2.3 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 .

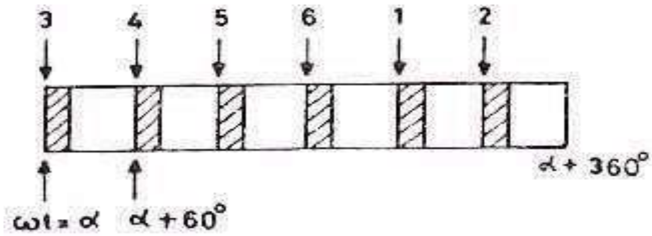


Figure 2.3.1 Timing diagram

[Source: “HVDC Power Transmission Systems” by K.P.Padiyar, page-51]

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.

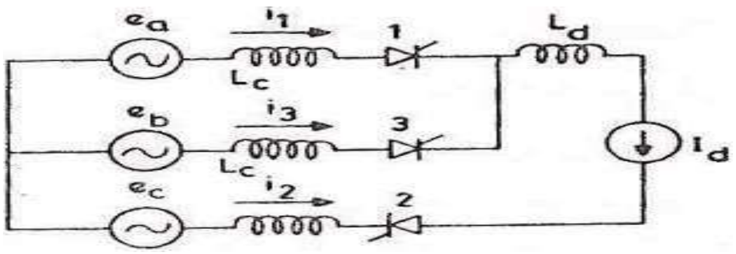


Figure 2.3.2 Equivelent circuit of 3 valve conduction

[Source: "HVDC Power Transmission Systems" by K.P.Padiyar, page-51]

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

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

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

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

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

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

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

Where,

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

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

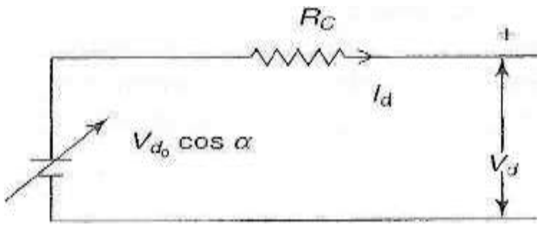


Figure 2.3.3 Equivalent circuit of a bridge converter

[Source: "HVDC Power Transmission Systems" by K.P.Padiyar, page-53]

Inverter Equations:

For an inverter, advance angle β is given by

$$\beta=\pi-\alpha$$

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

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

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

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

Where, the extinction angle γ is defined as

$$\gamma=\beta-\mu=\pi-\alpha-\mu$$

Similarly, it can be shown that

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

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

The subscript "i" refers to the inverter.

ii) Analysis of Three and Four Valve Conduction Mode:

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

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

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

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

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

The constant A can be determined from the initial condition

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

The constant C can be determined from the final condition

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

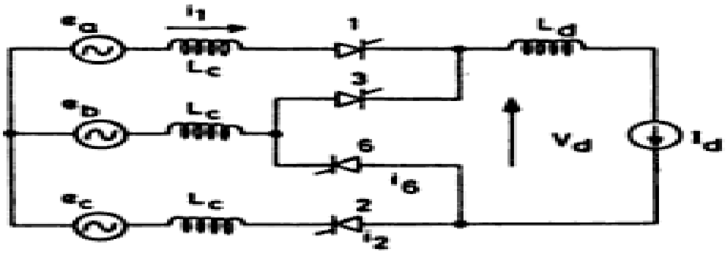


Figure 2.3.4 Equivalent circuit for four valve conduction

[Source: "HVDC Power Transmission Systems" by K.P.Padiyar, page-58]

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

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

The constant B can be determined from the continuity equation

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

Finally,

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

The expression for average direct voltage is given by

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

Since $e_c = E_m \cos\omega t$

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

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

Finally

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

2.2 Analysis of Graetz circuit without overlap

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

The following assumptions are made to simplify the analysis

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

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

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

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

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

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

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

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

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

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

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

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

DC Voltage Waveform:

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

$$h = np$$

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

The rms value of the hth 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.

