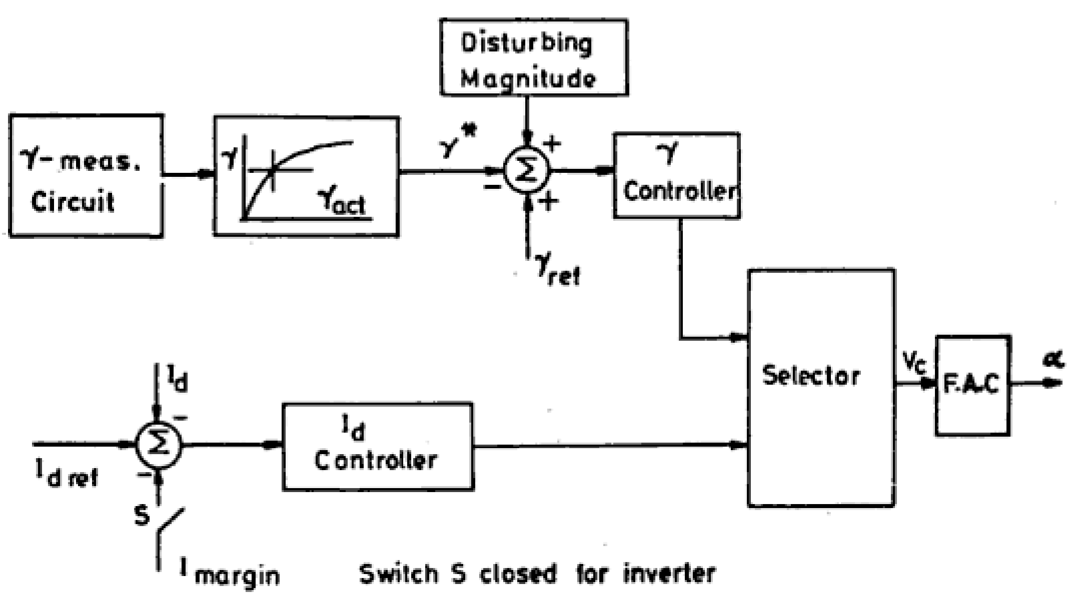
System Control Hierarchy

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



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

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



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

Firing Angle Control

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

1. The firing instant for all the valves are determined at ground potential and the firing signals sent to individual thyristors by light signals through fibre-optic cables. The required gate power is made available at the potential of individual thyristor.

2. While a single pulse is adequate to turn-on a thyristor, the gate pulse generated must send a pulse whenever required, if the particular valve is to be kept in a conducting state.

The two basic firing schemes are

1. Individual Phase Control (IPC)

2. Equidistant Pulse Control (EPC)

Individual Phase Control (IPC)

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

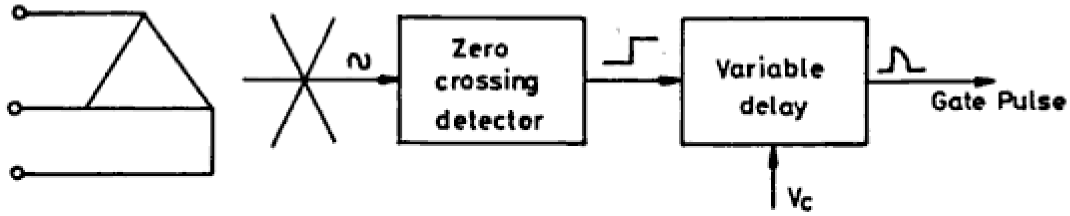
There are two ways in which this can be achieved

1. Constant α Control

2. Inverse Cosine Control

Constant α Control

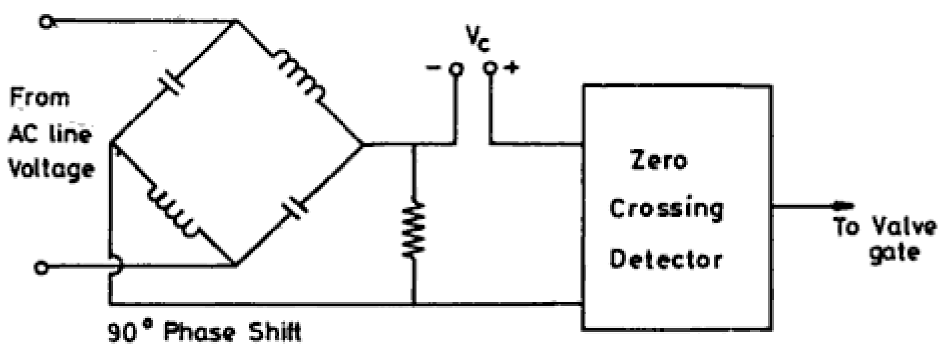
Six timing (commutation) voltages are derived from the converter AC bus via voltage transformers and the six gate pulses are generated at nominally identical delay times subsequent to the respective voltage zero crossings. The instant of zero crossing of a particular commutation voltage corresponds to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



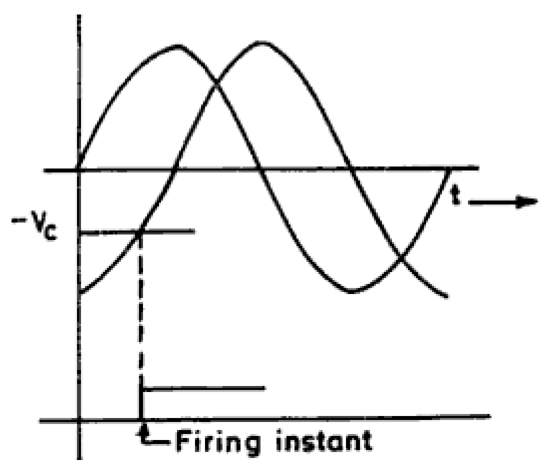
The delays are produced by independent delay circuits and controlled by a common control voltage V derived from the current controllers.

Inverse Cosine Control

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



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



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

Drawbacks of IPC Scheme

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

This is mainly due to the fact that any distortion in the system voltage leads to perturbations in the zero crossings which affect the instants of firing pulses in IPC scheme. This implies that even when the fundamental frequency voltage components are balanced, the firing

pulses are not equidistant in steady-state. This in turn leads to the generation of noncharacteristic harmonics (harmonics of order $h \neq np \pm 1$) in the AC current which can amplify the harmonic content of the AC voltage at the converter bus. The problem of harmonic instability can be overcome by the following measures

1. Through the provision of synchronous condensers or additional filters for filtering out noncharacteristic harmonics.

2. Use of filters in control circuit to filter out noncharacteristic harmonics in the commutation voltages.

3. The use of firing angle control independent of the zero crossings of the AC voltages. This is the most attractive solution and leads to the Equidistant Pulse Firing scheme.

Equidistant Pulse Control (EPC)

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

1. Pulse Frequency Control (PFC)

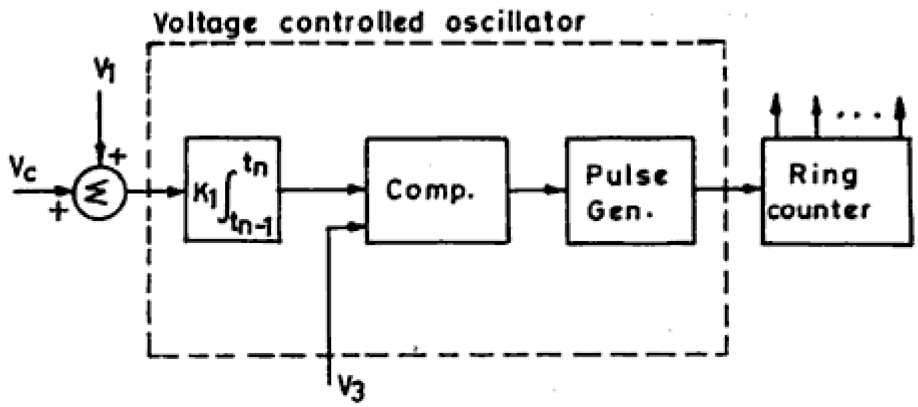
2. Pulse Period Control

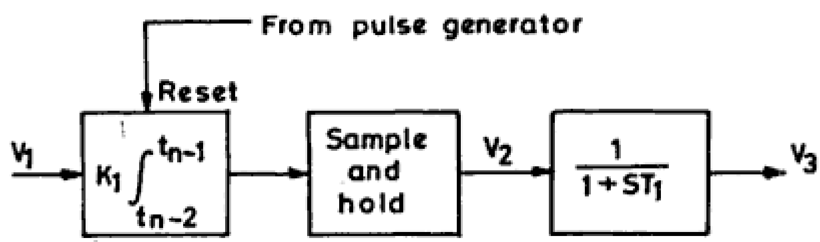
3. Pulse Phase Control (PPC)

Pulse Frequency Control (PFC)

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

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





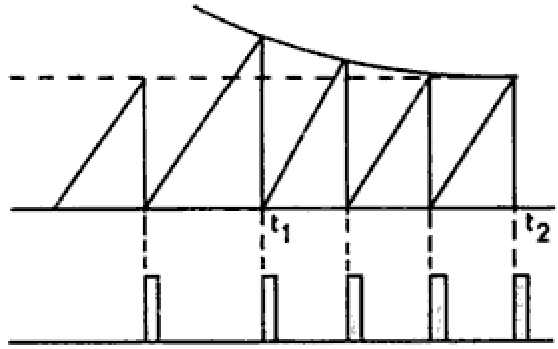
Pulse Period Control

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

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

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

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



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

Pulse Phase Control (PPC)

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

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

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

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

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

Drawbacks of EPC Scheme

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

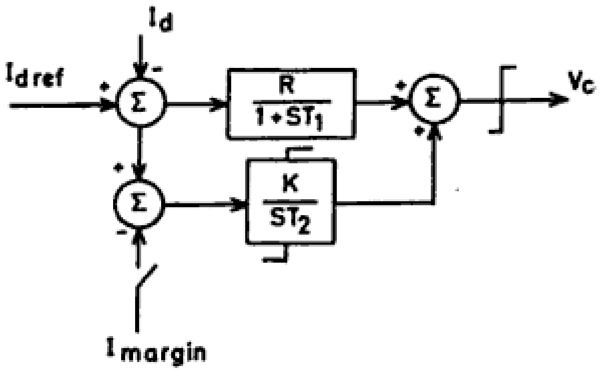
1. Under balanced voltage conditions, EPC results in less DC voltage compared to IPC. Unbalance in the voltage results from single phase to ground fault in the AC system

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

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

Current and Extinction Angle Control

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



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

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

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

where e_{cj} is the commutation voltage across valve j and t_n is the instant of its firing.

