11

High Voltage Direct Current Transmission

11.0 Historical Background

Power Transmission was initially carried out in the early 1880s using Direct Current (**d.c.**). 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 **a.c.** to **d.c.** when required, **a.c.** gradually replaced **d.c.** 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.

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

In 1961 the cross channel link between England and France was put into operation. The a.c. systems were connected by two single conductor submarine cables (64km) at ± 100kV with two bridges each rated at 80 MW. The mid-point of the converters was grounded at one terminal only so as not to permit ground currents to flow. Sea return was not used because of its effect on the navigation of ships using compasses. The link is an asynchronous link between the two systems with the same nominal frequency (60Hz).

The Sakuma Frequency Changer which was put into operation in 1965, interconnects the 50Hz and the 60Hz systems of Japan. It is the first d.c. link of zero length, and is confined to a single station. It is capable of transmitting 300 MW in either direction at a voltage of 250 kV.

In 1968 the Vancouver Island scheme was operated at +250 kV to supply 300 MW and is the first d.c. link operating in parallel with an a.c. link.

In 1970 a solid state addition (Thyristors) was made to the Gotland scheme with a rating of 30MW at -150kV.

Also in 1970 the Kingsnorth scheme in England was operated on an experimental basis. In this scheme transmission of power by underground d.c. cable at ± 200 kV, 640 MW is used to reinforce the a.c. system without increasing the interrupting duty of a.c. circuit breakers.

The first converter station using exclusively Thyristors was the Eel River scheme in Canada. Commissioned in 1972, it supplies 320 MW at 80 kV d.c. The link is of zero length and connects two a.c. systems of the same nominal frequency (60Hz).

The largest thyristors used in converter valves have blocking voltages of the order of kilovolts and currents of the order 100s of amperes. In order to obtain higher voltages the thyristor valve uses a single series string of these thyristors. With higher current ratings required, the valve utilizes thyristors directly connected in parallel on a common heat sink.

The largest operational converter stations have ratings of the order of gigawatts and operate at voltages of 100s of kilovolts, and maybe up to 1000 km in length.

The thyristors are mostly air cooled but may be oil cooled, water cooled or Freon cooled. With air cooled and oil cooled thyristors the same medium is used as insulant. With the Freon cooled thyristors, SF_6 may be used for insulation, leading to the design of a compact thyristor valve.

Unlike an a.c. transmission line which requires a transformer at each end, a d.c. transmission line requires a convertor at each end. At the sending end rectification is carried out, where as at the receiving end inversion is carried out.

11.1 Comparison of a.c and d.c transmission

11.1.1 Advantages of d.c.

(a) **More power can be transmitted per conductor per circuit.**

The capabilities of power transmission of an a.c. link and a d.c. link are different.
For the same insulation, the direct voltage V_d is equal to the peak value ($\sqrt{2}$ x rms value) of the alternating voltage V_d.

$$V_d = \sqrt{2}\, V_a$$

For the same conductor size, the same current can transmitted with both d.c. and a.c. if skin effect is not considered.

$$I_d = I_a$$

Thus the corresponding power transmission using 2 conductors with d.c. and a.c. are as follows.

d c power per conductor $P_d = V_d I_d$

a c power per conductor $P_a = V_a I_a \cos\varphi$

The greater power transmission with d.c. over a.c. is given by the ratio of powers.

$$\frac{P_d}{P_a} = \frac{\sqrt{2}}{\cos\varphi} = \begin{cases} 1.414 & \text{at p.f = unity} \\ 1.768 & \text{at p.f = 0.8} \end{cases}$$

In practice, a.c. transmission is carried out using either single circuit or double circuit 3 phase transmission using 3 or 6 conductors. In such a case the above ratio for power must be multiplied by **2/3** or by **4/3**.

In general, we are interested in transmitting a given quantity of power at a given insulation level, at a given efficiency of transmission. Thus for the same power transmitted P, same losses P_L and same peak voltage V, we can determine the reduction of conductor cross-section A_d over A_a.

Let R_d and R_a be the corresponding values of conductor resistance for d.c. and a.c. respectively, neglecting skin resistance.