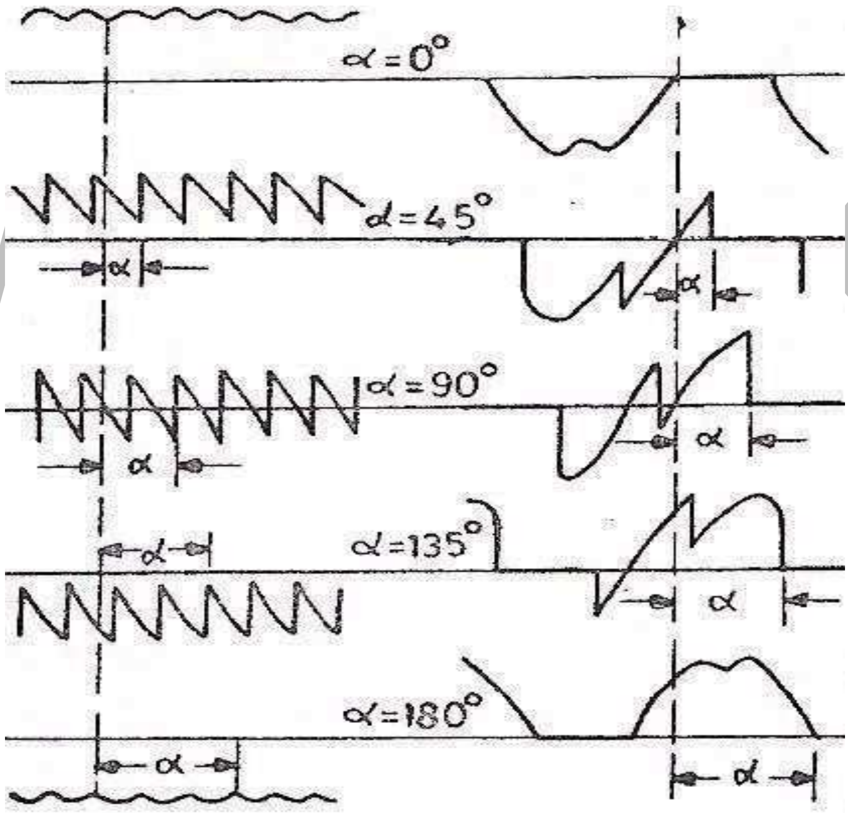


Figure 2.2.1 DC and valve voltage waveforms

[Source: "HVDC Power Transmission Systems" by K.P.Padiyar, page-28]

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.

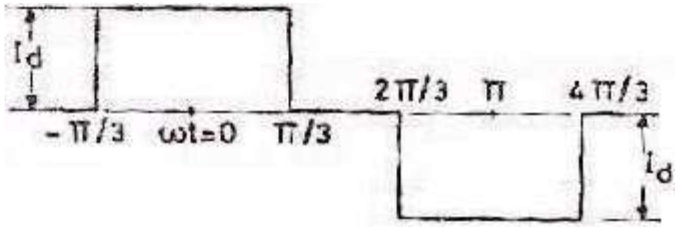


Figure 2.2.2 Valve current waveform

[Source: "HVDC Power Transmission Systems" by K.P.Padiyar, page-31]

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

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

where as the rms value of the current is

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

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

$$h = np \pm 1$$

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

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

Power Factor:

The AC power supplied to the converter is given by

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

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

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

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

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

$$\cos\phi = \cos\alpha$$

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

2.5 VSC topologies

Conventional HVDC transmission employs line-commutated, current-source converters with thyristor valves. These converters require a relatively strong synchronous voltage source in order to commutate. The conversion process demands reactive power from filters, shunt banks, or series capacitors, which are an integral part of the converter station.

Any surplus or deficit in reactive power must be accommodated by the ac system. This difference in reactive power needs to be kept within a given band to keep the ac voltage within the desired tolerance. The weaker the system or the further away from generation, the tighter the reactive power exchange must be to stay within the desired voltage tolerance.