In general, the prediction of firing angle is based on the equation

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

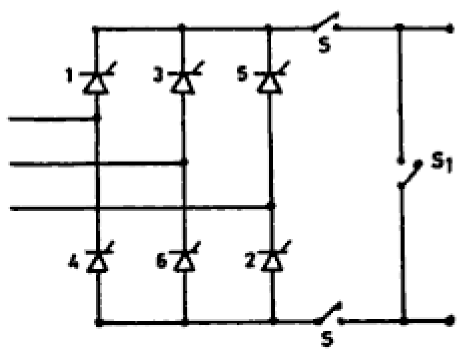
Under large disturbances such as a sudden dip in the AC voltage, signals derived from the derivative of voltage or DC current aid the advancing of delay angle for fast recovery from commutation failures.

Starting and Stopping of DC Link

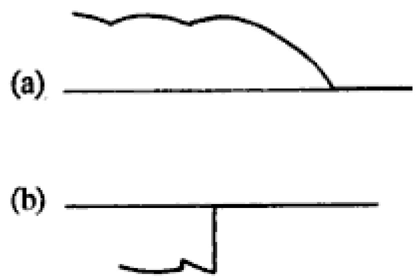
Energization and Deenergization of a Bridge:

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

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



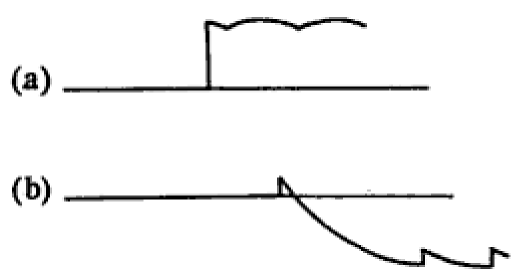
With the selection of bypass pair 1 and 4, the commutation from valve 2 to4 is there, but the commutation from valve 3 to valve 5 is prevented. In the case of a predetermined choice of the bypass path, the time lapse between the blocking command and the current transfer to bypass path can vary from 60^0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



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

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

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



Start-Up of DC Link:

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

Start-up with long pulse firing:

1. Deblock inverter at about $\gamma = 90^0$

2. Deblock rectifier at $\alpha = 85^0$ to establish low direct current

3. Ramp up voltage by inverter control and the current by rectifier control.

Start-up with short pulse firing:

1. Open bypass switch at one terminal

2. Deblock that terminal and load to minimum current in the rectifier mode

3. Open bypass switch at the second terminal and commutate current to the bypass pair

4. Start the second terminal also in the rectifier mode

5. The inverter terminal is put into the inversion mode

6. Ramp up voltage and current.

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

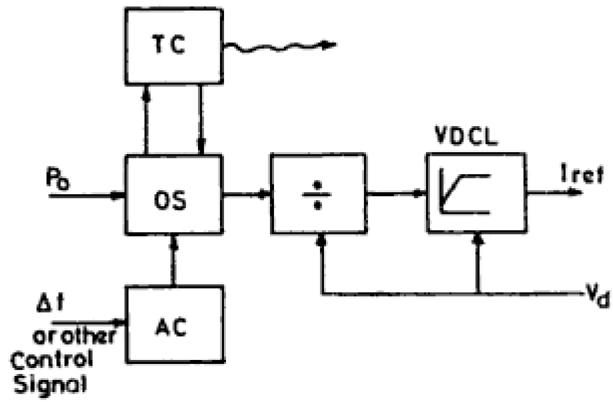
The required power ramping rate depends on the strength of the AC system. Weaker systems require fast restoration of DC power for maintaining transient stability.

Power Control

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

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

The figure below shows the basic power controller used.



TC-Telecommunication equipment
OS-Order Setting unit
VDCL-Voltage dependent current limiter

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

Unit –III
Harmonics, filters, and Reactive Power Control

3.1 Introduction:

Electrical energy transmitted through AC transmission or DC transmission is to be delivered at the consumer's terminals at specified voltage level of constant magnitude without deviation from the ideal waveform. An HVDC transmission system generates harmonic currents on the AC side and harmonic voltages on the DC side during operation. The harmonic currents generated at the AC bus of the converter get transmitted to the AC network and then cause the following adverse effects.

a) Heating of the equipments connected.

b) Instability of converter control.

c) Generates telephone and radio interference in adjacent communication lines, thereby inducing harmonic noise.

d) Harmonics can lead to generation of overvoltages due to resonance when filter circuits

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

1) Transformer.

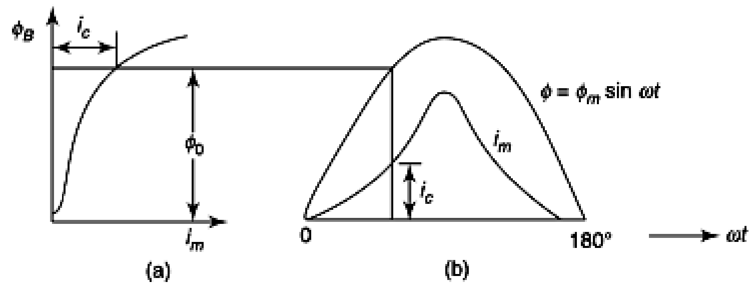
2) AC Generator.

3) Converter along with its control devices.

3.2 Transformer as source of harmonics

Transformers can be considered as source of harmonic voltages, which arise from magnetic distortion and magnetic saturation due to the presence of a DC component in its secondary. The magnitude of these harmonics depends upon the operating flux density. Converter transformers are usually operated at high flux densities than conventional 3-phase transformers, and therefore the possibility of generation of harmonics is more. Although the waveform is usually good, an AC generator may be regarded as a source of balanced harmonics because of non-uniform distribution of flux on the armature windings.

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



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

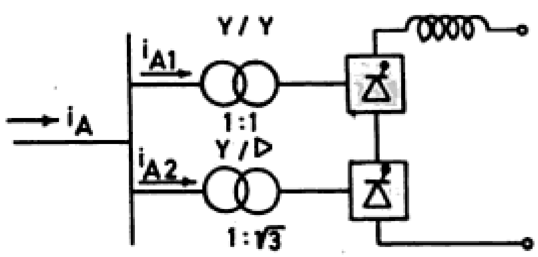
When hysteresis effect is considered, then the non-sinusoidal magnetizing current waveform is no longer symmetrical which is mainly caused by triple n harmonics and particularly the third harmonic. Thus, in order to maintain a reasonable sinusoidal voltage supply, it is necessary to supply a path for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

3.3 Harmonics due to Converters

A 12-pulse connection consists of two 6-pulse groups. One group having Y-Y connected

converter transformer with 1:1 turns ratio and the other group having Y- Δ converter transformer

bank with 1:$\sqrt{3}$ turns ratio.



Schematic Diagram of a 12 Pulse Converter Unit

3.4 Generation of Harmonics

The harmonics which are generated are of two types.

(i) Characteristic harmonics.

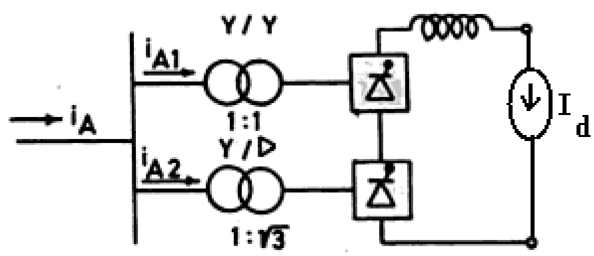
(ii) Non- characteristic harmonics.

3.5 Characteristic Harmonics

The characteristic harmonics are harmonics which are always present even under ideal operation. In the converter analysis, the DC current is assumed to be constant. But in AC current the harmonics exist which are of the order of h = np+1 and in DC current it is of the order of h = np where n is any integer and p is pulse number. Neglecting overlap, primary currents of Y-Y and Y- Δ connection of the transformer are considered taking the origin symmetrical where

i = Id for –π/3≤ ωt≤π/3= 0 for π/3≤ωt≤2π/3 and for Y-Y connection-π/3≤ωt≤-2π/3 converter

= - Id for –2π/3≤ ωt≤-π and transformer 2π/3≤ ωt≤π



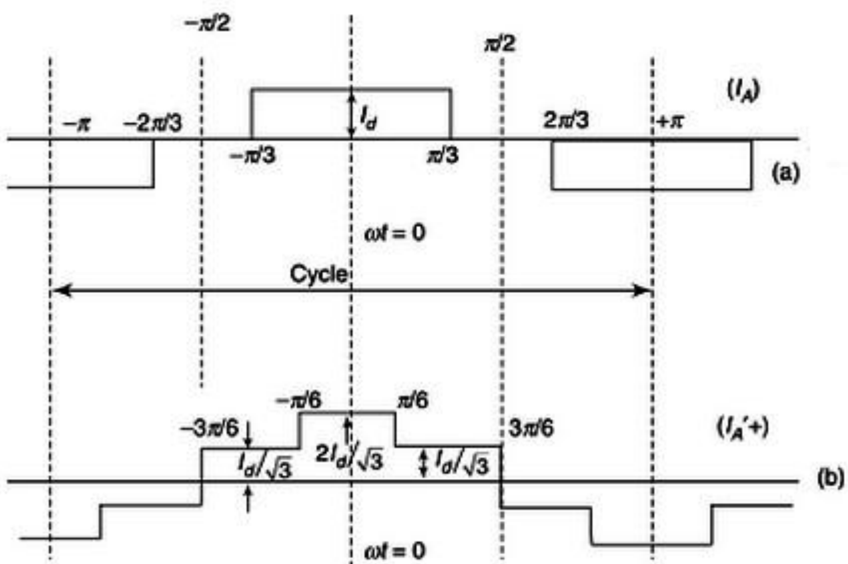


Figure (a): Phase current on primary side of Y-Y connection converter transformer
Figure (b): Phase current on primary side of Y-Δ connection converter transformer

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

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

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

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

$$\text{Therefore, } i_{A_1} = \sum_{n} a_{m_1} \cos n\omega t$$

$$\text{where, } a_{m_1} = \frac{2}{T} \int_0^{PeriodOfConduction} f(t)dt$$

Here total time period is T = π and period of conduction is π/3

So,

$$a_{m_1} = 2X \frac{2}{\pi} \int_0^{\pi/3} I_d \cos n\omega t d(\omega t)$$

3.4 Design of AC Filters

3.4.1. Harmonic Distortion:

Harmonic Distortion is given by,

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

In – harmonic current injected

Zn – harmonic impedance of the system

E1 – fundamental component of line to neutral voltage

m – highest harmonic considered

Harmonic Distortion is also given by,

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

3.5. Telephone Influence Factor (TIF):

An index of possible telephone interference and is given by, Fn = 5 n f1 pn where, Pn is the c message weighting used by Bell Telephone Systems (BTS) and Edison Electric Institute (EEI) in USA. This weighting reflects the frequency dependent sensitivity of the human ear and has a maximum value at the frequency of 1000Hz.

