LECTURE NOTES

ON

FUNDAMENTALS OF HVDC AND FACTS DEVICES

IV B.Tech II Sem (JNTU –R15)

Prepared by

Ms. B. Manogna
Assistant Professor

ELECTRICAL AND ELECTRONICS ENGINEERING

INSTITUTE OF AERONAUTICAL ENGINEERING
(Autonomous)
Dundigal, Hyderabad - 500043

UNIT – I

INTRODUCTION

1.1 Historical Background

A high-voltage, direct current (HVDC) electric power transmission system (also called a power super highway or an electrical super highway) uses direct current for the bulk transmission of electrical power, in contrast with the more common alternating current (AC) systems.[5] For long-distance transmission, HVDC systems may be less expensive and suffer lower electrical losses. For underwater power cables, HVDC avoids the heavy currents required to charge and discharge the cable capacitance each cycle. For shorter distances, the higher cost of DC conversion equipment compared to an AC system may still be justified, due to other benefits of direct current links.

HVDC allows power transmission between unsynchronized AC transmission systems. Since the power flow through an HVDC link can be controlled independently of the phase angle between source and load, it can stabilize a network against disturbances due to rapid changes in power. HVDC also allows transfer of power between grid systems running at different frequencies, such as 50 Hz and 60 Hz. This improves the stability and economy of each grid, by allowing exchange of power between incompatible networks.

Power Transmission was initially carried out in the early 1880s using Direct Current (DC). With the availability of transformers (for stepping up the voltage for transmission over long distances and for stepping down the voltage for safe use), the development of robust induction motor (to serve the users of rotary power), the availability of the superior synchronous generator, and the facilities of converting AC to DC when required, AC gradually replaced DC. However in 1928, arising out of the introduction of grid control to the mercury vapour rectifier around 1903, electronic devices began to show real prospects for high voltage direct current (HVDC) transmission, because of the ability of these devices for rectification and inversion. The most significant contribution to HVDC came when the Gotland Scheme in Sweden was commissioned in 1954 to be the World's first commercial HVDC transmission system. This was capable of transmitting 20 MW of power at a voltage of -100 kV and consisted of a single 96 km cable with sea return.

1.2 Comparison of AC and DC transmission:

1.2.1 Advantages of HVDC over AC:

1) Technical Merits of HVDC:

The advantages of a DC link over an AC link are:

- A DC link allows power transmission between AC networks with different frequencies or networks, which cannot be synchronized, for other reasons.
- Inductive and capacitive parameters do not limit the transmission capacity or the maximum length of a DC overhead line or cable. The conductor cross section is fully utilized because there is no skin effect.

For a long cable connection, e.g. beyond 40 km, HVDC will in most cases offer the only technical solution because of the high charging current of an AC cable. This is of particular interest for transmission across open sea or into large cities where a DC cable may provide the only possible solution.

1 A digital control system provides accurate and fast control of the active power flow.
2 Fast modulation of DC transmission power can be used to damp power oscillations in an AC grid and thus improve the system stability.

2) Economic considerations:

For a given transmission task, feasibility studies are carried out before the final decision on implementation of an HVAC or HVDC system can be taken. Fig.1 shows a typical cost comparison curve between AC and DC transmission considering:

- AC vs. DC station terminal costs
- AC vs. DC line costs
- AC vs. DC capitalized value of losses

The DC curve is not as steep as the AC curve because of considerably lower line costs per kilometer. For long AC lines the cost of intermediate reactive power compensation has to be taken into account. The break-even distance is in the range of 500 to 800 km depending on a number of other factors, like country-specific cost elements, interest rates for project financing, loss evaluation, cost of right of way etc.

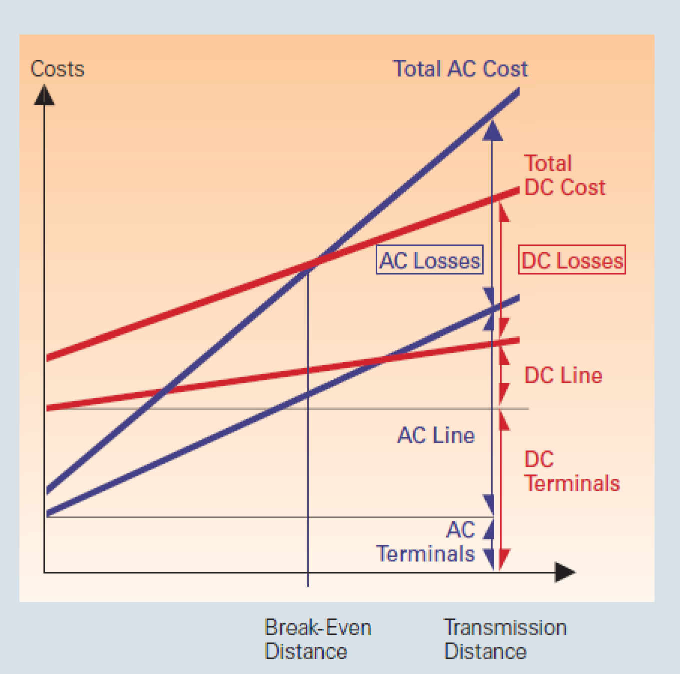


Fig 1: total cost/distance

3) During bad weather conditions, the corona loss and radio interference are lower for a HVDC line compared to that in an AC line of same voltage and same conductor size.

4. Due to the absence of inductance in DC, an HVDC line offers better voltage regulation. Also, HVDC offers greater controllability compared to HVAC.
5. AC power grids are standardized for 50 Hz in some countries and 60 Hz in other. It is impossible to interconnect two power grids working at different frequencies with the help of an AC interconnection. An HVDC link makes this possible.
6. Interference with nearby communication lines is lesser in the case of HVDC overhead line than that for an HVAC line.
7. In longer distance HVAC transmission, short circuit current level in the receiving system is high. An HVDC system does not contribute to the short circuit current of the interconnected AC system.
8. Power flow control is easy in HVDC link.
9. High reliability.

1.2.2 Disadvantages of HVDC transmission:

- Converter stations needed to connect to AC power grids are very expensive**.** Converter substations are more complex than HVAC substations, not only in additional converting equipment, but also in more complicated control and regulating systems.
- In contrast to AC systems, designing and operating multi-terminal HVDC systems is complex.
- Converter substations generate current and voltage harmonics, while the conversion process is accompanied by reactive power consumption. As a result, it is necessary to install expensive filter-compensation units and reactive power compensation units.

- During short-circuits in the AC power systems close to connected HVDC substations, power faults also occur in the HVDC transmission system for the duration of the short-circuit.
- The number of substations within a modern multi-terminal HVDC transmission system can be no larger than six to eight**,** and large differences in their capacities are not allowed. The larger the number of substations, the smaller may be the differences in their capacities.
- The high-frequency constituents found in direct current transmission systems can cause radio noise in communications lines that are situated near the HVDC transmission line.
- Grounding HVDC transmission involves a complex and difficult installation, as it is necessary to construct a reliable and permanent contact to the Earth for proper operation and to eliminate the possible creation of a dangerous “step voltage.”

1.3 Applications of HVDC transmission:

Connecting remote generation

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

Interconnecting grids

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

Connecting offshore wind

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

Power from shore

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

Dc links in ac grids

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

City-center in feed

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

Connecting remote loads

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

1.4 Types of DC link:

For connecting two networks or system, various types of HVDC links are used. HVDC links are classified into three types. These links are explained below:

1) Monopolar link**:**

It has a single conductor of negative polarity and uses earth or sea for the return path of current. Sometimes the metallic return is also used. In the Monopolar link, two converters are placed at the end of each pole. Earthling of poles is done by earth electrodes placed about 15 to 55 km away from the respective terminal stations. But this link has several disadvantages because it uses earth as a return path. The monopolar link is not much in use nowadays.

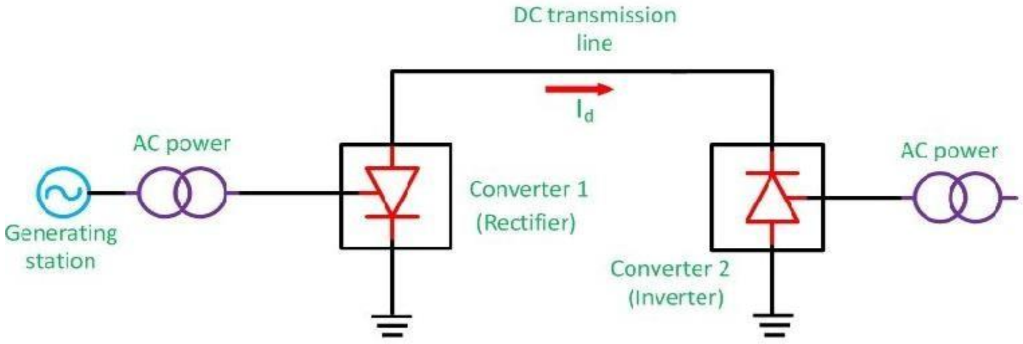


Fig 2: monopolar DC link

2) Bipolar link:

The Bipolar link has two conductors one is positive, and the other one is negative to the earth. The link has converter station at each end. The midpoints of the converter stations are earthed through electrodes. The voltage of the earthed electrodes is just half the voltage of the conductor used for transmission the HVDC.

The most significant advantage of the bipolar link is that if any of their links stop operating, the link is converted into Monopolar mode because of the ground return system. The half of the system continues supplies the power. Such types of links are commonly used in the HVDC systems.

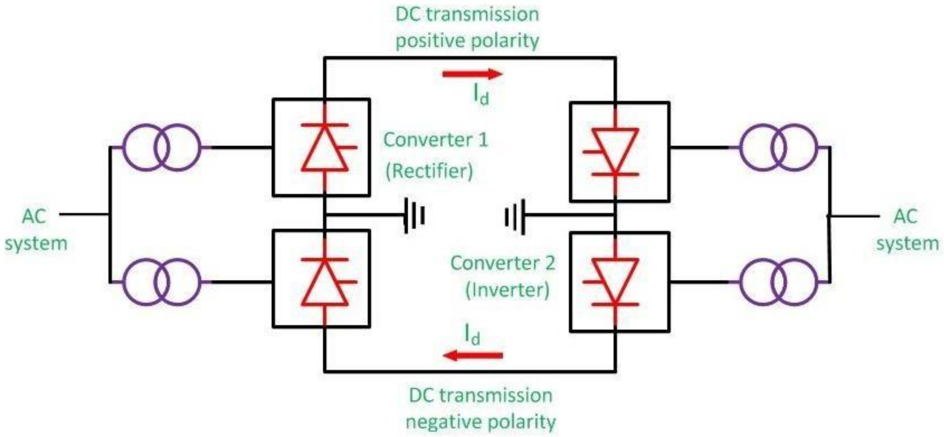


Fig 3: bipolar DC link

3) Homopolar link:

It has two conductors of the same polarity usually negative polarity, and always operates with earth or metallic return. In the homopolar link, poles are operated in parallel, which reduces the insulation cost. The homopolar system is not used presently.