These VSC-based systems are force-commutated with insulated-gate bipolar transistor (IGBT) valves and solid-dielectric, extruded HVDC cables HVDC transmission and reactive power compensation with VSC technology has certain attributes which can be beneficial to overall system performance. VSC converter technology can rapidly control both active and reactive power independently of one another. Reactive power can also be controlled at each terminal independent of the dc transmission voltage level. This control capability gives total flexibility to place converters anywhere in the ac network since there is no restriction on minimum network short-circuits capacity.

1. **Physical Structure**

The main function of the VSC-HVDC is to transmit constant DC power from the rectifier to the inverter. As shown in Figure.1, it consists of dc-link capacitors C_{dc}, two converters, passive high-pass filters, phase reactors, transformers and dc cable.

2. **Converters**

The converters are VSCs employing IGBT power semiconductors, one operating as a rectifier and the other as an inverter. The two converters are connected either back-to-back or through a dc cable, depending on the application.

3. **Transformers**

Normally, the converters are connected to the ac system via transformers. The most important function of the transformers is to transform the voltage of the ac system to a value suitable to the converter. It can use simple connection (two-winding instead of three to eight-winding transformers used for other schemes). The leakage inductance of the transformers is usually in the range 0.1-0.2p.u.

4. **Phase Reactors**

The phase reactors are used for controlling both the active and the reactive power flow by regulating currents through them. The reactors also function as ac filters to reduce the high frequency harmonic contents of the ac currents which are caused by the switching operation of the VSCs. The reactors are essential for both active and reactive power flow, since these properties are determined by the power frequency voltage across the reactors. The reactors are usually about 0.15p.u. Impedance.

5. **AC Filters**

The ac voltage output contains harmonic components, derived from the switching of the IGBTs. These harmonics have to be taken care of preventing them from being emitted into the ac system and causing malfunctioning of ac system equipment or radio and telecommunication disturbances. High-pass filter branches are installed to take care of these high order harmonics. With VSC converters there is no need to compensate any reactive power consumed by the converter itself and the current harmonics on the ac side are related directly to the PWM frequency. The amount of low-order harmonics in the current is small.

6. **Dc Capacitors**

On the dc side there are two capacitor stacks of the same size. The size of these capacitors depends on the required dc voltage. The objective for the dc capacitor is primarily to provide a low inductive path for the turned-off current and

energy storage to be able to control the power flow. The capacitor also reduces the voltage ripple on the dc side.

7. **Dc Cables**

The cable used in VSC-HVDC applications is a new developed type, where the insulation is made of an extruded polymer that is particularly resistant to dc voltage. Polymeric cables are the preferred choice for HVDC, mainly because of their mechanical strength, flexibility, and low weight.

8. IGBT Valves

The insulated gate bipolar transistor (IGBT) valves used in VSC converters are comprised of series-connected IGBT positions. The IGBT is a hybrid device exhibiting the low forward drop of a bipolar transistor as a conducting device. A complete IGBT position consists of an IGBT, an anti parallel diode, a gate unit, a voltage divider, and a water-cooled heat sink. Each gate unit includes gate-driving circuits, surveillance circuits, and optical interface. The gate-driving electronics control the gate voltage and current at turn-on and turn-off, to achieve optimal turn-on and turn-off processes of the IGBT. To be able to switch voltages higher than the rated voltage of one IGBT, many positions are connected in series in each valve similar to thyristors in conventional HVDC valves.

9. AC Grid

Usually a grid model can be developed by using the Thevenin equivalent circuit. However, for simplicity, the grid was modeled as an ideal symmetrical three-phase voltage source.

HVDC Circuit breakers & Operating problems

Circuit breakers will be positioned on DC grids and act when a fault occurs. Breakers would have to fulfill some basic requirements. Current zero crossing should be created to interrupt the current once a fault occurs. At the same time the energy that is stored in the system’s inductance should be dissipated and the breaker should withstand the voltage response of the network.