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

3.6. Telephone Harmonic Form Factor (THFF):

It is similar to TIF and is given by,

Fn = (n f1 / 800) Wn where, Wn – weight at the harmonic order n, defined by the Consultative Commission on Telephone and Telegraph Systems (CCITT). TIF is used in USA. THFF is popular in Europe.

3.7. IT Product:

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

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

Types of AC Filters

The various types of filters that are used are

1. Single Tuned Filter

2. Double Tuned Filter

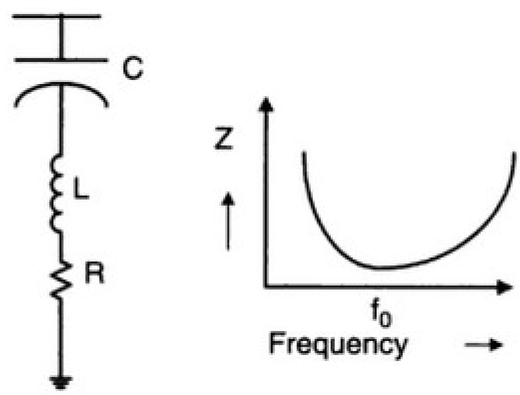
3. High Pass Filter

a) Second Order Filter

b) C Type Filter

Single Tuned Filter

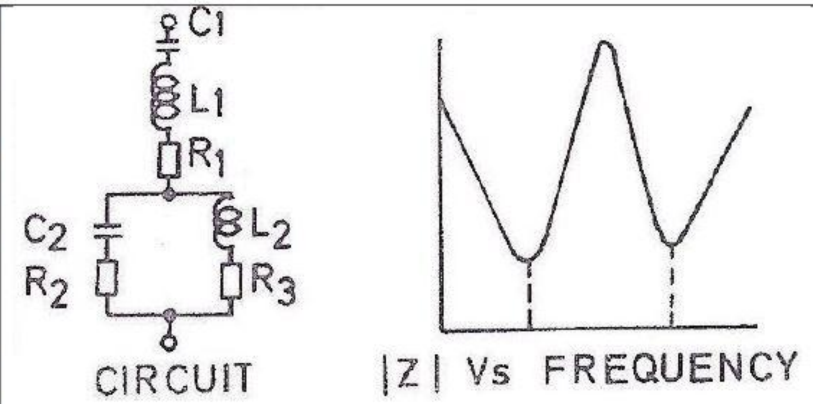
Single Tuned Filters are designed to filter out characteristic harmonics of single frequency.



Double Tuned Filter:

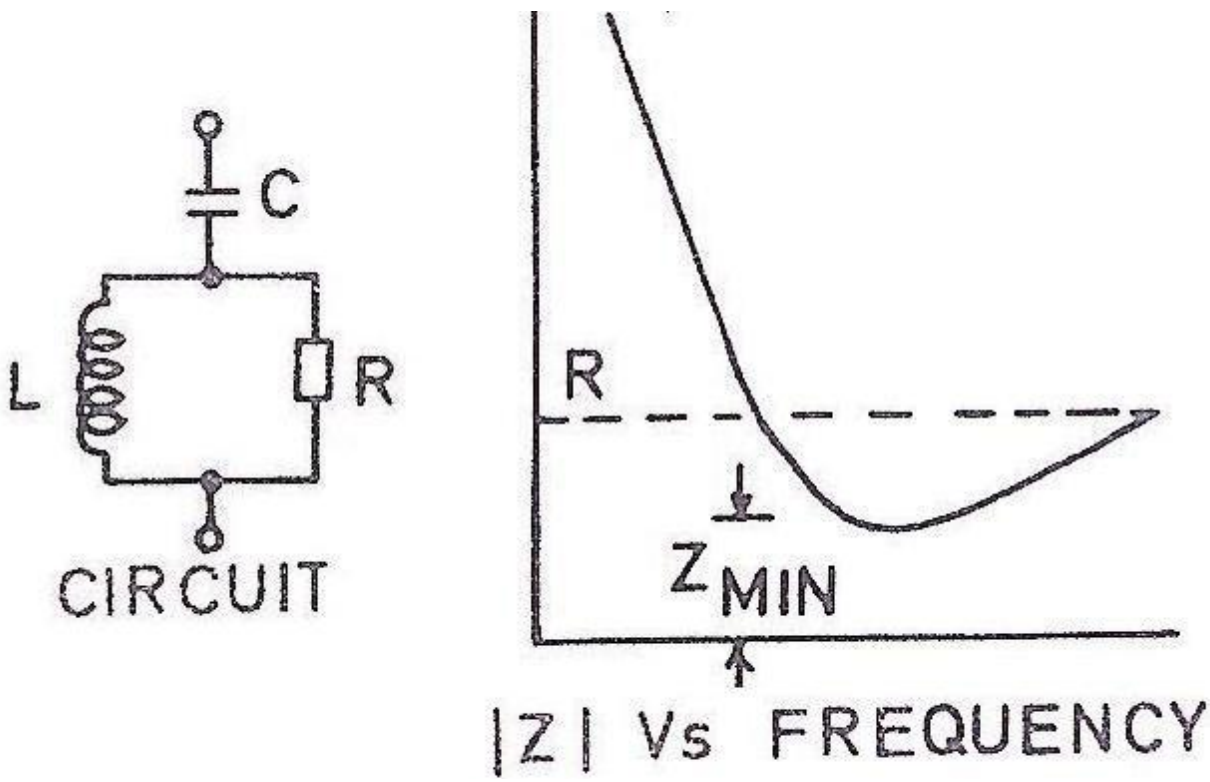
The Double Tuned Filters are used to filter out two discrete frequencies, instead of using two Single Tuned Filters. Their main disadvantages are

i. only one inductor is subject to full line impulse voltage.
ii. power loss at the fundamental frequency is considerably reduced.



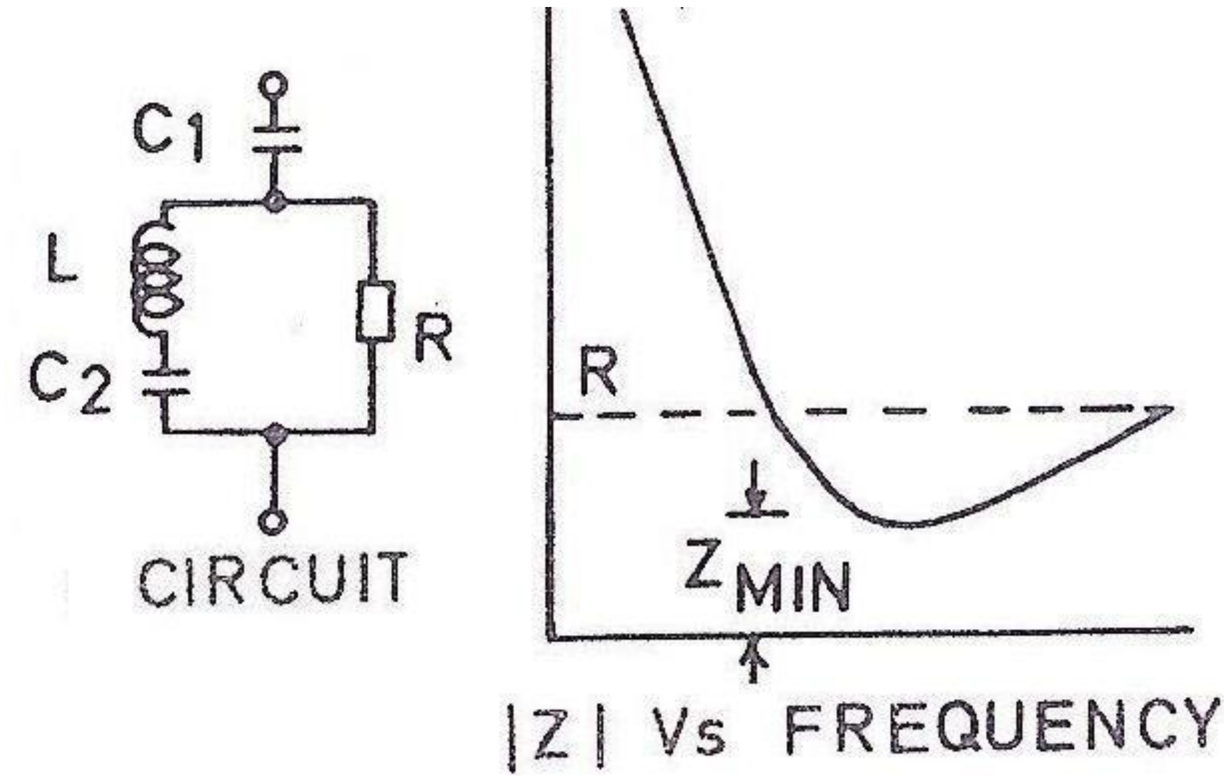
Second Order High Pass Filter

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



High Pass C Type Filter

The losses at the fundamental frequency can be reduced by using a C Type Filter where capacitor C2 is in series with inductor L, which provides a low impedance path to the fundamental component of current.