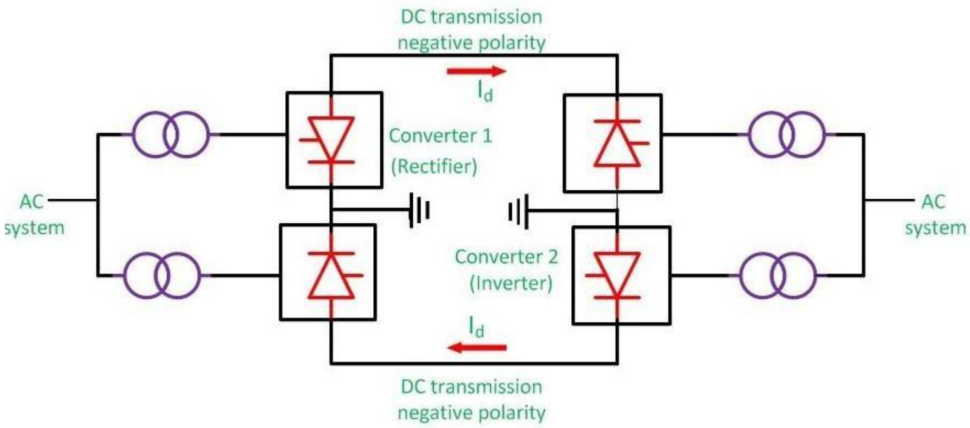


Fig 3: homopolar DC link

1.5 Typical layout of HVDC system:

The HVDC system has the following main components.

- Converter Station
- Converter Unit
- Converter Valves
- Converter Transformers
- Filters
  - AC filter
  - DC filter
  - High-frequency filter
- Reactive Power Source
- Smoothing Reactor
- HVDC System Pole

1.5.1 Converter Station:

The terminal substations which convert an AC to DC are called rectifier terminal while the terminal substations which convert DC to AC are called inverter terminal. Every terminal is designed to work in both the rectifier and inverter mode. Therefore, each terminal is called converter terminal, or rectifier terminal. A two-terminal HVDC system has only two terminals and one HVDC line.

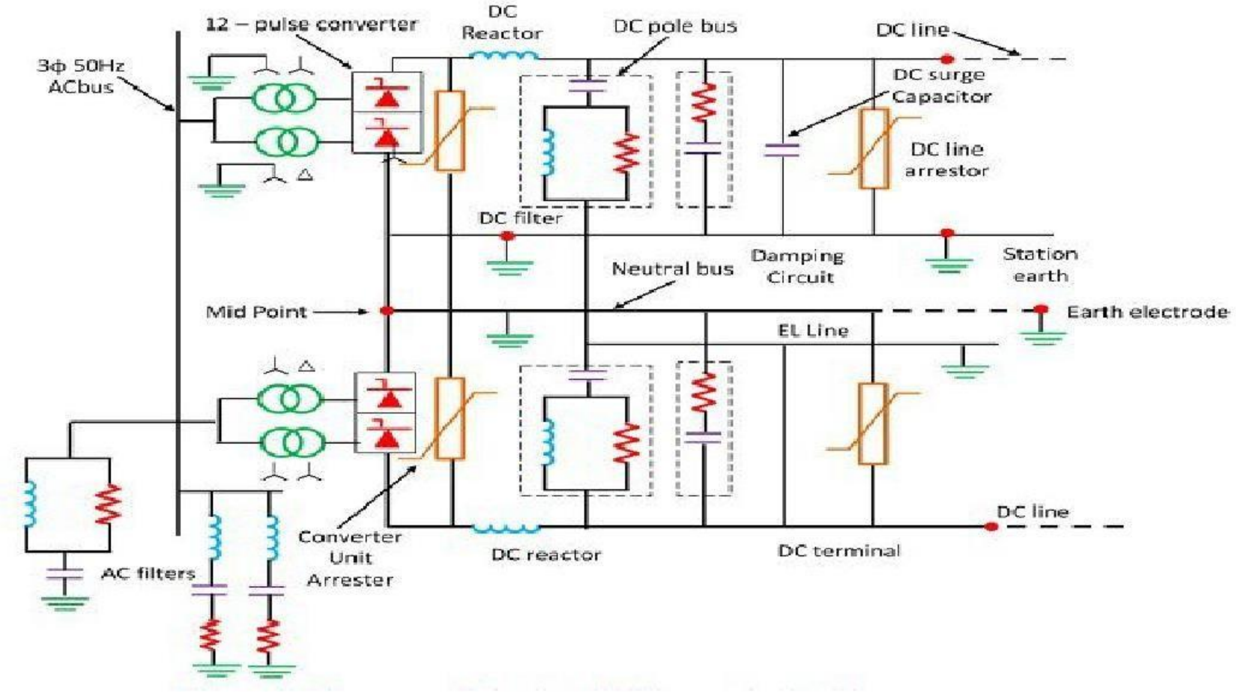


Fig 4: schematic diagram of typical HVDC converter station

1.5.2 Converter unit:

The conversion from AC to DC and vice versa is done in HVDC converter stations by using three-phase bridge converters. This bridge circuit is also called Graetz circuit. In

HVDC transmission a 12-pulse bridge converter is used. The converter obtains by connecting two or 6-pulse bridge in series.

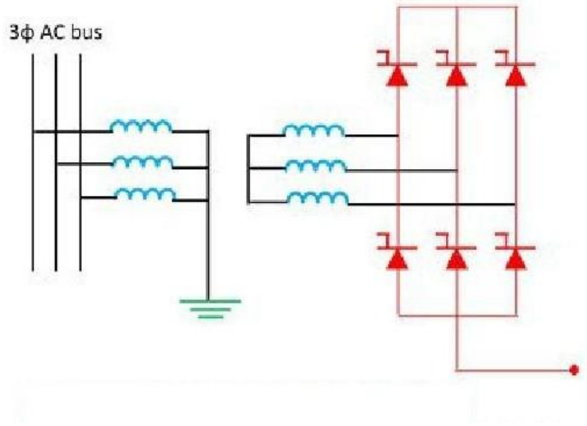


Fig 5: circuit for 6-pulse bridge

1.5.3 Converter transformer:

The converter transformer converts the AC networks to DC networks or vice versa. They have two sets of three phase windings. The AC side winding is connected to the AC bus bar, and the valve side winding is connected to valve Bridge. These windings are connected in star for one transformer and delta to another.

The AC side windings of the two, three phase transformer are connected in stars with their neutrals grounded. The valve side transformer winding is designed to withstand alternating voltage stress and direct voltage stress from Valve Bridge. There are increases in eddy current losses due to the harmonics current. The magnetization in the core of the converter transformer is because of the following reasons.

- The alternating voltage from AC network containing fundamentals and several harmonics.
- The direct voltage from valve side terminal also has some harmonics.

1.5.4 Filters:

The AC and DC harmonics are generated in HVDC converters. The AC harmonics are injected into the AC system, and the DC harmonics are injected into DC lines. The harmonics have the following advantages.

- It causes the interference in telephone lines.
- Due to the harmonics, the power losses in machines and capacitors are connected in the system.
- The harmonics produced resonance in an AC circuit resulting in over voltages.
- Instability of converter controls.

The harmonics are minimized by using the AC, DC and high-frequency filters. The types of filter are explained below in details.

- AC Filters – The AC filters are RLC circuit connected between phase and earth. They offered low impedances to the harmonic frequencies. Thus, the AC harmonic currents are passed to earth. Both tuned and damped filters are used. The AC harmonic filter also provided a reactive power required for satisfactory operation of converters.
- DC Filters – The DC filter is connected between the pole bus and neutral bus. It diverts the DC harmonics to earth and prevents them from entering DC lines.

Such a filter does not require reactive power as DC line does not require DC power.

- High-Frequency Filters – The HVDC converter may produce electrical noise in the carrier frequency band from 20 kHz to 490 kHz. They also generate radio interference noise in the megahertz range frequencies. High-frequency filters are used to minimise noise and interference with power line carrier communication. Such filters are placed between the converter transformer and the station AC bus.

1.5.5 Converter Valves:

The modern HVDC converters use 12-pulse converter units. The total number of a valve in each unit is 12. The valve is made up of series connected thyristor modules. The number of thyristor valve depends on the required voltage across the valve. The valves are installed in valve halls, and they are cooled by air, oil, water or Freon.

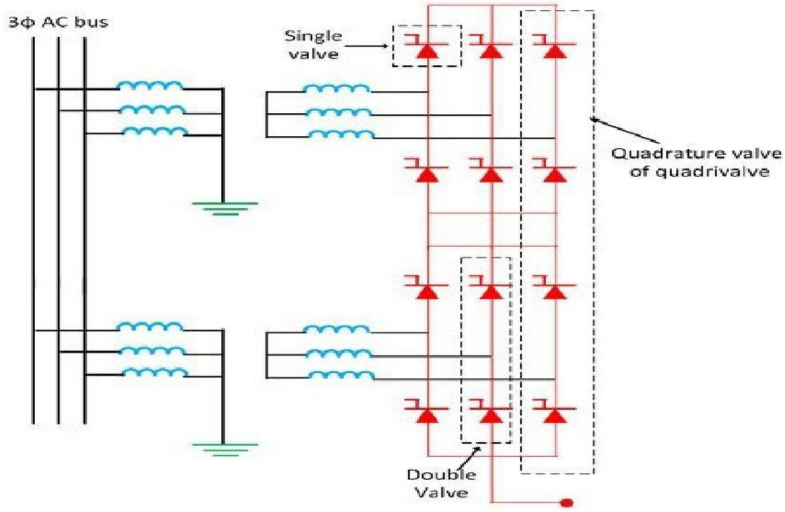


Fig 6:circuit for 12-pulse converter

1.5.6 Reactive power source:

Reactive power is required for the operations of the converters. The AC harmonic filters provide reactive power partly. The additional supply may also be obtained from shunt capacitors synchronous phase modifiers and static VAR systems. The choice depends on the speed of control desired.