There are two types of HVDC circuit breakers: electromechanical and solid-state. Electromechanical can be grouped into three categories: (1) inverse voltage generating method, (2) divergent current oscillating method, and (3) inverse current injecting method. Only the inverse current injecting method can be used in high voltage and current ratings. In this type of breaker, current zero can be created by superimposing an inverse current (of high frequency) on the input current by dis-charging a capacitor (that was pre- charged) through an inductor. (Explained on next section) The cost of components required for an electromechanical DC circuit breaker would not be significantly higher than that of an AC circuit breaker. Electromechanical HVDC circuit breakers are available up to 500 kV, 5 kA and have a fault-clearing time of the order of 100 ms.

Solid-state circuit breakers are the second type of HVDC breakers. These breakers can interrupt current much faster (which is required in some cases) than electromechanical circuit breakers, having an interruption time of a few milliseconds. They are based on Integrated Gate Commutated Thyristors (IGCT), which compared to IGBT (bipolar thyristors) have lower on-state losses. Current flows through the IGCT and in order to interrupt, the IGCT is turned off. Once that happens, voltage quickly increases until a varistor (that is in parallel to the thyristor) starts to conduct. The varistor is designed to block voltages above the voltage level of the system. The main disadvantages of these types of circuit breakers are the high on-state losses and the capital costs.Typical ratings of solid-state circuit breakers in operation are 4 kV, 2 kA, although in ratings of up to 150 kV, 2 kA were considered.

Electromechanical HVDC circuit breakers:

- The nominal current path is where DC current passes through and the switch is closed during normal operation
- The commutation path consists of a switch and a resonant circuit with an inductor and a capacitor and is used to create the inverse current
- The energy absorption path consists of a switch and a varistor

The commutation path has a series resonance. When interruption is required, current oscillation can occur between the nominal and the commutation path at the natural frequency (1/LC). If the amplitude of the oscillating current is larger than that of the input current then zero crossing occurs and the switch can interrupt the current in the nominal path. Current (Io) will continue to flow and will charge the capacitor.

If the capacitor voltage exceeds a given value, which is chosen to be the voltage capability of the circuit breaker, the energy absorption path will act causing the current to decrease.

This is a basic circuit that would need further implementations to be efficient in high voltages. Reduction in cost and better use of the costly components (varistor, capacitor) will be required. Also, the optimum capacitance value would minimize the breaker's interruption time and improve the whole interruption performance. Furthermore, current oscillations grow when the arc resistance (dU/dt) of the switch on the nominal path is negative. Growing oscillations can lead to faster current interruption. At the same time a large C/L ratio can help maximize the breaker's interruption performance.

Solid State Circuit Breakers:

The second type of circuit breaker we will be analyzing is the solid-state circuit breaker. In the following figure we can see that a solid-state circuit breaker uses gate-commuted thyristors instead of integrated gate-commuted thyristors for semiconductor devices, this is due to the fact that in this topology our immediate concern is lowering the on-state losses.

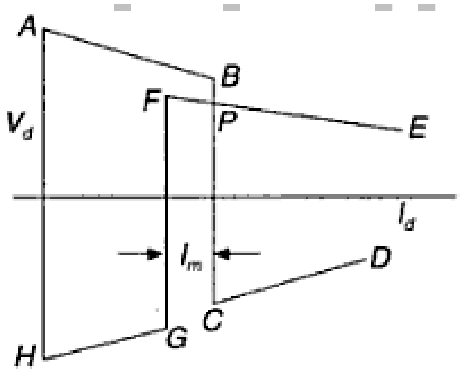
3.2 Converter control characteristics

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)

Figure 3.2.1 Converter control characteristics

[Source: "HVDC Power Transmission Systems" by K.P.Padiyar, page-87]

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} .