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

Design of Single Tuned Filter

The impedance ZFh of the single tuned filter at the harmonic order 'h' is given by

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

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

conditions. A tuned filter is designed to filter a single harmonic of order hr . If hr $\omega = \omega$ r , then ZFh=R=QX0 and is minimum. Since ω is variable and there could be errors in the tuning(ω r $\neq$hr ω n where ω n is the nominal (rated) frequency), it is necessary to compute the impedance of the tuned filter as a function of the detuning parameter (δ) defined by

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

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

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

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

where Ln and Cn are the nominal values of L and C such that hr ω n=(LnCn)-1/2

The variation in C can be due to

(i) error in the initial setting of C

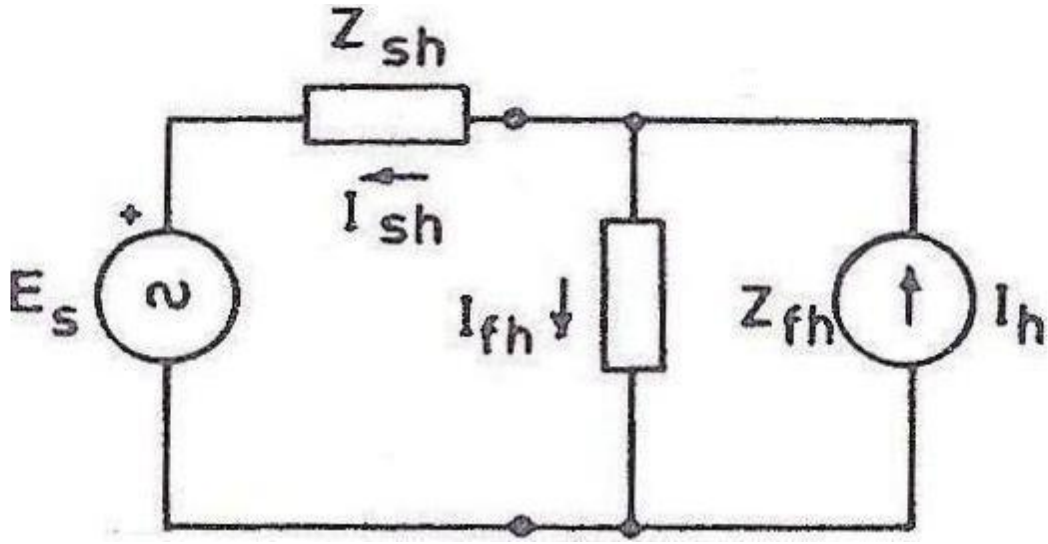
(ii) the variation in C due to the temperature dependence of the dielectric constant.

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

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

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

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

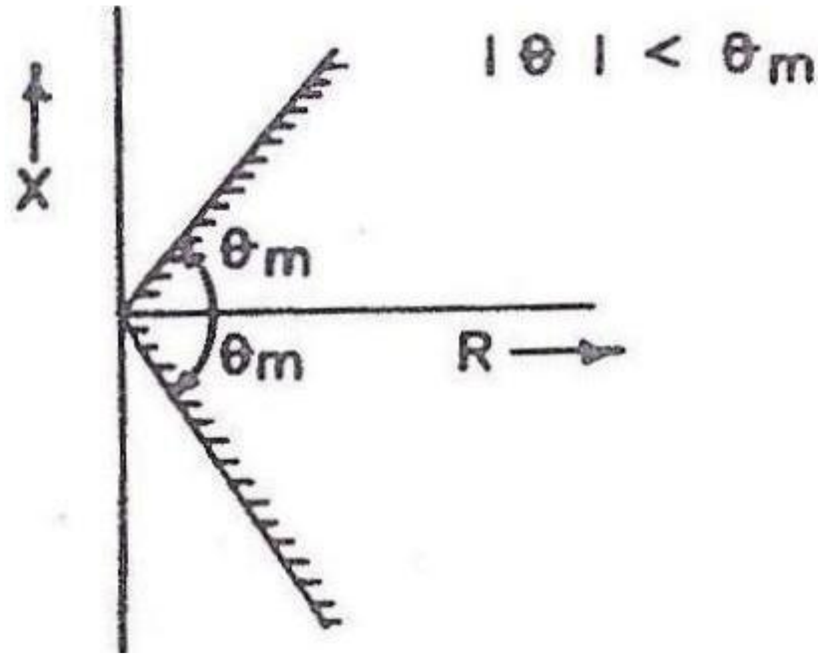


The harmonic voltage at the converter bus is

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

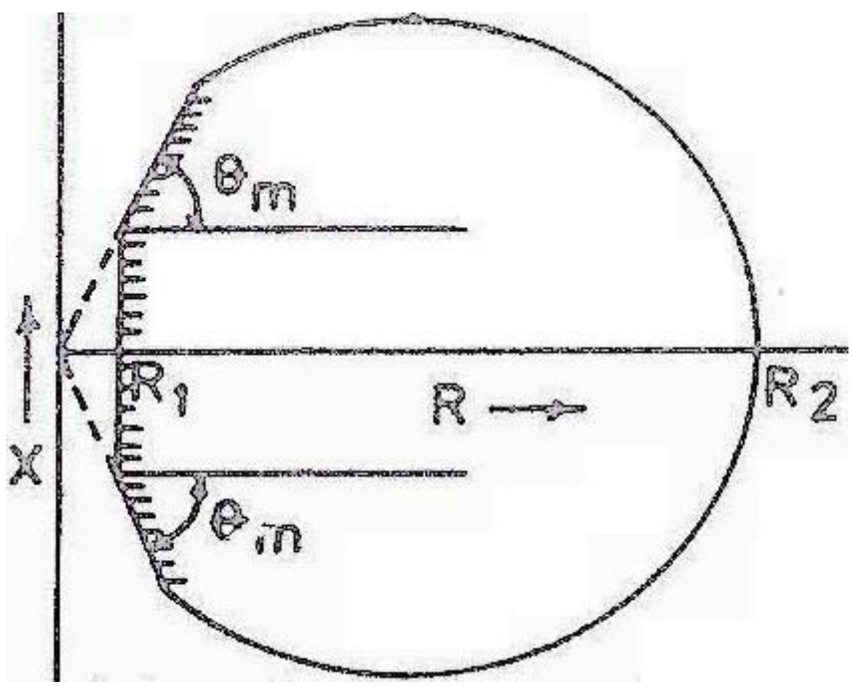
The basic objective in designing the filter is to select the filter admittance YFh in order to minimize Vh or satisfy the constraints on Vh . The problem of designing a filter is complicated by the uncertainty about the network admittance (YSh). There are two possible representations of system impedance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

(a) impedance angle is limited

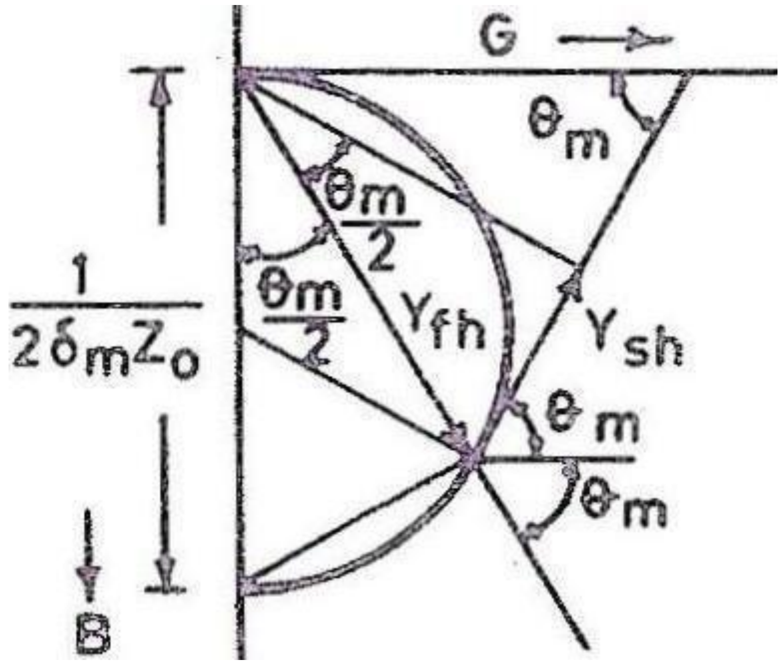


This allows a simplified computation of the optimum value of Q. In computing the optimum value of Q, we need to minimize the maximum value of Vh . The optimum value of Q corresponds to the lowest value of the upper limit on Vh .

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



The value of Yh is reduced if the detuning parameter δ is maximum = δ m . For a specified value δ m and X0 , the locus of the filter impedance as Q is varied is a semicircle in the 4th quadrant of the G-B plane as shown below.



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

Design of High Pass Filter

For harmonic frequencies of order equal to or higher than 17, a common second order

high pass filter is provided.

The following values can be chosen

0.5 < σ < 2 h0 ≤ $\sqrt{2}$ hmin where hmin is the smallest value of h to be handled by the filter. The choice of h0 given above implies that the filter impedance at hmin has decreased approximately to the value of R.

The filter impedance is given by

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

The reactive power supplied by the filter is

Qf = (h0 / (h02 ‐ 1)) . (V12 / Z0)

The filtering is improved if Qf is increased and higher value of h0 can be chosen. Hence, it is advantageous in designing high pass filter to exclude six pulse operation.

Protection of Filters

The filter is exposed to overvoltage during switching in and the magnitude of this overvoltage is a function of the short-circuit ratio (higher with low values of SCR) and the saturation characteristics of the converter transformer. During switching in, the filter current (at filter frequencies) can have magnitudes ranging from 20 to 100 times the harmonic current in normal (steady-state) operation. The lower values for tuned filters and higher values are applicable to high pass filters. These overcurrents are taken into consideration in the mechanical design of reactor coils. When filters are disconnected, their capacitors remain charged to the voltage at the instant of switching. The residual direct voltages can also occur on bus bars. To avoid, the capacitors may be discharged by short-circuiting devices or through converter transformers or by voltage transformers loaded with resistors. If the network frequency deviates from the nominal value, higher currents and losses will result in AC filters. If they exceed the limits,

Unit IV

INTRODUCTION of FACTS DEVICES

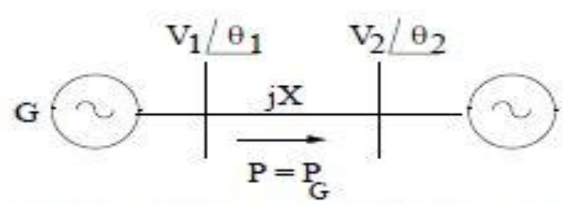
4.1 Introduction:

Modern power systems are designed to operate efficiently to supply power on demand to various load centres with high reliability. The generating stations are often located at distant locations for economic, environmental and safety reasons. For example, it may be cheaper to locate a thermal power station at pithead instead of transporting coal to load centres. Hydropower is generally available in remote areas. A nuclear plant may be located at a place away from urban areas. Thus, a grid of transmission lines operating at high or extra high voltages is required to transmit power from the generating stations to the load centres. In addition to transmission lines that carry power from the sources to loads, modern power systems are also highly interconnected for economic reasons. The interconnected systems between by (a) exploiting load diversity (b) sharing of generation reserves and (c) economy gained from the use of large efficient units without sacrificing reliability. However, there is also a downside to ac system interconnection { the security can be adversely accepted as the disturbances initiated in a particular area can spread and propagate over the entire system resulting in major blackouts caused bycascading outages.