1.5.7 Smoothing reactor:

Smoothing reactor is an oil filled oil cooled reactor having a large inductance. It is connected in series with the converter before the DC filter. It can be located either on the line side or on the neutral side. Smoothing reactors serve the following purposes.

1. They smooth the ripples in the direct current.
2. They decrease the harmonic voltage and current in the DC lines.
3. They limit the fault current in the DC line.
4. Consequent commutation failures in inverters are prevented by smoothing reactors by reducing the rate of rising of the DC line in the bridge when the direct voltage of another series connected voltage collapses.
5. Smoothing reactors reduce the steepness of voltage and current surges from the DC line. Thus, the stresses on the converter valves and valve surge diverters are reduced.

1.5.8 HVDC System Pole:

The HVDC system pole is the part of an HVDC system consisting of all the equipment in the HVDC substation. It also interconnects the transmission lines which during normal operating condition exhibit a common direct polarity with respect to earth. Thus the word pole refers to the path of DC which has the same polarity with respect to earth. The total pole includes substation pole and transmission line pole.

1.6 Analysis of Gratez circuit:

The basic module for HVDC converter is the three phase, full wave bridge circuit. This circuit is also known as a Graetz Bridge. The Graetz Bridge has been universally used for HVDC converters as it provides better utilization of the converter transformer and a lower voltage across the valve when not conducting, this voltage is called Peak Inverse Voltage called PIV and is important for selection of the Thyristor.

The bridge converter is represented by th e equivalent circuit in fig. (3) with transformer and source impedance with a loss less inductance. Direct current is assumed to be ripple free and valves as ideal switches with zero resistance when conducting and infinite resistance when not conducting.

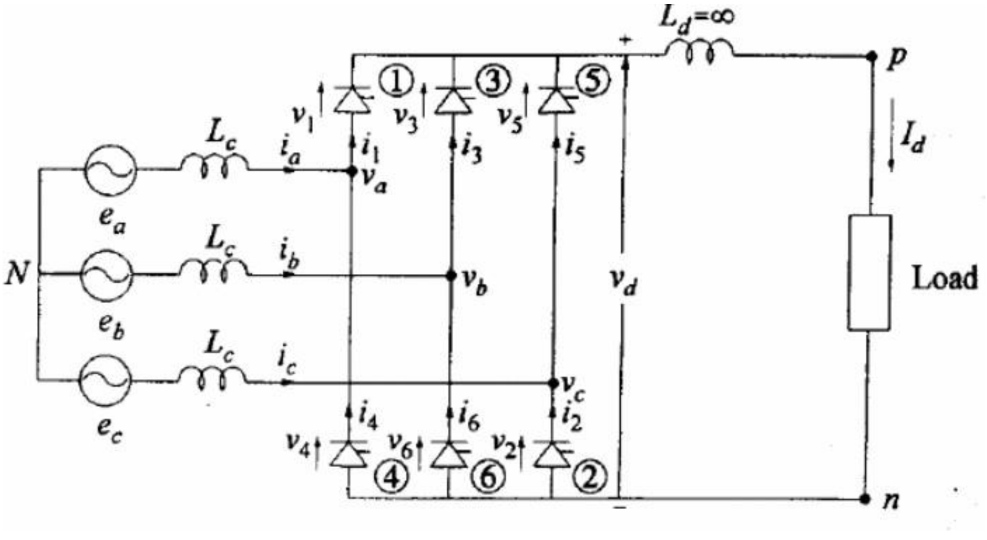


Fig 7: circuit diagram for Graetz Bridge

Let the instantaneous line – to – neutral source voltages be

$ea = Em\ Cos(\ \omega t+60^{o}\ )$

$eb = Em\ Cos(\ \omega t-60^{o}\ )$

$ec = Em\ Cos(\ \omega t-180^{o})$

Then the line-to-line voltages are

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

$e_{ba} = e_b - e_a = \sqrt{3}E_m\cos(\omega t-90^\circ)$

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

For the 6-valve bridge, with zero firing delay, the voltage waveforms across the thyristors are shown in figure. At any given instant, one thyristor valve on either side is conducting. The conducting period for the thyristor valve R1 is shown on the diagram.

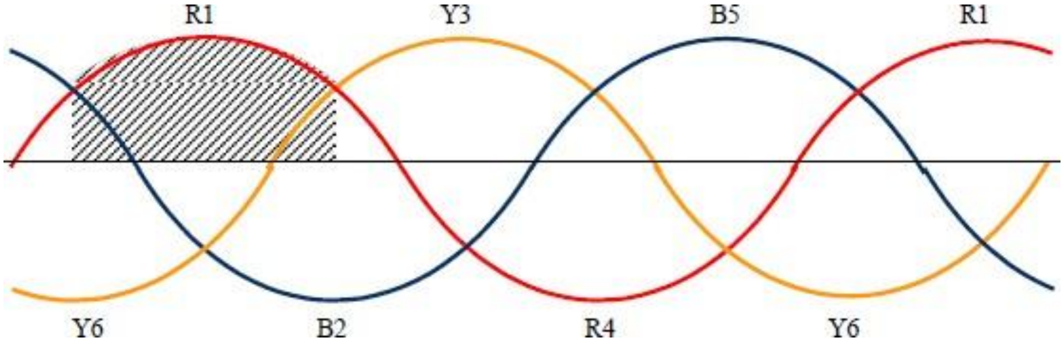


Fig 8: Thyristor voltage waveforms (α=0)

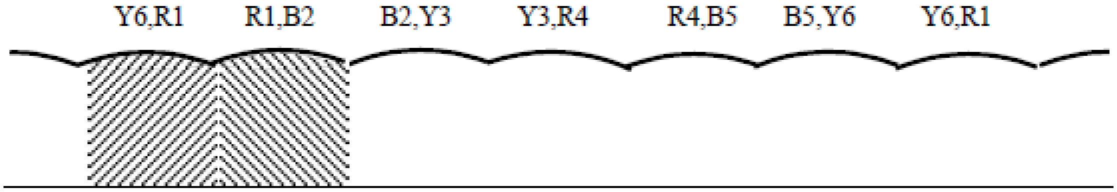


Fig 9: dc output waveforms (α=0)

It can be shown that for the 6-valve bridge, the total r.m.s. ripple is of the order of 4.2% of the d.c. value (for zero delay $\alpha=0$ and zero commutation $\gamma=0$.

The use of a choke reduces the ripple appearing in the direct current transmitted. If E is the r.m.s. line-to-line voltage, then if $\alpha=0$ and $\gamma=0$, the direct output voltage is given by

$$V_{do} = 2\,x\,\frac{E}{\sqrt{3}}\,x\,\sqrt{2}\,x\,\frac{3}{2\pi}\int_{-\frac{\pi}{3}}^{\frac{\pi}{3}}\cos\theta\;d\theta$$

$$= E\,.\,\frac{3\sqrt{2}}{\pi}\,.\,\frac{1}{\sqrt{3}}\left[2\,x\sin\frac{\pi}{3}\right]$$

$$V_{do} = \frac{3\sqrt{2}}{\pi}\,.\,E = 1.350\,E$$

1.6.1 Control angle (Delay angle):

The control angle for rectification (also known as the ignition angle) is the angle by which firing is delayed beyond the natural take over for the next thyristor. The transition could be delayed using grid control. Grid control is obtained by superposing a positive pulse on a permanent negative bias to make the grid positive. Once the thyristor fires, the grid loses control.

Assuming no commutation (2 thyristors on same side conducting simultaneously during transfer), the voltage waveforms across the thyristors as shown in figure:

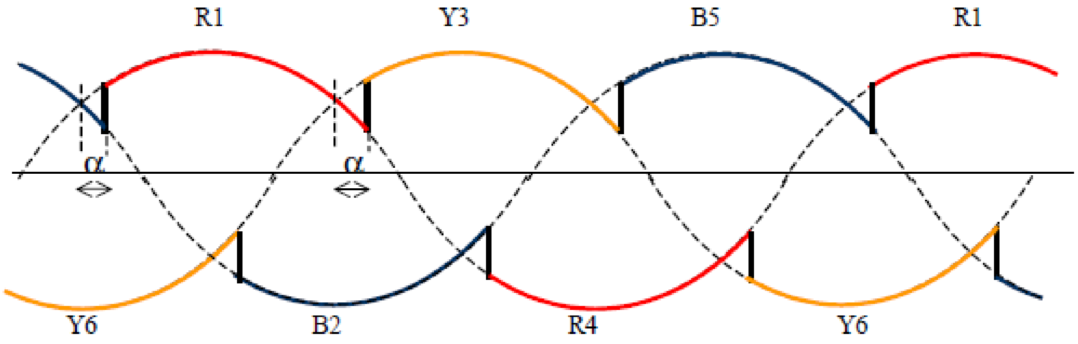


Fig 10: Thyristor voltage waveforms (with delay α)

In this case, the magnitude of the direct voltage output is given by the equation

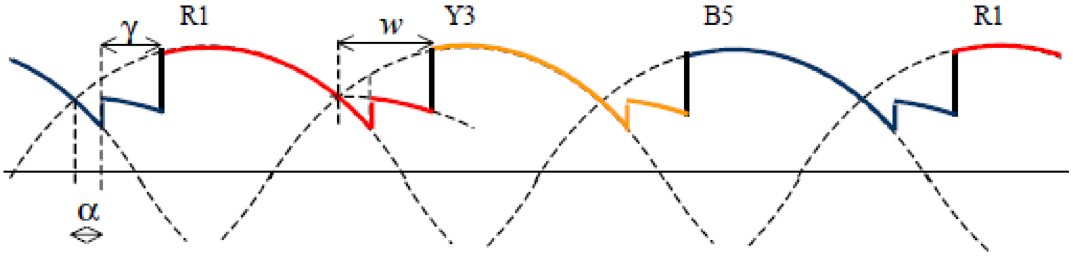
$$V_d = 2\,x\,\frac{E}{\sqrt{3}}\,x\,\sqrt{2}\,x\,\frac{3}{2\pi}\int_{-\frac{\pi}{3}+\alpha}^{\frac{\pi}{3}+\alpha}\cos\theta\;d\theta$$

$$= E\,.\,\frac{3\sqrt{2}}{\pi}\,.\,\frac{1}{\sqrt{3}}\left[\sin\left(\frac{\pi}{3}+\alpha\right)+\sin\left(\frac{\pi}{3}-\alpha\right)\right]$$

$$V_d = \frac{3\sqrt{2}}{\pi}\,E\cos\alpha = V_{do}\cos\alpha$$

1.6.2 Commutation angle (overlap angle):

The commutation period between two thyristors on the same side of the bridge is the angle by which one thyristor commutates to the next. During this period γ 2 conducting thyristors on the same side. This is shown in figure.