For **d.c** current $= \dfrac{P}{V_m}$

power loss $P_L = (P/V_m)^2 R_d = (P/V_m)^2.(\rho l/A_d)$

For **a.c** current $= \dfrac{P}{(V_m/\sqrt{2})\cos\varphi} = \dfrac{\sqrt{2}\,P}{V_m \cos\varphi}$

power loss $P_L = [\sqrt{2}P/(V_m \cos\varphi)]^2 R_a$

$= 2\,(P/V_m)^2.(\rho l/A_a \cos^2\varphi)$

Equating power loss for d.c. and a.c.

$$(P/V_m)^2.(\rho l/A_d) = 2\,(P/V_m)^2.(\rho l/A_a \cos^2\varphi)$$

This gives the result for the ratio of areas as

$$\frac{A_d}{A_a} = \frac{\cos^2\varphi}{2} = \left[\begin{array}{l} 0.5 \text{ at p.f.} = \text{unity} \\ 0.32 \text{ at p.f.} = 0.8 \end{array}\right.$$

The result has been calculated at unity power factor and at 0.8 lag to illustrate the effect of power factor on the ratio. It is seen that only one-half the amount of copper is required for the same power transmission at unity power factor, and less than one-third is required at the power factor of 0.8 lag.

(b) **Use of Ground Return Possible**

In the case of hvdc transmission, ground return (especially submarine crossing) may be used, as in the case of a monopolar d.c. link. Also the single circuit bipolar d.c. link is more reliable, than the corresponding a.c. link, as in the event of a fault on one conductor, the other conductor can continue to operate at reduced power with ground return. For the same length of transmission, the impedance of the ground path is much less for d.c. than for the corresponding a.c. because d.c. spreads over a much larger width and depth. In fact, in the case of d.c. the ground path resistance is almost entirely dependant on the earth electrode resistance at the two ends of the line, rather than on the line length. However it must be borne in mind that ground return has the following disadvantages. The ground currents cause electrolytic corrosion of buried metals, interfere with the operation of signalling and ships' compasses, and can cause dangerous step and touch potentials.

(c) **Smaller Tower Size**

The d.c. insulation level for the same power transmission is likely to be lower than the corresponding a.c. level. Also the d.c. line will only need two conductors whereas three conductors (if not six to obtain the same reliability) are required for a.c. Thus both electrical and mechanical considerations dictate a smaller tower.

(d) **Higher Capacity available for cables**

In contrast to the overhead line, in the cable breakdown occurs by puncture and not by external flashover. Mainly due to the absence of ionic motion, the working stress of the d.c. cable insulation may be 3 to 4 times higher than under a.c.

Also, the absence of continuous charging current in a d.c. cable permits higher active power transfer, especially over long lengths.

(Charging current of the order of 6 A/km for 132 kV). Critical length at 132 kV ≈ 80 km for a.c cable. Beyond the critical length no power can be transmitted without series compensation in a.c. lines. Thus derating which is required in a.c. cables, thus does not limit the length of transmission in d.c.

A comparison made between d.c. and a.c. for the transmission of about 1550 MVA is as follows. Six number a.c. 275 kV cables, in two groups of 3 cables in horizontal formation, require a total trench width of 5.2 m, whereas for two number d.c. ±500 kV cables with the same capacity require only a trench width of about 0.7 m.

(e) **No skin effect**

Under a.c. conditions, the current is not uniformly distributed over the cross section of the conductor. The current density is higher in the outer region (skin effect) and result in under utilisation of the conductor cross-section. Skin effect under conditions of smooth d.c. is completely absent and hence there is a uniform current in the conductor, and the conductor metal is better utilised.

(f) **Less corona and radio interference**

Since corona loss increases with frequency (in fact it is known to be proportional to **f+25**), for a given conductor diameter and applied voltage, there is much lower corona loss and hence more importantly less radio interference with d.c. Due to this bundle conductors become unnecessary and hence give a substantial saving in line costs. [Tests have also shown that bundle conductors would anyway not offer a significant advantage for d.c as the lower reactance effect so beneficial for a.c is not applicable for d.c.]

(g) **No Stability Problem**

The d.c. link is an asynchronous link and hence any a.c. supplied through converters or d.c. generation do not have to be synchronised with the link. Hence the length of d.c. link is not governed by stability.