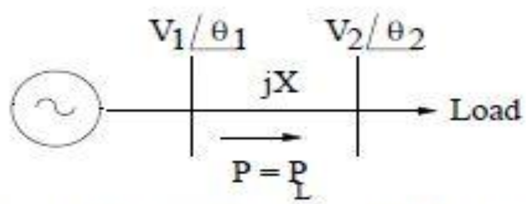
4.2 Basics of Power Transmission Networks

A large majority of power transmission lines are AC lines operating at dif- ferent voltages (10 kV to 800 kV). The distribution networks generally op- erate below 100 kV while the bulk power is transmitted at higher voltages. The lines operating at di®erent voltages are connected through transformers which operate at high e±ciency. Traditionally, AC lines have no provision for the control of power °ow. The mechanically operated circuit breakers (CB) are meant for protection against faults (caused by °ashovers due to overvoltages on the lines or reduced clearances to ground). A CB is rated for a limited number of open and close operations at a time and cannot be used for power °ow control. (unlike a high power electronic switch such as thyris- tor, GTO, IGBT, IGCT, etc.). Fortunately, ac lines have inherent power °ow control as the power °ow is determined by the power at the sending end or receiving end. For example, consider a trasmission line connecting a generating station to a load centre in Fig.1.1(a). Assuming the line to be lossless and ignoring the line charging, the power °ow (P) is given by

P =V1V2/X*sin(µ1 ¡ µ2) (1.1) where X is the series line reactance. Assuming V1 and V2 to be held constants (through voltage regulators at the two ends), the power injected by the power station determines the °ow of power in the line. The di®erence in the bus angles is automatically adjusted to enable P = PG (Note that usually there could be more than one line transmitting power from a generating station to a load centre). If one or more lines trip, the output of the power station may have to be reduced by tripping generators, so as to avoid overloading the remaining lines in operation.



(a) A line transmitting power from a generating station



(b) A line supplying power to a load

Fig. (b) shows another situation where a line supplies power to a load located at bus (2). Here also the eq. applies but the power °ow in the line is determined by the load supplied. The essential difference between the two situations is that in Fig. 1.1(a), the load centre is modelled as an infinite bus which can absorb (theoretically) any amount of power supplied to it from the generating station. This model of the load centre assumes that the generation available at the load centre is much higher than the power supplied from the remote power station (obviously, the total load supplied at the load centre is equal to the net generation available at that bus). The reliability of the power supply at a load bus can be improved by arranging two (or more) sources of power as shown in Fig. 1.2. Here, P1 is the output of G1 while P2 is the output of G2 (Note that we are neglecting losses as before). However, the tripping of any one line will reduce the availability of power at the load bus. This problem can be overcome by providing a line (shown dotted in Fig.) to interconnect the two power stations. Note that this results in the creation of a mesh in the transmission network. This improves the system reliability, as tripping of any one line does not result in curtailment of the load. However, in steady state, P1 can be higher or lower than PG1 (the output of G1). The actual power °ows in the 3 lines forming a mesh are determined by Kirchho's Voltage Law (KVL). In general, the addition of an (interconnecting) line can result in increase of power °ow in a line (while decreasing the power °ow in some other line). This is an interesting feature of AC transmission lines and not usually well understood (in the context of restructuring). In general, it can be stated that in an uncontrolled AC transmission network with loops (to improve system reliability), the power °ows in individual lines are determined by KVL and do not follow the requirements of the contracts (between energy producers and customers). In other words, it is almost impossible to ensure that the power °ow between two nodes follows a predetermined path. This is only feasible in radial networks (with no loops), but the reliability is adversely accepted as even a single outage can result in load curtailment. Consider two power systems, each with a single power station meeting its own local load, interconnected by a tie line as shown in Fig. 1.3(a). In this case, the power °ow in the tie line (P) in steady state is determined by the mismatch between the generation and load in the individual areas. Under dynamic conditions, this power °ow is determined from the equivalent circuit shown in Fig. (b). If the capacity of the tie is small compared to the size

(generation) of the two areas, the angles ±1 and ±2 are not accepted much by the tie line power °ow. Thus, power °ow in AC tie is generally uncontrolled and it becomes essential to trip the tie during a disturbance, either to protect the tie line or preserve system security. In comparison with a AC transmission line, the power °ow in a HVDC line in controlled and regulated. However, HVDC converter stations are expensive and HVDC option is used primarily for (a) long distance bulk power transmission (b) interconnection of asynchronous systems and (c) un-derwater (submarine) transmission. The application of HVDC transmission (using thyristor converters) is also constrained by the problem of commuta-tion failures a®ecting operation of multiterminal or multi-feed HVDC sys-tems. This implies that HVDC links are primarily used for point-to-point transmission of power and asynchronous interconnection (using Back to Back (BTB) links).

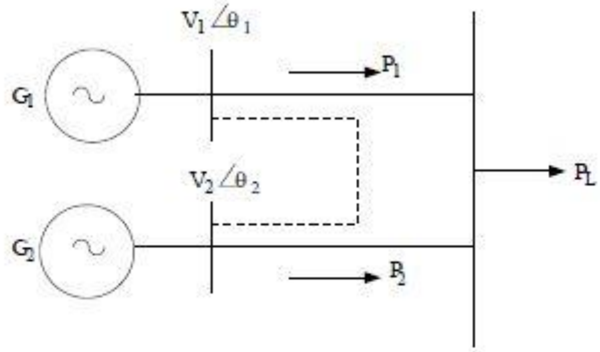
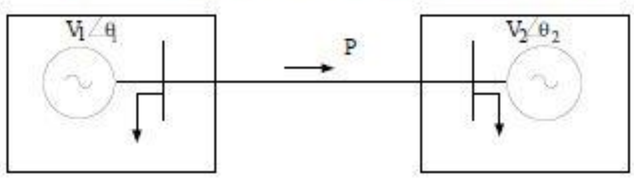
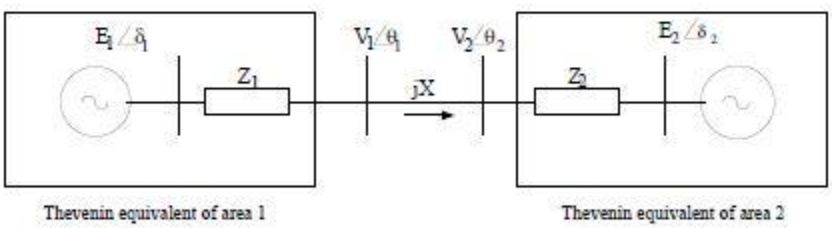


Figure 1.2: Two generating stations supplying a load



(a)Single line diagram



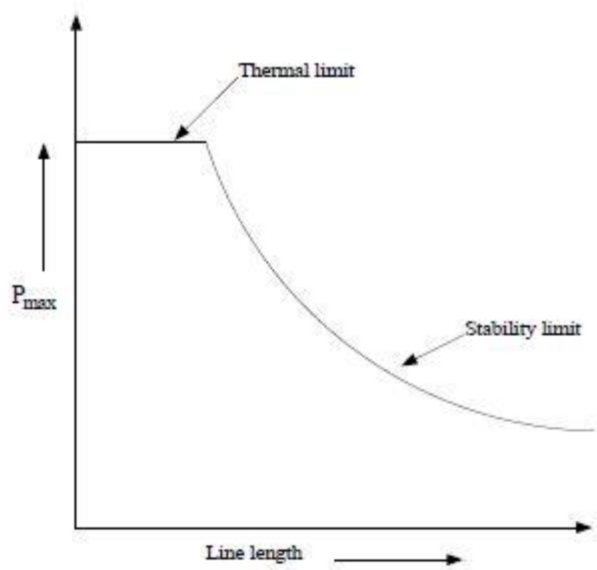
(b)Equivalent circuit

4.3 Control of Power Flow in AC Transmission Line

We may like to control the power °ow in a AC transmission line to (a) enhance power transfer capacity and or (b) to change power °ow under dynamic conditions (subjected to disturbances such as sudden increase in load, line trip or generator outage) to ensure system stability and security. The stability can be a®ected by growing low frequency, power oscillations (due to generator rotor swings), loss of synchronism and voltage collapse caused by major disturbances. From eq. (1.1), we have the maximum power (Pmax) transmitted over a line as

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

where ±max (30±{40±) is selected depending on the stability margins and the sternness of the terminal buses to which the line is connected. For line lengths exceeding a limit, Pmax is less than the thermal limit on the power transfer determined by the current carrying capacity of the conductors (Note this is also a function of the ambient temperature). As the line length increases, X increases in a linear fashion and Pmax reduces as shown in Fig. 1.4.



The FACTS controllers can be classified as

1. Shunt connected controllers

2. Series connected controllers

3. Combined series-series controllers

4. Combined shunt-series controllers

Depending on the power electronic devices used in the control, the

FACTS controllers can be classified as

(A) Variable impedance type

(B) Voltage Source Converter (VSC) { based.

The variable impedance type controllers include:

(i) Static Var Compensator (SVC), (shunt connected)

(ii) Thyrister Controlled Series Capacitor or compensator (TCSC), (series

connected)

(iii) Thyristor Controlled Phase Shifting Transformer (TCPST) of Static

PST (combined shunt and series)

The VSC based FACTS controllers are:

(i) Static synchronous Compensator (STATCOM) (shunt connected)

(ii) Static Synchronous Series Compensator (SSSC) (series connected)

(iii) Interline Power Flow Controller (IPFC) (combined series-series)

(iv) Uni¯ed Power Flow Controller (UPFC) (combined shunt-series)

Some of the special purpose FACTS controllers are

(a) Thyristor Controller Braking Resistor (TCBR)

(b) Thyristor Controlled Voltage Limiter (TCVL)

(c) Thyristor Controlled Voltage Regulator (TCVR)

(d) Interphase Power Controller (IPC)

(e) NGH-SSR damping

The FACTS controllers based on VSC have several advantages over the variable impedance type. For example, a STATCOM is much more compact than a SVC for similar rating and is technically superior. It can supply required reactive current even at low values of the bus voltage and

can be designed to have in built short term overload capability. Also, a STATCOM can supply active power if it has an energy source or large energy storage at its DC terminals. The only drawback with VSC based controllers is the requiremen of using self commutating power semiconductor devices such as Gate Turn- (GTO) thyristors, Insulated Gate Bipolar Transistors (IGBT), Integrated Gate Commutated Thyristors (IGCT). Thyristors do not have this capability and cannot be used although they are available in higher voltage ratings and tend to be cheaper with reduced losses. However, the technical advantages with VSC based controllers coupled will emerging power semiconductor devices using silicon carbide technology are expected to lead to the wide spread use of VSC based controllers in future. It is interesting to note that while SVC was the first FACTS con-trollers (which utilized the thyristor valves developed in connection with HVDC line commutated convertors) several new FACTS controller based on VSC have been developed. This has led to the introduction of VSC in HVDC transmission for ratings up to 300 MW.