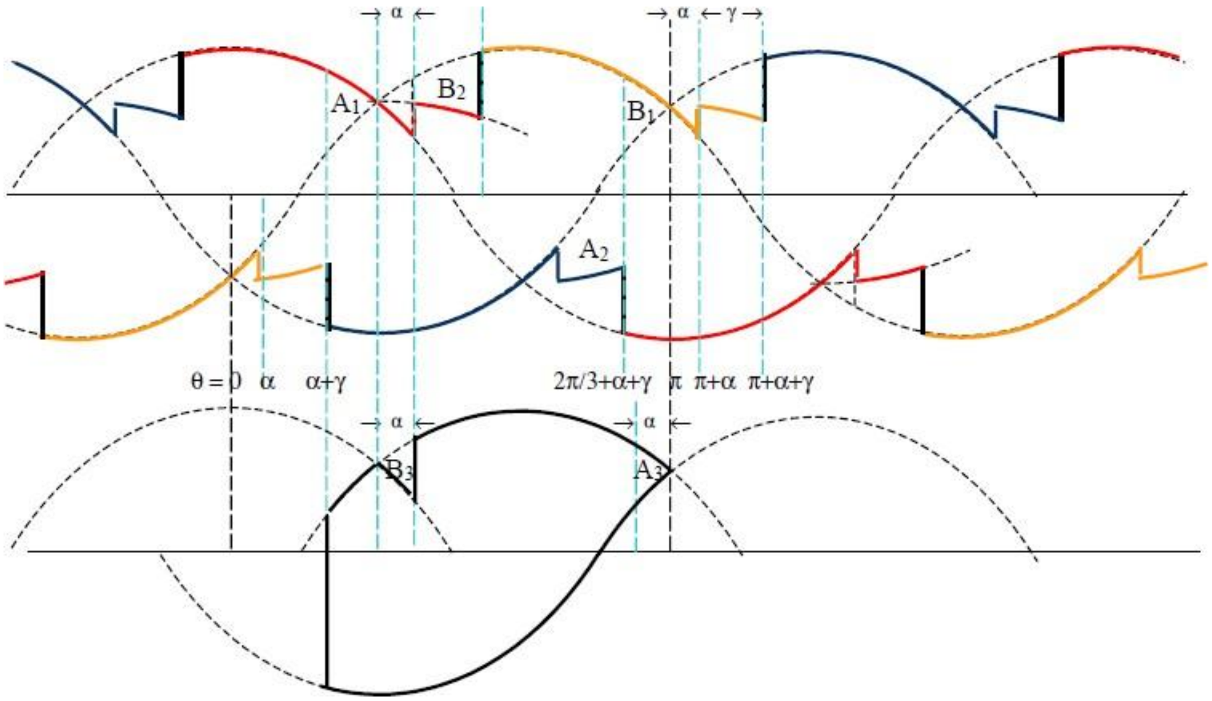
With both the delay angle and commutation being present, the magnitude of the direct voltage may be determined from equation

$$V_d = 2\frac{E}{\sqrt{3}}\sqrt{2}\,\frac{3}{2\pi}\int_{-\frac{\pi}{3}+\alpha}^{\frac{\pi}{3}+\alpha} f(\theta)\,d\theta$$

$$= \frac{3\sqrt{2}\,E}{\sqrt{3}\,\pi}\left[\int_{-\frac{\pi}{3}+\alpha}^{-\frac{\pi}{3}+\alpha+\gamma} \tfrac{1}{2}\left(\cos\left(\theta+\tfrac{2\pi}{3}\right)+\cos\theta\right).d\theta + \int_{-\frac{\pi}{3}+\alpha+\gamma}^{\frac{\pi}{3}+\alpha} \cos\theta\,.\,d\theta\right]$$

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

An alternate method of derivation of the result is based on comparison of similar areas on the waveform. Figure



d.c. output = average value of waveform

$$V_d = \frac{1}{2\pi / 3} \int_{\alpha+\gamma}^{\alpha+\gamma+\frac{2\pi}{3}} V(\theta).d\theta$$

In this integral, in graphical form, area A1 can be replaced by area B1. Similarly, area A2 can be replaced by area B2 and area A3 by area B3. The integral equation then reduces to the form shown below.

$$V_d = \frac{3\sqrt{2}\,E}{2\pi} \int_{\alpha+\gamma}^{\pi-\alpha} \sin\theta \, d\theta$$

$$= \frac{3\sqrt{2}\,E}{2\pi} \left[\cos(\alpha+\gamma) - \cos(\pi-\alpha) \right]$$

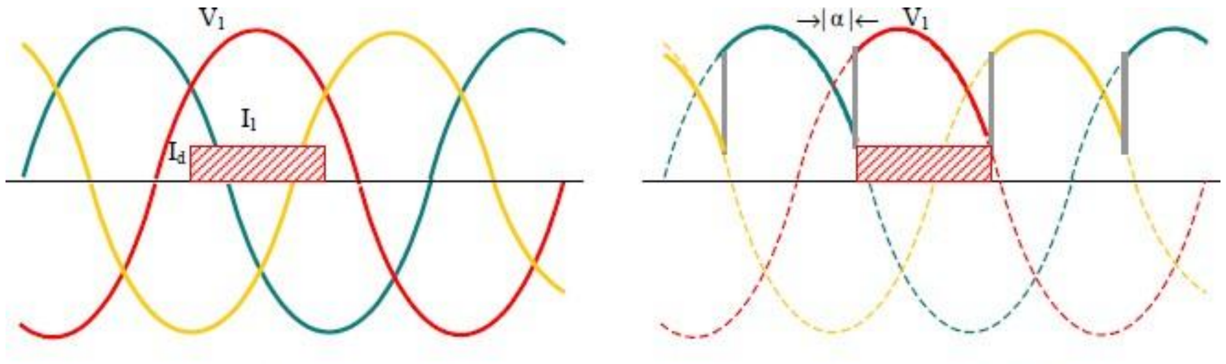
Where √2 E is the peak value of the line voltage. Simplification gives the desired result as in equation

$$V_d = \frac{3\sqrt{2}\,E}{2\pi}\left[\cos\alpha + \cos(\alpha+\gamma)\right]$$

$$= \frac{V_0}{2}\left[\cos\alpha + \cos(\alpha+\gamma)\right]$$

1.6.3 Current Waveforms:

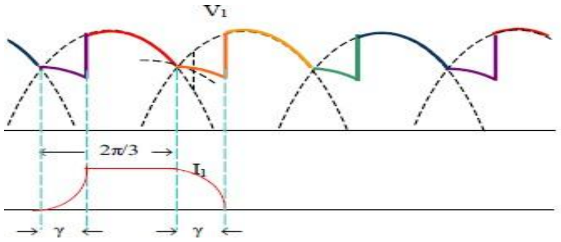
If Commutation is not considered, the current waveforms through each thyristor (assuming a very high value of inductance Ld in the DC circuit to give complete smoothing) is a rectangular pulse lasting exactly one-third of a cycle. This is shown in figure for the cases without delay and with delay.

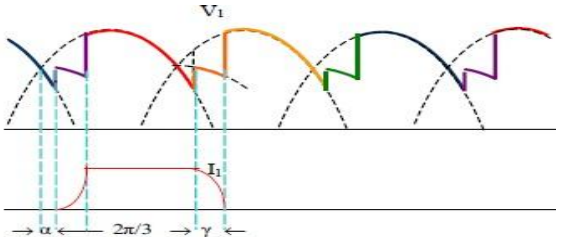


α = 0 withα

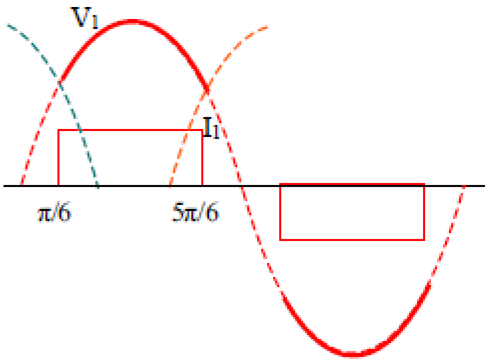
Fig 11: Thyristor current waveforms

When commutation is considered, the rise and fall of the current waveforms would be modified as they would no longer be instantaneous, as shown in figure.

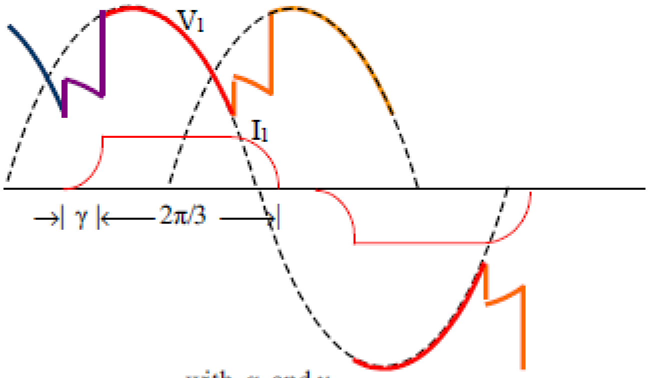




Since each phase has 2 thyristors on the opposite half cycles, the a.c. current waveform on the secondary side of the transformer has a non-sinusoidal waveform as shown in figure



α = 0, γ = 0



with α and γ

If commutation angle is not considered, we can easily calculate the r.m.s. value of the AC current on the transformer secondary Is as in equation.

$$I_s = \sqrt{\frac{1}{\pi} \cdot \frac{2\pi}{3} \cdot I_d^{\,2}} = \sqrt{\tfrac{2}{3}}\, I_d = 0.8165\, I_d$$

Usually harmonic filters are provided on the AC system, so that only the fundamental component need to be supplied/absorbed from the AC system. From Fourier analysis, it can be shown that the fundamental component is given as follows, resulting in equation

$$I = \frac{I_{\max}}{\sqrt{2}} = \frac{1}{\sqrt{2}} \cdot \frac{2}{\pi} \cdot \int_{-\frac{\pi}{3}}^{\frac{\pi}{3}} I_d \cos \omega t \, d(\omega t)$$

$$I = \frac{\sqrt{2}}{\pi} I_d \, 2 \sin \frac{\pi}{3} = \frac{\sqrt{6}}{\pi} I_d = 0.78\, I_d$$

If filters were not provided, it can be shown, using the Fourier series analysis, that the RMS ripple on the AC system would be 0.242 Id (or 31 % of the fundamental)

Note: For normal operation neglecting the commutation angle, in the above calculations of the alternating current, gives rise to an error only of the order of 1%.