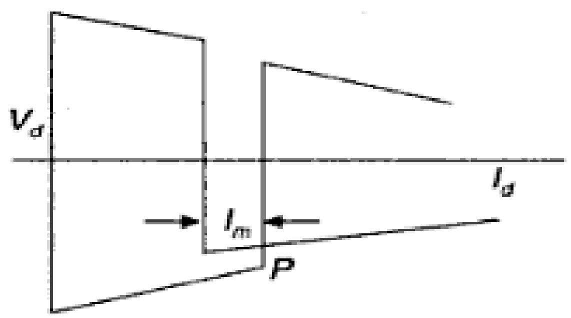


Figure 3.2.2 Converter control characteristics for negative current margin

[Source: "HVDC Power Transmission Systems" by K.P.Padiyar, page-87]

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

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

Voltage Dependent Current Limit:

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

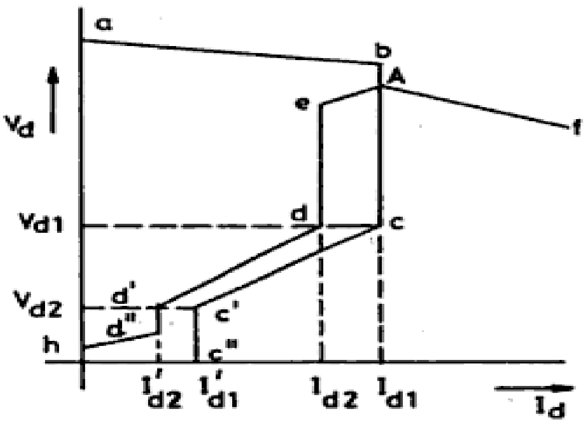


Figure 3.2.3 Converter control characteristics including VDCOL

[Source: "HVDC Power Transmission Systems" by K.P.Padiyar, page-84]

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.

2.6 firing schemes

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

The two basic firing schemes are

1. Individual Phase Control (IPC)
2. Equidistant Pulse Control (EPC)

Individual Phase Control (IPC)

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

There are two ways in which this can be achieved

1. Constant α Control
2. Inverse Cosine Control

Constant α Control

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

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

Inverse Cosine Control

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

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

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

Drawbacks of IPC Scheme

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

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

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

Equidistant Pulse Control (EPC)

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

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

Pulse Frequency Control (PFC)

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

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 .

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

Pulse Phase Control (PPC)

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

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

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

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

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

Drawbacks of EPC Scheme

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

1. Under balanced voltage conditions, EPC results in less DC voltage compared to IPC. Unbalance in the voltage results from single phase to ground fault in the AC system which may persist for over 10 cycles due to stuck breakers. Under such conditions, it is desirable to maximize DC power transfer in the link which calls for IPC.
2. EPC Scheme also results in higher negative damping contribution to torsional oscillations when HVDC is the major transmission link from a thermal station.

2.1 Line commutated converter

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

Pulse Number

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

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

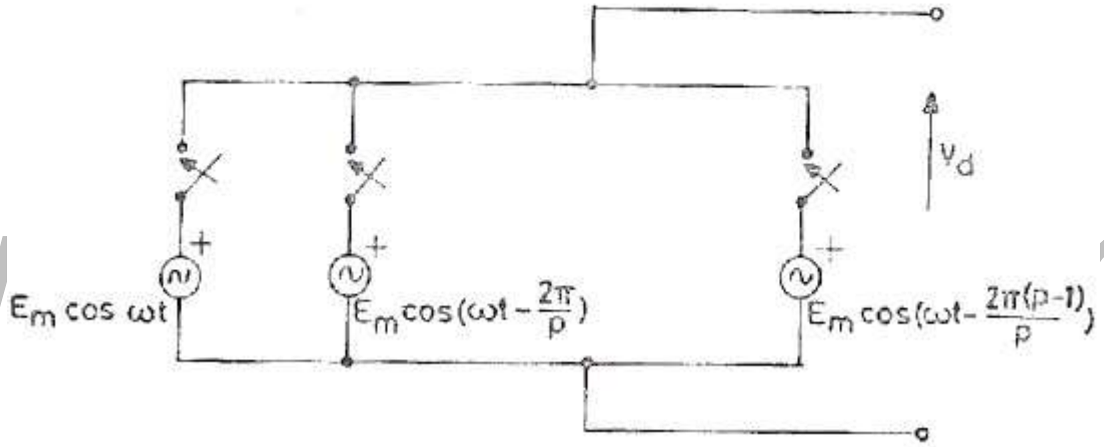


Figure 2.1.1 A Valve group with 'p' valves

[Source: "HVDC Power Transmission Systems" by K.P.Padiyar, page-32]

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.