Static Var Compensator (SVC)

The Static Var Compensator (SVC), a first generation FACTS controller is taken up for study. It is a variable impedance device where the current through a reactor is controlled using back to back connected thyristor valves. The application of thyristor valve technology to SVC is an shoot of the developments in HVDC technology. The major difference is that thyristor valves used in SVC are rated for lower voltages as the SVC is connected to an EHV line through a step down transformer or connected to the tertiary winding of a power transformer. The application of SVC was initially for load compensation of fast changing loads such as steel mills and arc furnaces. Here the objective is to provide dynamic power factor improvement and also balance the currents on the source side whenever required. The application for transmission line compensators commenced in the late seventies.

Here the objectives are:

1. Increase power transfer in long lines [1,3,6]

2. Improve stability with fast acting voltage regulation [7,8]

3. Damp low frequency oscillations due to swing (rotor) modes [9{12]

4. Damp subsynchronous frequency oscillations due to torsional modes

[13{15]

5. Control dynamic overvoltages [1,5]

A SVC has no inertia compared to synchronous condensers and can be extremely fast in response (2-3 cycles). This enables the fast control of reactive power in the control range.

Analysis of SVC

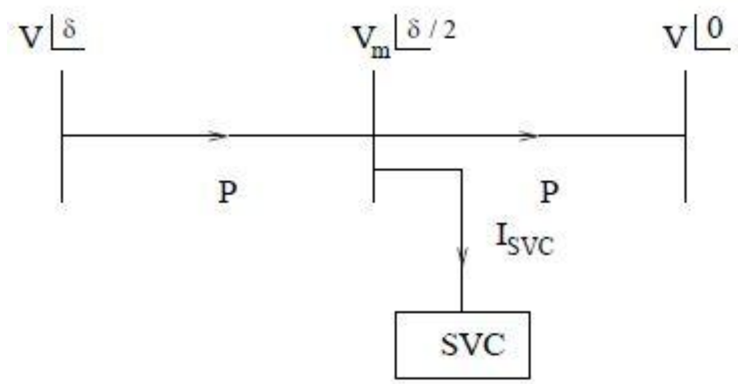
The location of SVC is important in determining its effectiveness. Ideally, it should be located at the electrical centre of the system or midpoint of a transmission line. For example, consider a symmetric lossless transmission line with SVC connected at the midpoint (see Fig. 3.1). Without SVC, the voltage at the midpoint is given by,

$$V_{mo} = \frac{V \cos \delta/2}{\cos \theta/2}$$

where µ = ¯l is the electrical length of the line, l is the length of the line and ¯ is the phase constant given by

$$\beta = \omega\sqrt{lc} = 2\pi f\sqrt{lc}$$

where l and c are positive sequence inductance and capacitance of the line per unit length, f is the operating frequency.

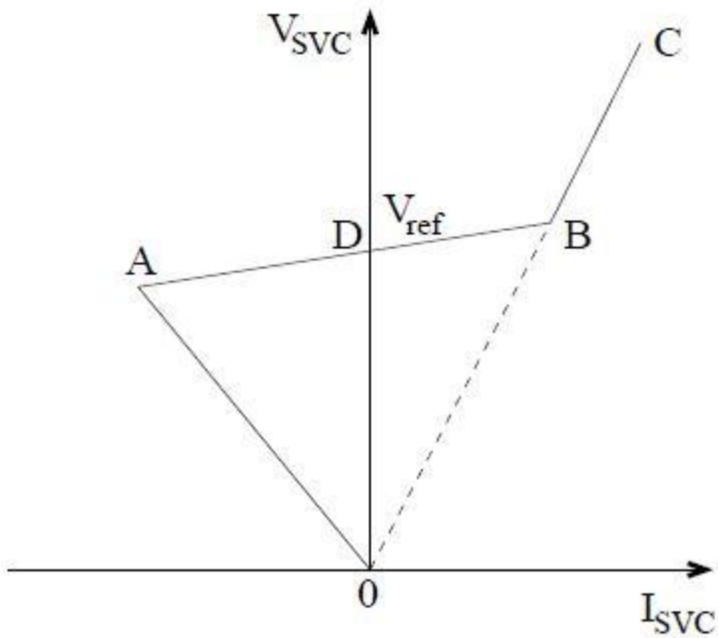


It can be shown that the voltage variation in the line (due to varia- tion in ±) is maximum at the midpoint. SVC helps to limit the variation by suitable control. The steady state control characteristics of SVC is shown in Fig. 3.2 where ADB is the control range. OA represents the charac- teristic where the SVC hits the capacitor limit, BC represents the SVC at its inductor limit. Note that SVC current is considered positive when SVC susceptance is inductive. Thus

$$I_{SVC} = -B_{SVC}V_{SVC}$$

The slope of OA is BC (susceptance of the capacitor) and the slope of OBC is BL (susceptance of the reactor). A positive slope (in the range of 1-5%) is given in the control range to (a) enable parallel operation of more than one SVC connected at the same or neighboring buses and

(b) prevent SVC hitting the limits frequently.



Modern power systems are highly complex and are expected to fulfill the growing demands of power wherever required, with acceptable quality and costs. The economic and environmental factors necessitate the location of generation at places away from load centers. The restructuring of power utilities has increased the uncertainties in system operation. The regulatory constraints on the expansion of the transmission network has resulted in reduction of stability margins and increased the risks of cascading outages and blackouts. This problem can be effectively tackled by the introduction of high power electronic controllers for the regulation of power flows and voltages in AC transmission networks. This allows 'flexible' operation of AC transmission systems whereby the changes can be accommodated easily without stressing the system. Power electronic based systems and other static equipment that provide controllability of power flow and voltage are termed as FACTS controllers. The technology of thyristor valves and digital controls was initially extended to the development of Static Var Compensator (SVC) for load compensation and voltage regulation in long transmission lines. In 1988, Dr. Narain G. Hingorani introduced the concept of Flexible AC Transmission Systems (FACTS) by incorporating power electronic controllers to enhance power transfer in existing AC transmission lines, improve voltage regulation and system security without adding new lines. The FACTS controllers can also be used to regulate power flow in critical lines and hence, ease congestion in electrical networks. FACTS does not refer to any single device, but a host of controllers such as SVC, Thyristor Controlled Series Capacitor (TCSC), Static Phase Shifting Transformer (SPST), and newer controllers based on Voltage Source Converters (VSC)-Static synchronous Compensator (STATCOM), Static Synchronous Series Compensator (SSSC), Unified Power Flow Controller (UPFC), Interline Power Flow Controller (IPFC) etc. The advent of FACTS controllers has already made a major impact on the planning and operation of power delivery systems. The concept of Custom Power introduced by Dr. Hingorani in 1995 has extended the application of FACTS controllers for distribution systems with the objective of improving power quality. Although the concept of FACTS was developed originally for transmission network; this has been extended since last 10 years for improvement of Power Quality (PQ) in distribution systems operating at low or medium voltages. In the early days, the power quality referred primarily to the continuity of power supply at acceptable voltage and frequency. However, the prolific increase in the use of computers, microprocessors and power electronic systems has resulted in power quality issues involving transient disturbances in voltage magnitude, waveform and frequency. The nonlinear loads not only cause PQ problems but are also very sensitive to the voltage deviations. In the modern context, PQ problem is defined as “Any problem manifested in voltage, current or frequency deviations that result in failure or disoperation of customer equipment" .The first power electronics based static shunt compensator applied for load compensation was SVC using thyristor-controlled reactor in parallel with fixed or thyristor-switched capacitors. This shunt connected static compensator was developed as an advanced static VAR compensator where a Voltage Source Convertor (VSC) is used instead of the controllable reactors and switched capacitors. Although VSCs require self commutated power semiconductor devices such as GTO, IGBT, IGCT, MCT, etc (with higher costs and losses) unlike in the case of variable impedance type SVC which use thyristor devices, there are many technical advantages of a DSTATCOM over a SVC.

These are primarily:

(i) Faster response

(ii) Requires less space as bulky passive components (such as reactors) are eliminated

(iii) Inherently modular and relocatable

(iv) It can be interfaced with real power sources such as battery, fuel cell or SMES

(superconducting magnetic energy storage)

(v) A STATCOM has superior performance during low voltage condition as the reactive current can be maintained constant. In a SVC, the capacitive reactive current drops linearly with the voltage.

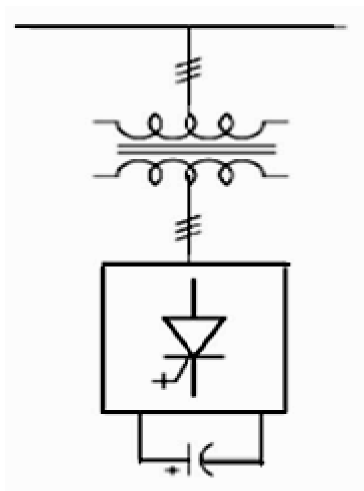
(vi) The application of VSC also permits multi-function (or composite) compensation that includes active filtering to prevent the flow of harmonic currents on the source side.

The STATCOM consists of a current-controlled Voltage Source Inverter (VSI) which injects current at the Point of Common Coupling (PCC) through the interface inductor. The operation of VSI is supported by a dc storage capacitor. The transient response of the STATCOM is very significant while compensating ac and dc loads [117]. In some of the electric power consumers, such as the telecommunications industry, power-electronics drive applications, etc., there is a constraint for ac as well as dc loads. The telecommunication industry uses several parallel-connected switch-mode rectifiers to support dc bus voltage. Such an arrangement draws nonlinear load currents from the utility. This causes reduced power factor, more losses and less efficiency. Obviously, there are Power Quality issues, such as unbalance, poor power factor, and harmonics produced by telecom equipment in power distribution networks. Therefore, the functionalities of the conventional STATCOM should be increased to mitigate the above mentioned PQ problems and to supply the dc loads from its DC Link as well [51]. Static Synchronous Compensator (STATCOM) is an effective measure to maintain voltage stability and improve power quality of distribution grid. This chapter deals with the

modeling and control scheme of STATCOM. A stability analysis of STATCOM is obtained by bode plot approach. The theoretical analysis and design are verified by the results.