As can be seen from the voltage and current waveforms on the AC side, the current lags the voltage due to the presence of the delay angle α and commutation angle γ.

1.6.4 Inversion:

Because the thyristors conduct only in one direction, the current in a convertor cannot be reversed. Power reversal can only be obtained by the reversal of the direct voltage (average value) V_d.

For inversion to be possible, a high value of inductance must be present, and the delay angle $\alpha>90^0$ since V_d changes polarity at this angle. The theoretical maximum delay for inversion would occur at $\alpha=180^0$.

Thus it is common practice to define a period of advance from this point rather than a delay from the previous cross-over as defined for rectification. Thus we define $\beta=\pi-\alpha$ as the ignition angle for inversion or angle of advance. Similarly extinction angle is defined as $\delta=\pi-w$. The definition of the commutation angle γ is unchanged. Thus $\beta=\delta+\gamma$.

Thus we have the practical relationship $\delta_0<\beta<\pi/2$.

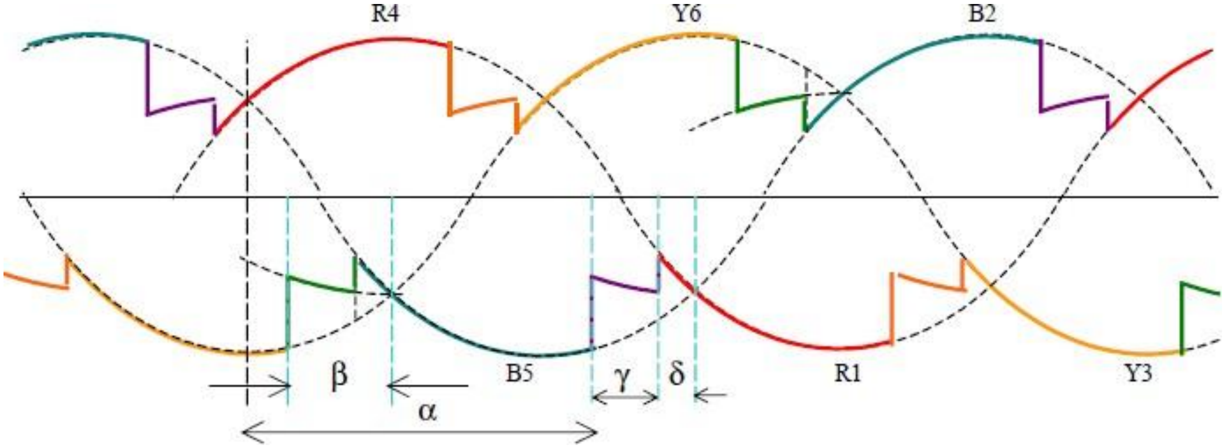


Fig 12: Thyristor voltage waveforms for inversion

Inversion cannot of course be carried out without a DC power source. Further, to obtain the necessary frequency for the AC on inversion, the commutation voltage is obtained from either synchronous machines or from the AC system fed. In isolated systems, L C circuits may also be sometimes used for the purpose. Figure shows the thyristor voltage waveforms for inversion.

During inversion, each thyristor conducts during the negative half cycle, so that the direct voltage waveform and the corresponding current have the form shown in figure.

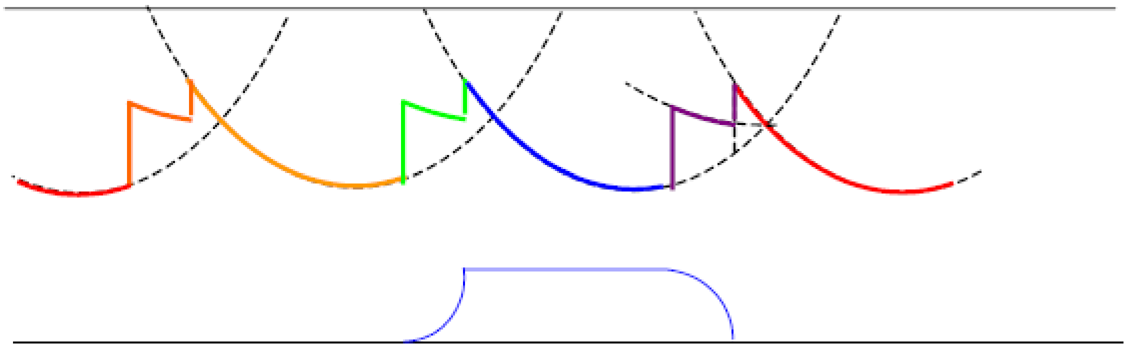


Fig 13: Direct voltage waveform & thyristor current waveform

The equations derived earlier for the convertor are valid. However, they are usually written in terms of the variables β and δ instead of α and ω.

$$V_d = \tfrac{1}{2} V_0 [\cos(\pi - \beta) + \cos(\pi - \delta)]$$

or

$$(-)\, V_d = \tfrac{1}{2} V_0 [\cos\beta + \cos\delta] = V_0 \cos\beta + (3\omega L_c/\pi)\, I_d$$

Since the direct voltage is always negative during inversion, it is common practice to omit the negative sign from the expression. It can also be shown that

$$(-)\, V_d = V_0 \cos\delta - (3\omega L_c/\pi)\, I_d$$

The power factor of the inverter can be shown to be given by the equation

$$\cos\varphi = \tfrac{1}{2} (\cos\delta + \cos\beta)$$

It is common practice to operate the inverter at a constant extinction angle δ (10^0 to 20^0).

Unit-II

Converter and HVDC system Control

2.1 Principle of DC link control:

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

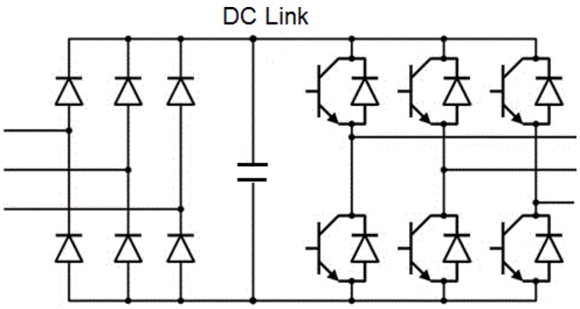


Fig 14: DC Link

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

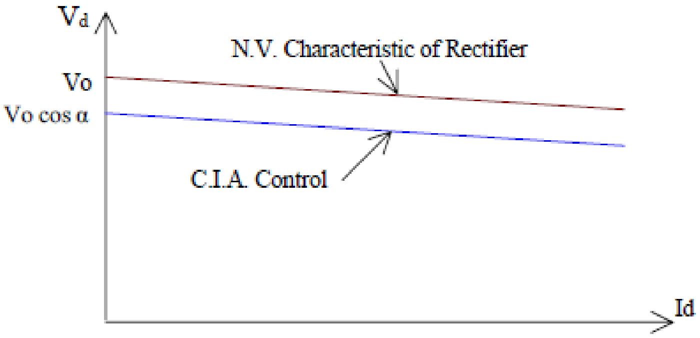
The DC capacitor helps prevent the transients from the load side from going back to the distributor side. It also serves to smoothen the pulses in the rectified DC.

2.2 control characteristics of converter:

The control characteristics of the convertor are the plots of the variation of the direct voltage against the direct current. These are described in the following sections.

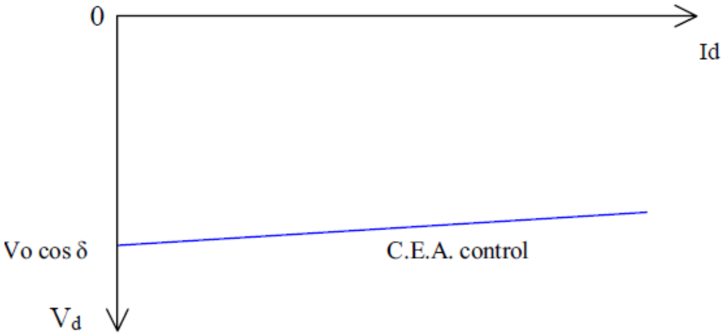
2.2.1 Natural Voltage Characteristic (NV) and the Constant Ignition Angle (CIA) control:

The Natural Voltage Characteristic corresponds to zero delay angle α=0. This has characteristic equation given by $V_d = V_0(3wL_c/\pi)I_d$. The Constant Ignition Angle control is a similar characteristic which is parallel to the NV characteristic with a controllable intercept $V_0\cos\alpha$.



2.2.2 Constant Extinction Angle (CEA) control:

The Invertor is usually operated at constant extinction angle. This has the characteristic equation given by $V_d = V_0(3wL_c/\pi)I_d$. This is shown in below fig.