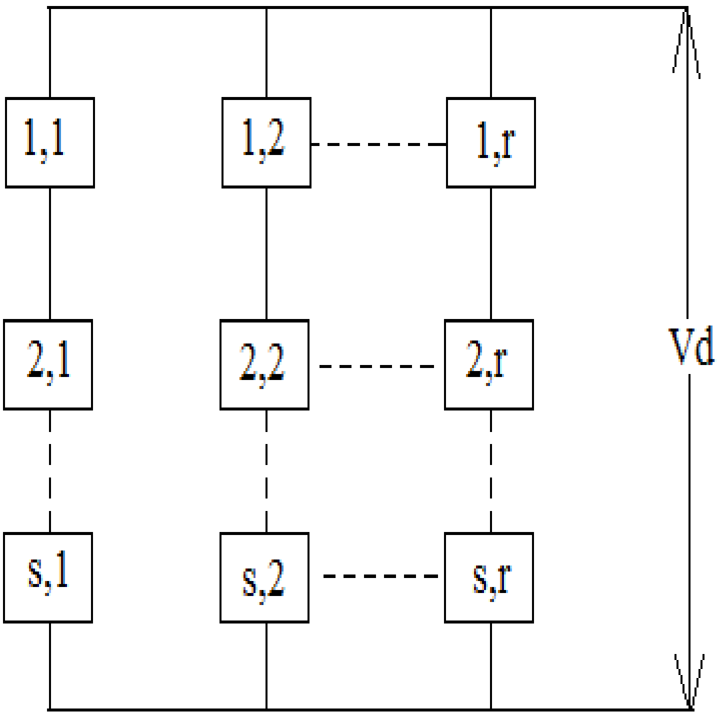


Figure 2.1.2 Converter made up of series and parallel connection of communication groups

[Source: "HVDC Power Transmission Systems" by K.P.Padiyar, page-33]

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

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

$$p = q\ r\ s$$

Note:

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

Valve Rating:

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

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

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

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

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

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

$$\text{PIV} = 2E_m$$

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

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

The valve utilization factor is given by

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

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

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

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

Transformer Rating:

The current rating of a valve is given by,

$$I_v = \frac{I_d}{\sqrt{q}}$$

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

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

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

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

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

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

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

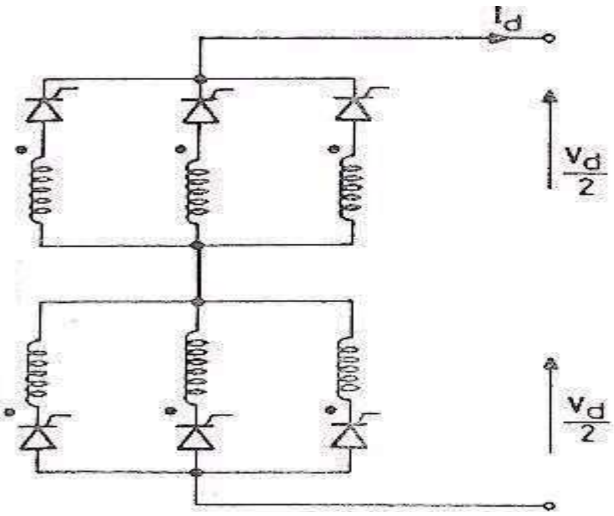


Figure 2.1.3 Six pulse converter

[Source: "HVDC Power Transmission Systems" by K.P.Padiyar, page-35]

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

$$\frac{S_{tv}}{V_{do} I_d} = \frac{\pi}{\sqrt{(2X3)}\sin\frac{\pi}{3}}$$

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

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

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

It is a 6-pulse converter consisting of two winding transformer where the transformer utilization factor is increased when compared to three winding transformer. The series conduction of converter groups has been preferred because of controlling and protection as well as the requirements for high voltage ratings. So, a 12 pulse converter is obtained by series connection of two bridges.

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

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