Static Synchronous Compensator

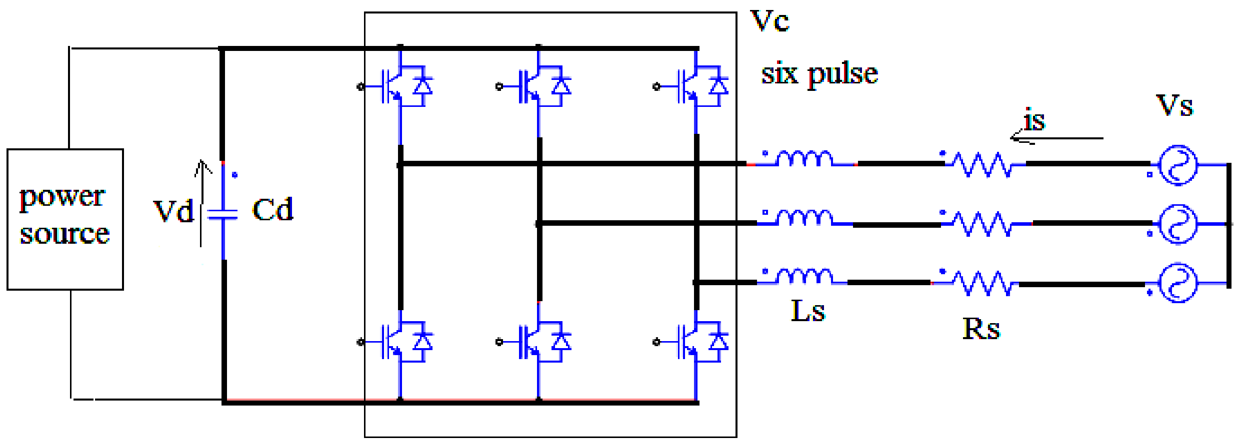
Static Synchronous Compensator (STATCOM) is a voltage source converter based FACTS controller. It is a shunt controller mainly used to regulate voltage by generating/absorbing reactive power. The schematic diagram of STATCOM is shown in Fig. 4.1. STATCOM has no long term energy support in the DC Side and cannot exchange real power with the ac system; however it can exchange reactive power. The reactive power is varied by varying the magnitude of the converter output voltage. A small phase difference exists between the converter output voltage and STATCOM bus voltage so that real power is drawn from the lines to compensate for the losses. STATCOMs are employed at distribution and transmission levels – though for different purposes. When a STATCOM is employed at the distribution level or at the load end for power factor improvement and voltage regulation alone it is called STATCOM.



4.3 Voltage Source Converter

In recent years, voltage source converter technology has made a great progress through the development of high power self-turnoff type semiconductor devices. The rating for converter of this type in practical application has already reached as high. Because of its advantage over the line commutated type in performance characteristics and compactness, various applications of the voltage source converter have been developed and researched. Three phase Voltage Source Converter (VSC) is the heart of most new FACTS and custom power equipments. It may be employed as a series or shunt element or combination of both, as in case of Unified Power Flow Controller (UPFC). Multilevel voltage source converter topology is superior alternative to multi-pulse arrangement for high power applications like STATCOM. Voltage Source Converters (VSC) are commonly used to transfer power between a DC system and an AC system or back to back connection for AC systems with different frequencies, such as variable speed wind turbine systems [118]. A basic VSC structure is shown in Fig. 3.2 where Rs and Ls represent the resistance and is the current injected into the grid. A DC capacitor is connected on the DC side to produce a smooth DC voltage. The switches in the circuit represent controllable semiconductors, such as IGBT or power transistors. Six-pulse

DSTATCOM configuration with the IGBT's can be used as power devices. The IGBTs are connected anti parallel with diodes for commutation purposes and charging of the DC capacitor. Fig. 3.3 represents simulink model of six pulse voltage source converter and in Fig. 3.4 waveform of converter and load voltage are shown.



Unit-V

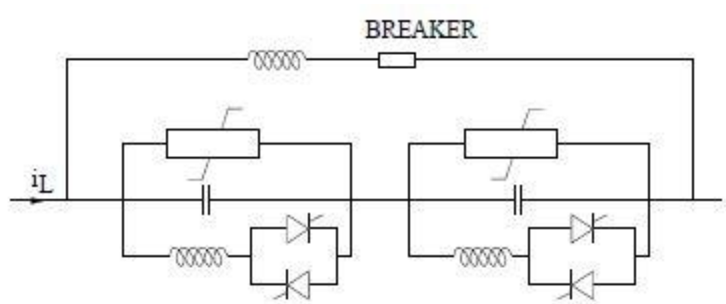
STATIC SERIES COMPENSATORS

5.1Introduction:

The Static Synchronous Series Compensator (SSSC) is a series connected FACTS controller based on VSC and can be viewed as an advanced type of controlled series compensation, just as a STATCOM is an advanced SVC. A SSSC has several advantages over a TCSC such as (a) elimination of bulky passive components { capacitors and reactors, (b) improved technical characteristics (c) symmetric capability in both inductive and capacitive operating modes (d) possibility of connecting an energy source on the DC side to exchange real power with the AC network. However, a SSSC is yet to be installed in practice except as a part of UPFC or Convertible Static Compensator (CSC). An example of the former is a 160 MVAR series connected converter as part of the Uni¯ed Power Flow Controller installed at Inez station of American Electric Power (AEP). An example of the latter are the two, 100 MVA series connected converters at Marcy 345 kV substation in Central New York belonging to NYPA. In both cases, 24 pulse three-level converters are used. This topology reduces the injected harmonic voltages considerably and there is no need for harmonic filters.

5.2 Operation of TCSC

A single line diagram of a TCSC is shown in Fig. 4.3 which shows two modules connected in series. There can be one or more modules depending on the requirement. To reduce the costs, TCSC may be used in conjunction with series capacitors.



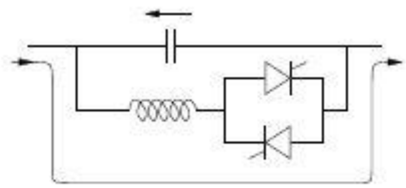
(a) Bypassed

Here the thyristor valves are gated for 180± conduction (in each direction) and the current °ow in the reactor is continuous and sinusoidal. The net reactance of the module is slightly inductive as the susceptance of the reactor is larger than that of the capacitor. During this mode, most of the line current is °owing through the reactor and thyristor valves with some current °owing through the capacitor. This mode is used mainly for protecting the capacitor against overvoltages (during transient overcurrents in the line). This mode is also termed as TSR (Thyristor Switched Reactor) mode.

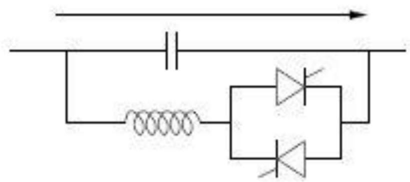
(b) Inserted with Thyristor Valve Blocked

In this operating mode no current flows through the valves with the blocking of gate pulses. Here, the TCSC reactance is same as that of the capacitor and there is no difference in the performance of TCSC in this mode with that of a capacitor. Hence this operating mode is generally avoided.

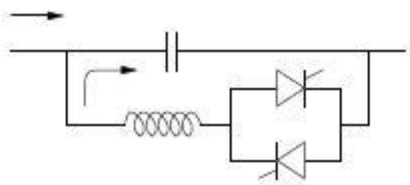
This mode is also termed as waiting mode.



(a) Bypassed



(b)Thyristor blocked



(c)Vernier operation

(c) Inserted with Vernier Control

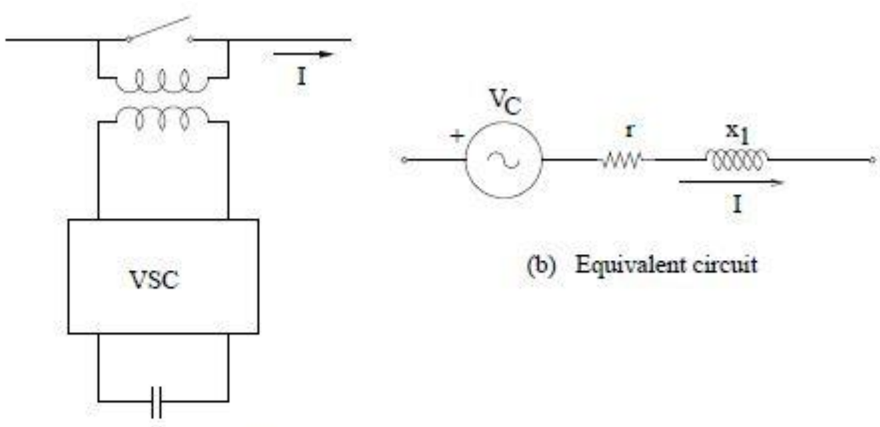
In this operating mode, the thyristor valves are gated in the region of such that they conduct for the part of a cycle. The effective value of TCSC reactance (in the capacitive region) increases as the conduction angle increases from zero. ®min is above the value of ® corresponding to the parallel resonance of TCR and the capacitor (at fundamental frequency). In the inductive vernier mode, the TCSC (inductive) reactance increases as the conduction angle reduced from 180±. Generally, vernier control is used only in the capacitive region and not in the inductive region.

Static Synchronous Series Compensator (SSSC)

The Static Synchronous Series Compensator (SSSC) is a series connected FACTS controller based on VSC and can be viewed as an advanced type of controlled series compensation, just as a STATCOM is an advanced SVC. A SSSC has several advantages over a TCSC such as (a) elimination of bulky passive components { capacitors and reactors, (b) improved technical characteristics (c) symmetric capability in both inductive and capacitive operating modes (d) possibility of connecting an energy source on the DC side to exchange real power with the AC network. However, a SSSC is yet to be installed in practice except as a part of UPFC or Convertible Static Compensator (CSC). An example of the former is a 160 MVAR series connected converter as part of the Uni¯ed Power Flow Controller installed at Inez station of American Electric Power (AEP). An example of the latter are the two, 100 MVA series connected converters at Marcy 345 kV substation in Central New York belonging to NYPA. In both cases, 24 pulse three-level converters are used. This topology reduces the injected harmonic voltages considerably and there is no need for harmonic filters.

Operation of SSSC and the Control of Power Flow

The schematic of a SSSC is shown in Fig. 5.1(a). The equivalent circuit of the SSSC is shown in Fig. 5.1(b). The magnitude of VC can be controlled to regulate power flow. The winding resistance and leakage reactance of the connecting transformer ap- pear is series with the voltage source VC. If there is no energy source on



(a) Schematic of SSSC

(b) Equivalent circuit

the DC side, neglecting losses in the converter and DC capacitor, the power balance in steady state leads to Re[VcI¤] = 0 The above equation shows that VC is in quadrature with I. If VC lags I by 90±, the operating mode is capacitive and the current (magnitude) in the line is increased with resultant increase in power °ow. On the other hand, if VC leads I by 90±, the operating mode is inductive, and the line current is decreased. Note that we are assuming the injected voltage is sinusoidal (neglecting harmonics). Since the losses are always present, the phase shift between I and VC is less than 90± (in steady state). In general, we can write

$$\hat{V}_C = V_C(\cos\gamma - j\sin\gamma)e^{j\phi} = (V_{Cp} - jV_{Cr})e^{j\phi}$$

where Á is the phase angle of the line current, ° is the angle by which ^ VC lags the current. VCp and VCr are the in-phase and quadrature components of the injected voltage (with reference to the line current). We can also term them as active (or real) and reactive components. The real component is required to meet the losses in the converter and the DC capacitor.