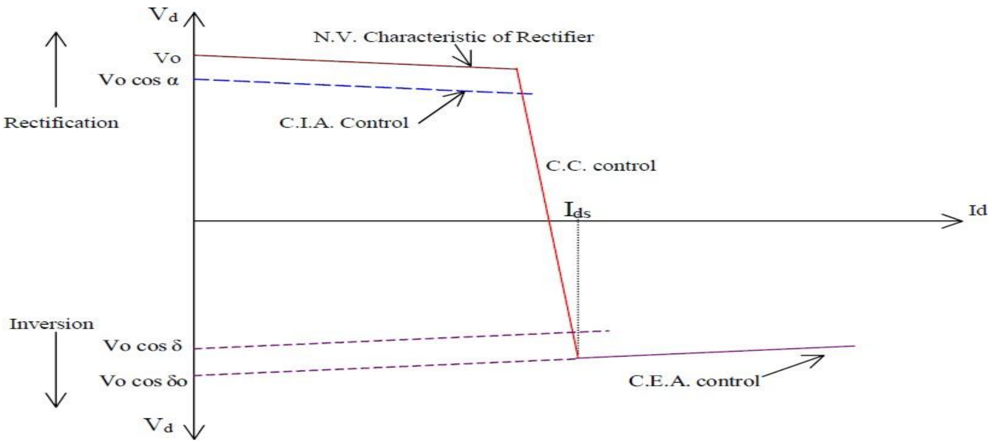


2.2.3 Constant Current Control (CC):

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

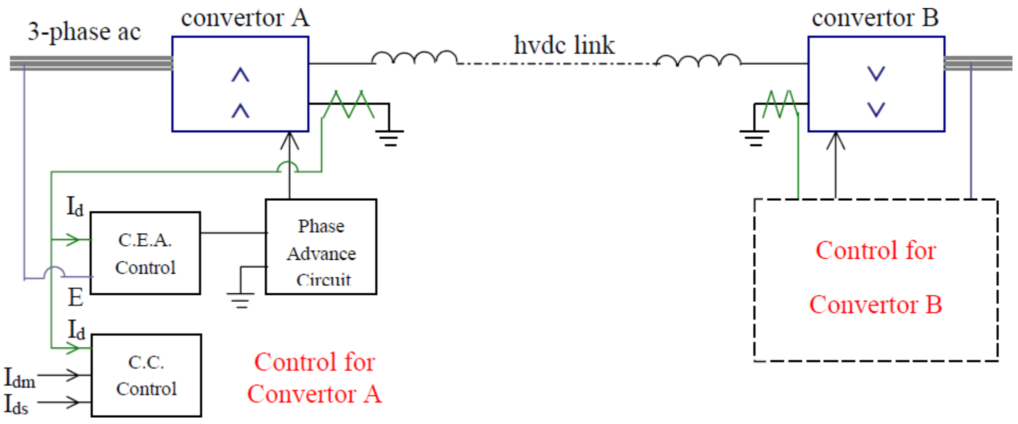
2.2.4 Full Characteristic of Convertor:

The complete characteristic of each convertor has the N.V. characteristic and equipped with C.C. control and the C.E.A. control. This is shown in figure for a single convertor.

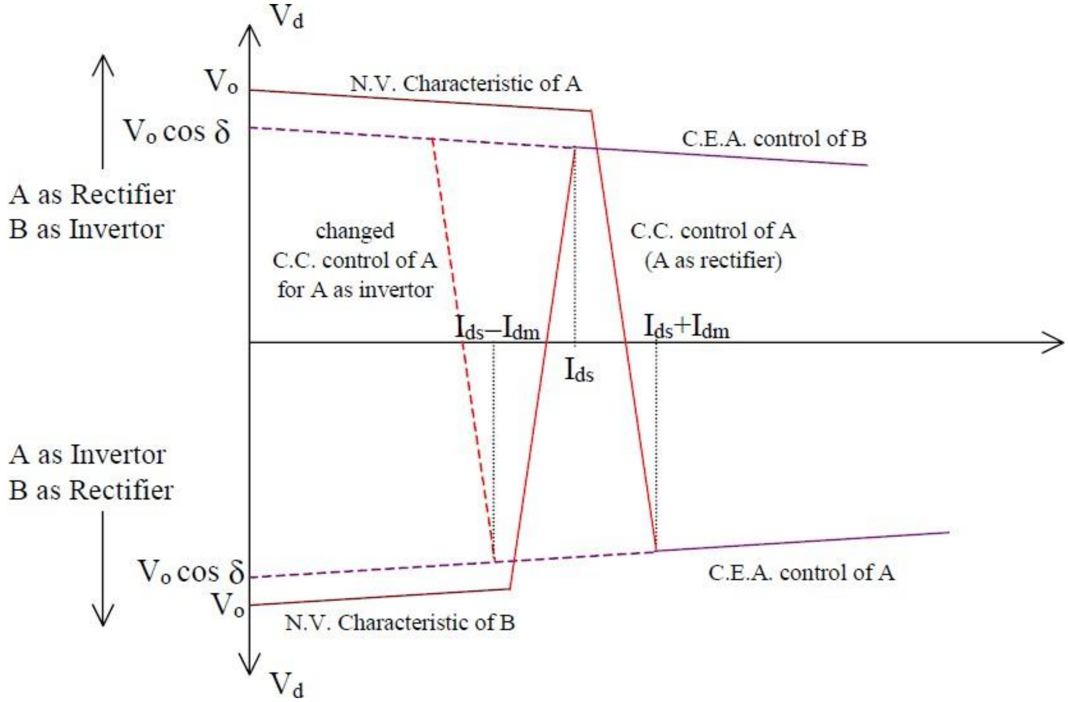


2.2.5 Compounding of Convertors:

Figure shows a system of 2 convertors, connected by a hvdc link. Both convertors are provided with CEA and CC control so that either can work as a rectifier or an invertor. The compounded characteristics are shown in figure.



The margin setting Idm between the current setting Ids for the invertor and for the rectifier is usually kept at about 10% to 20% of the current setting. The setting of the convertor operating as rectifier is kept higher than the setting of that as invertor by the margin setting Idm.



The usual operating point for power transfer is the intersection of the CC control of the rectifier and the CEA control of the inverter. (For comparison, the characteristics of convertor B have been drawn inverted). It must also be ensured by proper tap changing that the N.V. characteristic of the convertor operating in the rectification mode is higher than the C.E.A. characteristic of the inverter, as Vo of the two ends are not necessarily equal.

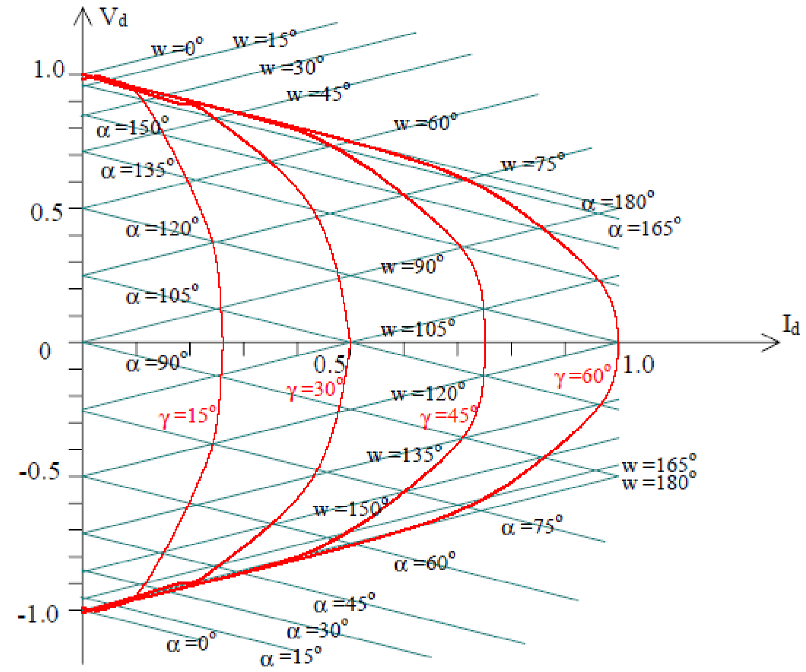
With convertor A operating as rectifier, and convertor B operating as inverter, the steady state current under all circumstances will remain within the upper limit (I_{ds} + I_{dm}) and the lower limit Ids. That is, the system direct current will not change by more than I_{dm} under all operating conditions. By reversing the margin setting I_{dm}, that is making the setting of convertor B to exceed that of A, power flow can be automatically reversed. Convertor B will then operate as a rectifier and A as an inverter. The reversal of power occurs as a result of the reversal of polarity of the voltage.

2.2.5 Compounding of Convertors:

The convertor operating equations for voltage V_d and current I_d are expressed as follows.

$$V_d = \frac{3\sqrt{2}\,E}{\pi}\,\frac{(\cos\alpha + \cos w)}{2}$$

$$I_d = \frac{E}{\sqrt{2}\,\omega\,L_c}(\cos\alpha - \cos w)$$



It is useful to draw the convertor chart in per unit. For this purpose the natural selection for the base voltage is the maximum direct voltage output Vdo. There is no such natural current base. Thus it is convenient to select the constant appearing in equation for current as the base quantity.

UNIT-III

HARMONICS FILTERS AND REACTIVE POWER CONTROL

3.1 HARMONIC FILTERS:

The filter arrangements on the AC side of an HVDC converter station have two main duties:

- to absorb harmonic currents generated by the HVDC converter and thus to reduce the impact of the harmonics on the connected AC systems, like AC voltage distortion and telephone interference
- to supply reactive power for compensating the demand of the converter station

3.1.1 Design Criteria for AC Filters:

3.1.1.1 Reactive Power Requirements:

The reactive power consumption of an HVDC converter depends on the active power, the transformer reactance and the control angle. It increases with increasing active power. A common requirement to a converter station is full compensation or overcompensation at rated load. In addition, a reactive band for the load and voltage range and the permitted voltage step during bank switching must be determined. These factors will determine the size and number of filter and shunt capacitor banks.

3.1.1.2 Harmonic Performance Requirements:

HVDC converter stations generate characteristic and non-characteristic harmonic currents. For a twelve-pulse converter, the characteristic harmonics are of the order $n = (12 * k) \pm 1$ $(k = 1,2,3...)$. These are the harmonic components that are generated even during ideal conditions, i.e. ideal smoothing of the direct current, symmetrical AC voltages, transformer impedance and firing angles. The characteristic harmonic components are the ones with the highest current level, but other components may also be of importance. The third harmonic, which is mainly caused by the negative sequence component of the AC system, will in many cases require filtering.

The purpose of the filter circuit is to provide sufficiently low impedances for the relevant harmonic components in order to reduce the harmonic voltages to an acceptable level. The acceptance criteria for the harmonic distortion depend on local conditions and regulations. A commonly used criterion for all harmonic components up to the 49th order is as follows: Dn individual harmonic voltage distortion of order n in percent of the fundamental AC busbar voltage (typical limit 1%) Drms total geometric sum of individual voltage distortion Dn (typical limit 2%)

3.1.1.3 Network Impedance:

The distortion level on the AC busbar depends on the grid impedance as well as the filter impedance. An open circuit model of the grid for all harmonics is not on the safe side. Parallel resonance between the filter impedance and the grid impedance may create unacceptable amplification of harmonic components for which the filters are not tuned. For this reason, an adequate impedance model of the grid for all relevant harmonics is required in order to optimize the filter design.

There are basically two methods to include the network impedance in the filter calculations:

- to calculate impedance vectors for all relevant harmonics and grid conditions
- to assume locus area for the impedance vectors

The modelling of a complete AC network with all its components is very complex and time-consuming. For this reason, the locus method is very often used. It is based on a limited number of measurements or calculations. Different locus areas for different harmonics or bands are often determined to give a more precise base for the harmonic performance calculation.

3.1.2 Requirements to Ratings:

3.1.2.1 Steady state calculation:

The voltage and current stresses of AC filters consist of the fundamental frequency and harmonic components. Their magnitudes depend on the AC system voltage, harmonic currents, operating conditions and AC system impedances. The rating calculations are carried out in the whole range of operation to determine the highest steady-state current and voltage stresses for each individual filter component.

3.1.2.2 Transient Calculation:

The objective of the transient rating calculation is to determine the highest transient stresses for each component of the designed filter arrangement. The results of the transient calculation should contain the voltage and current stresses for each component, energy duty for filter resistors and arresters, and the insulation levels for each filter component.

To calculate the highest stresses of both lightning and switching surge type, different circuit configurations and fault cases should be studied:

- Single-Phase Ground Fault

  The fault is applied on the converter AC bus next to the AC filter. It is assumed that the filter capacitor is charged to a voltage level corresponding to the switching impulse protective level of the AC bus arrester.

- Switching Surge

  For the calculation of switching surge stresses, a standard wave of 250/2500 with a crest value equal to the switching impulse protective level of the AC bus arrester is applied at the AC converter bus.

3.1.2.3 Filter Energization:

The AC filter is assumed to be energized at the moment for the maximum AC bus peak voltage. This case is decisive for the inrush currents of AC filters.

3.1.2.4 Fault Recovery after Three-Phase Ground Fault:

Various fault-clearing parameters should be investigated to determine the maximum energy stresses for AC filter arresters and resistors. The worst case stresses are achieved if the HVDC converters are blocked after fault initiation, while the AC filters remain connected to the AC bus after fault clearing and recovery of the AC system voltage. In this case, a temporary overvoltage with high contents of non-characteristic harmonics will occur at the AC bus due to the effects of load rejection, transformer saturation and resonance between filter and AC network at low frequency.

3.1.3 DC Filter Circuits:

Harmonic voltages which occur on the DC side of a converter station cause AC currents which are superimposed on the direct current in the transmission line. These alternating currents of higher frequencies can create interference in neighbouring telephone systems despite limitation by smoothing reactors. DC filter circuits, which are connected in parallel to the station poles, are an effective tool for combating these problems. The configuration of the DC filters very strongly resembles the filters on the AC side of the HVDC station. There are several types of filter design. Single and multiple-tuned filters with or without the high-pass feature are common. One or several types of DC filter can be utilized in a converter station.

3.1.3.1 Design Criteria for DC Filter Circuits:

The interference voltage induced on the telephone line can be characterized by the following equation:

$$I_{eq} = \sqrt{\sum_{1}^{m} (H_\mu \cdot C_\mu \cdot I_{\mu(x)})^2}$$

$$V_{in(x)} = Z \cdot I_{eq}$$

The equivalent disturbing current combines all harmonic currents with the aid of weighting factors to a single interference current. With respect to telephone interference, it is the equivalent to the sum of all harmonic currents. It also encompasses the factors which determine the coupling between the HVDC and telephone lines:

- Operating mode of the HVDC system (bipolar or monopolar with metallic or ground return)
- Specific ground resistance at point x the intensity of interference currents is strongly dependent on the operating condition of the HVDC. In monopolar operation, telephone interference is significantly stronger than in bipolar operation.

Unit –IV

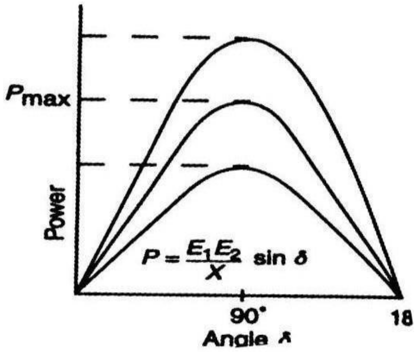
Introduction to FACTS:

4.1 INTRODUCTION:

FACTS ie., Flexible AC transmission system incorporate power electronic based static controllers to control power (both active and reactive power needed) and enhance power transfer capability of the AC lines . Let Bus 1and Bus 2shown in fig 1: represent two AC systems where in power is to be transmitted from 1 to 2through a line of impedance r+jx.

By changing the effective value of ‘x’ ,the power transmitted can be increased or decreased .Further it modifies reactive power needed.

- Increase or decrease of ‘x’ will change value.
- Maximum power that can be transmitted is obtained when δ= (provided are fixed).



- The FACTS technology is not a single high-power controller but rather a collection of controllers. which can be applied individually or in coordination with others to control one or more of the interrelated system parameters.
- The parameters that govern the operation of transmission system including .
  - Series impedance
  - Shunt impedance
  - Current

  - Voltage
  - Phase and
  - Damping of oscillations at various frequencies below the required system frequency.
- The FACTS controllers can enable a line to carry power closer to its thermal rating.
- In flexible (or) controllable AC systems, the controllable parameters are

  a) Control of line reactance.

  b) Control of phase angle δ when it is not large(which controls the active power flow)

  c) Injecting voltage in series with line and at 90°phase with line current ie.. injection of reactive power in series. This will control active power flow.

  d) Injecting voltage in series with line but at variable phase angle . This will control both active & reactive power flow .

  e) Controlling the magnitude of either V1or V2.

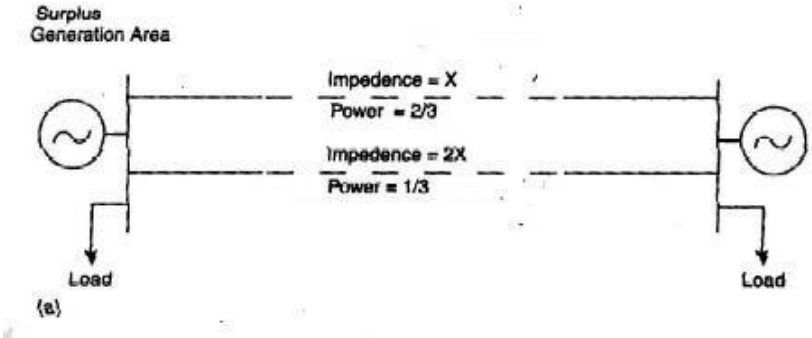
  f) Controlling or variation of line reactance with a series controller and regulating the voltage with a shunt controller. This can control both active and reactive power.

4.2 Flow of Power in A.C Systems:

In AC power systems the electrical generation and load must balance at al times .To some extent, the electrical system is self –regulating. In generation is less than load ,the voltage and frequency drop. However there is only a few percent margin for such a self regulation .[If voltage propped up with reactive power support ,then the load will go up and consequently frequency will keep dropping and system will collapse .If there is inadequate reactive power support, the system can have voltage collapse. When adequate generation is available , active power flows from the surplus generation areas to defect areas through all parallel paths available which frequently involves EHV (extra high voltage)and medium voltage lines .

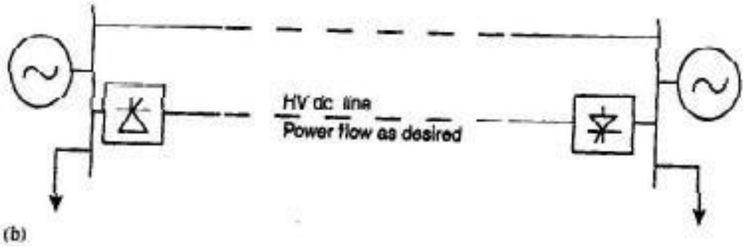
4.2.1 Power Flow in a parallel path system:

Consider power flow through two parallel paths from a surplus generation area to a defect generation area on right as shown in fig



With out any control ,power flow is based on the inverse of various transmission line impedances.

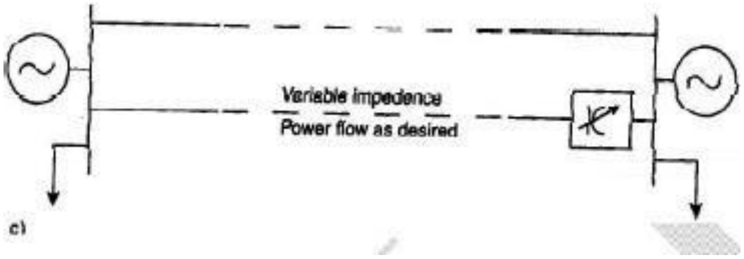
A part from ownership and contractual issues, lines carry how much power. It is likely that lower impedance line may become overloaded and there by limit the loading on both paths even though the higher impedance path is not fully loaded. Fig: shows the same to paths, but one of these has HVDC transmission.



With HVDC, power flows as ordered by the operator because with HVDC power electronic converters power is electronically controlled.

An HVDC line can also help the parallel AC transmission line to maintain stability. However, HVDC is expensive for general use ,and is considered when long distances are involved .

Fig 3: and Fig 4: show one of the parallel transmission lines with different types of series type FACTS controllers.



4.2.2 Power Flow in a meshed system:

Consider two generators at two different locations are sending power to a load centre through a network consisting of three lines in a meshed connection as shown in fig:

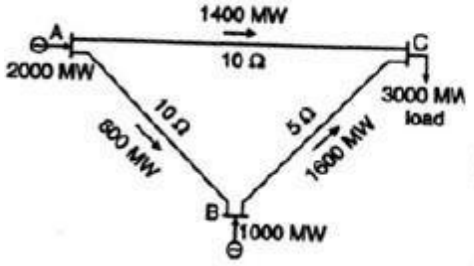


Fig: (a) Power flow in a mesh network

- Suppose the lines AB,BC and AC have continuous ratings of 1000 MW ,1250 MW and 2000 MW
- These lines have energy ratings of twice those numbers for a sufficient time toallow rescheduling of incase of loss of one of these lines.

- If one of the generators is generating 2000MW and the other 1000MW, a total of 3000 MW would be delivered to the load centre.
- For impedances shown three lines would carry 600,1600 and 1400 MW respectively as shown in fig:(a);
- If a capacitor of reactance -5Ω at synchronous frequency is inserted in one line as shown in fig: (b).It reduces the line's impedance from 10Ω to5Ω.