Unified Power Flow Controller

The Unified Power Flow Controller (UPFC) proposed by Gyugyi [1] is the most versatile FACTS controller for the regulation of voltage and power flow in a transmission line. It consists of two voltage source converters (VSC) one shunt connected and the other series connected. The DC capacitors of the two converters are connected in parallel (see Fig.). If the switches 1 and 2 are open, the two converters work as STATCOM and SSSC controlling the

reactive current and reactive voltage injected in shunt and series respectively in the line. The closing of the switches 1 and 2 enable the two converters to exchange real (active) power °ow between the two converters. The active power can be either absorbed or supplied by the series connected converter. As discussed in the previous chapter, the provision of a controllable power source on the DC side of the series connected converter, results in the

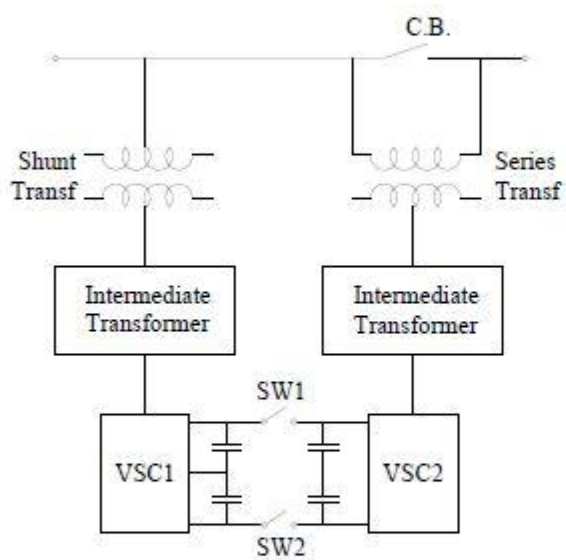
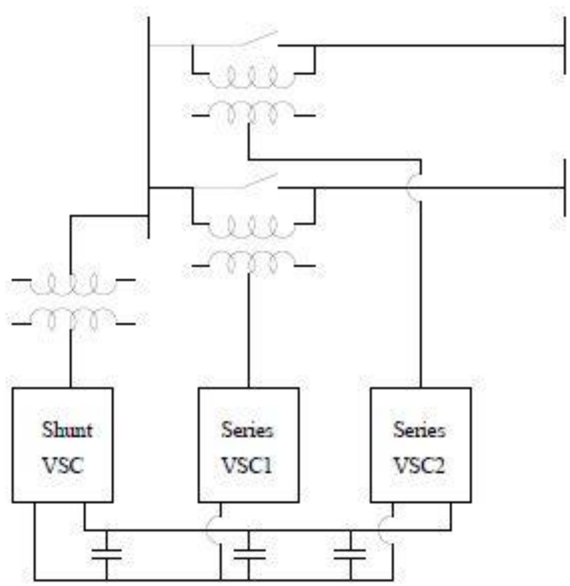


Figure 8.1: A UPFC schematic



control of both real and reactive power °ow in the line (say, measured at the

receiving end of the line). The shunt connected converter not only provides the necessary power required, but also the reactive current injected at the converter bus. Thus, a UPFC has 3 degrees of freedom unlike other FACTS controllers which have only one degree of freedom (control variable).

The concept of combining two or more converters can be extended to provide flexibility and additional degrees of freedom. A Generalized UPFC (GUPFC) refers to 3 or more converters out of which one is shunt connected while the remaining converters are series connected [16]. (see Fig. 8.2). An Interline Power Flow Controller (IPFC) refers to the configuration of two or more series connected converters sharing a common DC bus (see Fig). Even when only two converters are used, they may be designed to operate in the shunt or series mode. Depending on the requirement, there can be up to 11 configurations of the two converters resulting in (i) one or two STATCOMs (ii) one or two SSSCs (iii) combinations of a STATCOM and SSSC (iv) UPFC with series converter connected in either of the two lines and (v) IPFC. Such flexible configuration of the two converters is termed as the Convertible Static Compensator (CSC) and has been installed at New York Power Authority's (NYPA) Marcy 345 kV substation. The CSC which consists of two 100 MVA, three-level VSCs, a 200 MVA shunt transformer and two 100 MVA series transformers was commissioned in 2002.

JNTHU PREVIOUS YEAR QUESTIONS

1.Explain various types of HVDC links.

2.What is extinction angle control?

3. Why harmonics get generated in power systems? What are their harmful effects? How can they be removed from the systems?

4. How DC/AC converters are modelled for power flow studies? Describe simultaneous approach for load flow studies of AC/DC systems.

5.How do you justify the name “Flexible AC transmission systems” for certain equipment connected in a power system?

6.Describe control schemes of SSSC (static series synchronous compensator).

7.What are the objectives of shunt compensation? Describe midpoint compensation of a transmission line.

8.Describe the function of UPFC (unified power flow controller). How do you justify the name‘

9.Analyse the bridge circuit of twelve pulse converter and arrive at the equivalent circuit.

10.What are the various applications of high voltage DC transmission?

11.Explain typical layout of HVDC converter station.

12.Explain the control of HVDC link with reference to power transmitted between two areas connected by the link.

13.Explain principles of static VAr compensators and their applications.

14.Describe briefly various types of FACTS controllers available

15.What is meant by midpoint compensation with respect to shunt compensation? Explain the advantages to the power system by adapting to it.

16.Why is TCSC (thyristor controlled series capacitor) used in transmission line? Explain its advantages and disadvantages.

17.What is the basic principle of a UPFC (unified power flow controller)?

18.With a neat sketch explain typical layout of a HVDC converter station

19.Explain the sequence of steps taken in starting and stopping of a DC link.

20.What are the various sources of reactive power in a power system? Explain the necessity of compensating reactive power. List out relative advantages and disadvantages of each source of reactive power.

21.Explain various approaches to the solution of AC-DC power flow.

22.Describe various types of FACTS controllers briefly and what improvements can they bring about in the performance of a power system.

23.Compare the performance and advantages of SVC and STATCOM

24.What are the objectives of series compensation? Describe the functioning of static series synchronous compensator (SSSC).

25.Describe the working principle of a FACTS device capable of supply and control of independent real and reactive power

26.Compare the HVDC transmission system with HVAC transmission system listing advantages and disadvantages of them.

27.What are the principles of DC link control?

28.How do harmonics arise in power systems? Describe various filters used for controlling harmonics.

29.How is DC load flow conducted?

30.Explain how FACTS devices help in controlling power flows.

31.Explain in detail principle of working of static VAr compensator (SVC).

32.Explain the improvement that a TCSC can bring about in a power system and what are its disadvantages

33.Describe the basic operating principle of a UPFC (unified power flow controller).

Objective Questions

1. The relation between traveling voltage wave and current wave is

(A) $e = i (L/C)^{1/2}$

(B) $e = i (C/L)^{1/2}$

(C) $e = i (iL/C)^{1/2}$

(D) $(L/iC)^{1/2}$

2. The protection against direct lightening strokes and high voltage steep waves is provided by

(A) earthing of neutral

(B) lightening arresters

(C) ground wires

(D) lightening arresters and ground wires.

3. Voltages under Extra High Voltage are

(A) 1 kV and above

(B) 11 kV and above

(C) 132 kV and above

(D) 330 kV and above.

4. In order to increase the limit of distance of transmission line

(A) series resistances are used

(B) synchronous condensers are used

(C) shunt capacitors and series reactors are used

(D) series capacitors and shunt reactors are used.

5. The permissible voltage variable in voltage in distribution is

(A) 0.1%

(B) 1%

(C) 10%

(D) 50%.

6. 750 kV is termed as

(A) Medium high voltage

(B) High voltage

(C) Extra high voltage

(D) Ultra high voltage.

7. The highest transmission voltage in the world is __________ kV.

8.Shunt capacitors as compared to synchronous condensers have __________ losses.

9. In harmonic voltage the possibility of resonance exists in case of __________.

10. Initial cost of synchronous condensers is __ ________as compared to that of shunt capacitors.

11. FACTS stands for______________

(a) Flexible Alternating Current Transmission System

(b) Flexible Alternating Conductor Transmission System

(c) Flexible Alternator Current Transmission System

(d) Non of these

12. Skin effect present in

(a) HVDC Transmission System

(b) HVAC Transmission System

(c) both HVDC and HVAC Transmission System

(d) None

13. Corona Effect present in

(a) HVDC Transmission System

(b) HVAC Transmission System

(c) both HVDC and HVAC Transmission System

(d) None

14. size of the insulators depends on

(a) Voltage Level

(b) Current

(c) voltage and current

(d) none

15.How many conductors are used in HVDC System

(a) Three conductors

(b) two conductors

(c) one conductor

(d) none

(16). Which among these HVDC projects are commissioned in India**?**

a. Rihand – Delhi HVDC
b. Vindhyachal Back to Back only
c. Chandrapur only
d. All of these
e. None of these

Ans:d

17 **At what location are the shunt capacitors installed for voltages above 33 kV and above?**

a. Are located near the motors
b. Are installed in distribution substations
c. Both (A) and (B)
d. None of these

Ans:b

18. **Which among these is a part of HVDC link?**

a. Two earth electrodes
b. Converter valves
c. Bipolar DC line
d. All of these
e. None of these

Ans:d

19. **At what level is the load shedding carried out?**

a. Distribution level
b. Transmission level
c. Both (A) and (B)
d. Depending upon the load

Ans: a

20. **What type of insulation is preferred for DC smoothing Reactors?**

a. Air
b. Oil
c. Paper
d. Varnish

Ans:b

21. **At what condition does the corona start, if Es is the electrical stress and Ecr is the critical voltage?**

a. Es > Ecr
b. Es = Ecr
c. Es < Ecr
d. Es << Ecr

Ans:a

22. **Which method of voltage control is applied for long line AC transmissions?**

a. Switching by shunt capacitors
b. Tap changing transformers
c. Switching by shunt reactors
d. Static Var sources

Ans:c

23. **For what voltage is Twin conductor bundle used in India?**

a. 220 kV
b. 500 kV
c. 750 kV
d. 330 kV

Ans:b