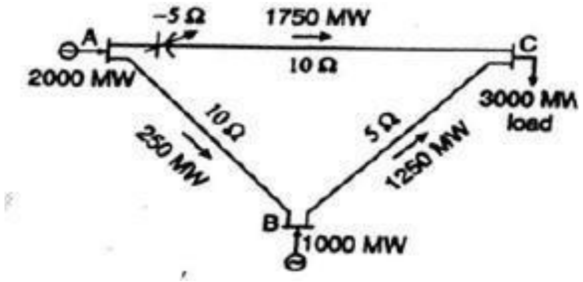


Fig : (b) Power of flow in a mesh network with thyristor controlled from the figure ,it is clear that

Power flow through AB will be 250 MW

BC will be 1250 MW

AC will be 1750 MW respectively

- Although, this capacitor could be modular and mechanically switched ,the numberof operations would be limited by wear on mechanical components.
- There complications may arise if the series capacitor is mechanically controlled. Aseries capacitor in a line may lead to sub synchronous resonance.
- A transistor controlled series capacitor (TCSC) can greatly enhance the stability of the network. It is practical that series compensation must be partly mechanically controlled and constraints at the least cost.

- By increasing the impedance of one of the lines in the same meshed configuration thepower flow can be controlled.

4.3 BASIC TYPES OF FACTS CONTROLLERS:

In general FACTS controllers can be divided into four categories.

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

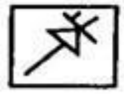
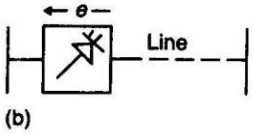


Figure shows general symbol for a FACTS controller.

4.4 SERIES CONTROLLER:

Figure shows series type FACTS controller.



- A series controller is variable impedance like a capacitor an inductor or a power electronic switched device of variable source with either mains frequency or sub harmonic frequency. Series controller injects voltage in series with a line.
- As long as the voltage is in phase quadrature with the line current, the series controlleronly supplies or consumes variable reactive power.
- Any other phase relationship will involve handling of real power as well.

4.5 SHUNT CONTROLLER :

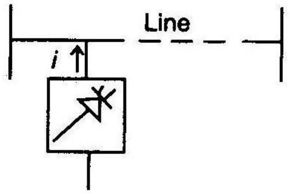
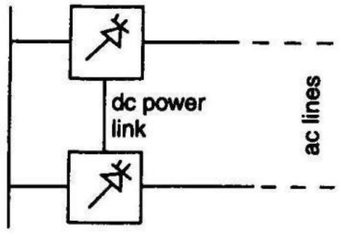


Fig: shows shunt FACTS controller

- A shunt controller can be variable impedance, variable source or combination of both .
- Shunt controller inject current into the line (system) at the point of connection.
- As long as the injected current is in quadrature with line voltage, shunt controller onlysupplies or consumes variable reactive power.
- Any other phase relationship will involve handling of real power as well.

Fig: shows series-series FACTS controller



This could be a combination of separate series controllers which are controlled in a co-ordinate manner, in multi-line transmission systems.

- Series controllers provide independent series reactive compensation for each line but also transfer real power among the lines via the power link.

- The real power transfer capability of unified series controller ,referred to as “Inter Line Power Flow controller”, makes it possible to balance both real & reactive power flow in the lines and there by maximize the utilization of transmission system.

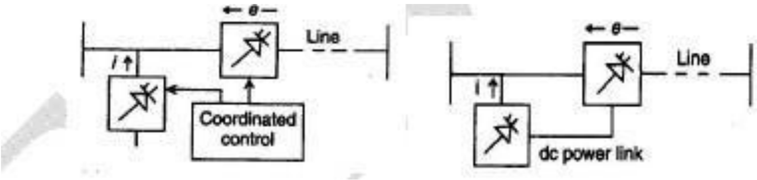
Note: The term “Unified” means that the DC terminals of all controller converters are all connected together for real power transfer.

UNIT-V

STATIC SERIES AND COMBINES COMPENSATORS

5.1 COMBINED SERIES –SHUNT CONTROLLERS :

Figures shows combinations of series and shunt controllers ,which are controlled in a co-ordinate manner .



- The combined shunt and series controllers inject current into the system with the shunt part of the controller and voltage in series in the line with series part of controller.

  When shunt and series controllers are unified .there can be a real power exchange between the series and shunt controllers via the power link.

5.2 SHUNT CONNECTED CONTROLLERS:

(i) Static Synchronous Compensators (STATCOM): A static synchronous generator operated as a shunt connected static var compensator whose4 capacitive or inductive output current can be controlled independent of the AC system voltage.

STATCOM is one of the key FACTS controllers. It can be based on a voltage sourced or current sourced converter.

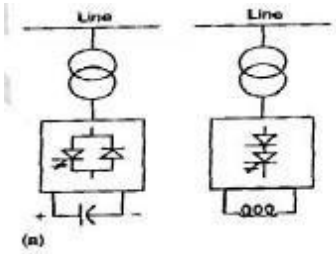
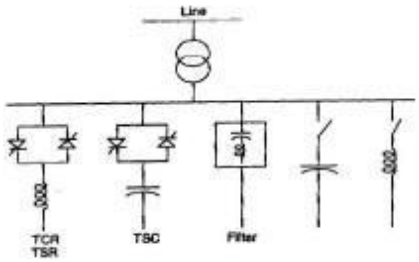


Figure 1(a) shows a simple one-line diagram of STATCOM based on a voltage sourced converter and a current sourced converter.STATCOM can be designed to also act as an active filter to absorb system harmonics.

(ii) Static Var Compensator (SVC): A shunt connected static var generator or absorber whose output is adjusted to exchange capacitive or inductive current so as to maintain or control specific parameters of the electrical power system.

This is a general term for a thyristor controlled or thyristor switched reactor and/or thyristor switched capacitor or combination. SVC is based on thyristors without gate turn-off capability. It includes separate equipment for leading and lagging vars, the thyristor controlled or thyristor switched reactor for absorbing reactive power on thyristor switched capacitor for supplying the reactive power.



(iii) Thyristor Controlled Reactor (TCR): A shunt connected thyristor controlled inductor whose effective reactance is varied in a continuous manner by partial-conduction control of the thyristor valve.

subset of SVC in which conduction time and hence, current in a shunt reactor is controlled by a thyristor based ac switch with firing angle control.

(iv) Thyristor Switched Reactor (TSR): A shunt connected thyristor-switched inductor whose effective reactance is varied in a stepwise manner by full-or zero-conduction operation of the thyristor valve. TSR is another subset of SVC. TSR is made up of several shunt connected inductors which are switched in and out by thyristor switches without any firing angle controls in order to achieve the required step changes in the reactive power consumed from the system. Use of thyristor switches without firing angle control results in lower cost and losses, but without a continuous control.

(v) Thyristor Switched Capacitor (TSC): A shunt connected thyristor-switched capacitor whose effective reactance is varied in a stepwise manner by full-or zero-conduction operation of the thyristor valve.

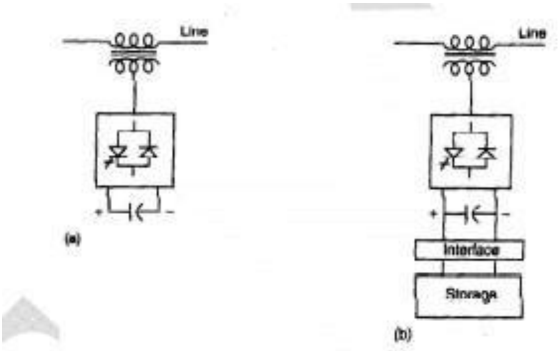
TSC is also a subset of SVC in which thyristor based ac switches are used to switch in and out shunt capacitors units, in order to achieve the required step change in the reactive power supplied to the system. Unlike shunt reactors, shunt capacitors cannot be switched continuously with variable firing angle control.

(vi) Static VAR System (SVS): A combination of different static and mechanically-switched VAR compensators whose outputs are coordinated..

5.3 SERIES CONNECTED CONTROLLERS

Static Synchronous Series Compensator (SSSC): A static synchronous generator operated without an external electric energy source as a series compensator whose output voltage is quadrature with, and controllable independently of, the line current for the purpose of increasing or decreasing the overall reactive voltage drop across the line and thereby controlling the transmitted electric power. The SSSC may include transiently rated energy storage or energy absorbing devices to enhance the dynamic behavior of the power system by additional temporary real power compensation, to increase or decrease momentarily, the overall real (resistive) voltage drop across the line.

SSSC is one of the most important FACTS controllers. It is like a STATCOM, except that the output ac voltage is in series with the line. It can be based on a voltage-sourced converter or current- sourced converter. Battery-storage or superconducting magnetic storage can also be connected to a series controller to inject a voltage vector of variable angle in series with the line.



(i) Interline Power Flow Controller (IPFC):The combination of two or more Static synchronous Series Compensators which are coupled via a common dc link to facilitate bi-directional flow of real power between the ac terminals of the SSSCs, and are controlled to provide independent reactive compensation for the adjustment of real power flow in each line and maintain the desired distribution of reactive power flow among the lines. The IPFC structure may also include a STATCOM, coupled to the IPFC's common dc link, to provide shunt reactive compensation and supply or absorb the overall real power deficit of the combined SSSCs.

(ii) Thyristor Controlled Series Capacitor (TCSC): A capacitive reactance compensator which consists of a series capacitor bank shunted by a thyristor-controlled reactor in order to provide a smoothly variable series capacitive reactance.

The TCSC is based on thyristors without the gate turn-off capability. It is an alternative to SSSC above and like an SSSC, it is a very important FACTS Controller. A variable reactor such as a Thyristor- Controlled Reactor (TCR) is connected across a series capacitor.

(iii) Thyristor-Switched Series Capacitor (TSSC): A capacitive reactance compensator which consists of a series capacitor bank shunted by a thyristor-switched reactor to provide a stepwise control of series capacitive reactance. Instead of continuous control of capacitive impedance, this approach of switching inductors at firing angle of 90 degrees or 180 degrees but without firing angle control, could reduce cost and losses of the Controller. It is reasonable to arrange one of the modules to have thyristor control, while others could be thyristor switched.

(iv) Thyristor-Controlled Series Reactor (TCSR):

An inductive reactance compensator which consists of a series reactor shunted by a thyristor controlled reactor in order to provide a smoothly variable series inductive reactance. When the firing angle of the thyristor controlled reactor is 180 degrees, it stops conducting, and the uncontrolled reactor acts as a fault current limiter. As the angle decreases below 180 degrees, the net inductance decreases until firing angle of 90 degrees, when the net inductance is the parallel combination of the two reactors. As for the TCSC, the TCSR may be a single large unit or several smaller series units.

(v) Thyristor-Switched Series Reactor (TSSR): An inductive reactance compensator which consists of a series reactor shunted by a thyristor-controlled switched reactor in order to provide a stepwise control of series inductive reactance. This is a complement of TCSR, but with thyristor switches fully on or off (without firing angle control) to achieve a combination of stepped series inductance.