In a.c. links the phase angle between sending end and receiving end should not exceed 30^o at full-load for transient stability (maximum theoretical steady state limit is 90^o).

Note: $\theta = w\sqrt{lc}$ per km $= (2\pi \times 50)/(3 \times 10^5)$ rad/km $\approx (2 \times 180 \times 50)/(3 \times 10^5) \approx 0.06^0$/km

The phase angle change at the natural load of a line is thus 0.6^o per 10 km.

The maximum permissible length without compensation ≈ 30/0.06 = 500 km

With compensation, this length can be doubled to 1000 km.

(h) **Asynchronous interconnection possible**

With a.c. links, interconnections between power systems must be synchronous. Thus different frequency systems cannot be interconnected. Such systems can be easily interconnected through hvdc links. For different frequency interconnections both convertors can be confined to the same station.

In addition, different power authorities may need to maintain different tolerances on their supplies, even though nominally of the same frequency. This option is not available with a.c. With d.c. there is no such problem.

(i) **Lower short circuit fault levels**

When an a.c. transmission system is extended, the fault level of the whole system goes up, sometimes necessitating the expensive replacement of circuit breakers with those of higher fault levels. This problem can be overcome with hvdc as it does not contribute current to the a.c. short circuit beyond its rated current. In fact it is possible to operate a d.c. link in "parallel" with an a.c. link to limit the fault level on an expansion. In the event of a fault on the d.c line, after a momentary transient due to the discharge of the line capacitance, the current is limited by automatic grid control. Also the d.c. line does not draw excessive current from the a.c. system.

(j) **Tie line power is easily controlled**

In the case of an a.c. tie line, the power cannot be easily controlled between the two systems. With d.c. tie lines, the control is easily accomplished through grid control. In fact even the reversal of the power flow is just as easy.

11.1.2 Inherent problems associated with hvdc

(a) **Expensive convertors**

Expensive Convertor Stations are required at each end of a d.c. transmission link, whereas only transformer stations are required in an a.c. link.

(b) **Reactive power requirement**

Convertors require much reactive power, both in rectification as well as in inversion. At each convertor the reactive power consumed may be as much at 50% of the active power rating of the d.c. link. The reactive power requirement is partly supplied by the filter capacitance, and partly by synchronous or static capacitors that need to be installed for the purpose.

(c) **Generation of harmonics**

Convertors generate a lot of harmonics both on the d.c. side and on the a.c. side. Filters are used on the a.c. side to reduce the amount of harmonics transferred to the a.c. system. On the d.c. system, smoothing reactors are used. These components add to the cost of the convertor.

(d) **Difficulty of circuit breaking**

Due to the absence of a natural current zero with d.c., circuit breaking is difficult. This is not a major problem in single hvdc link systems, as circuit breaking can be accomplished by a very rapid absorbing of the energy back into the a.c. system. (The blocking action of thyristors is faster than the operation of mechanical circuit breakers). However the lack of hvdc circuit breakers hampers multi-terminal operation.

(e) **Difficulty of voltage transformation**

Power is generally used at low voltage, but for reasons of efficiency must be transmitted at high voltage. The absence of the equivalent of d.c. transformers makes it necessary for voltage transformation to carried out on the a.c. side of the system and prevents a purely d.c. system being used.

(f) **Difficulty of high power generation**

Due to the problems of commutation with d.c. machines, voltage, speed and size are limited. Thus comparatively lower power can be generated with d.c.

(g) **Absence of overload capacity**

Convertors have very little overload capacity unlike transformers.

11.1.3 Economic Comparison

The hvdc system has a lower line cost per unit length as compared to an equally reliable a.c. system due to the lesser number of conductors and smaller tower size. However, the d.c. system needs two expensive convertor stations which may cost around two to three times the corresponding a.c. transformer stations. Thus hvdc transmission is not generally economical for short distances, unless other factors dictate otherwise. Economic considerations call for a certain minimum transmission distance (break-even distance) before hvdc can be considered competitive purely on cost.

Estimates for the break even distance of overhead lines are around 500 km with a wide variation about this value depending on the magnitude of power transfer and the range of costs of lines and equipment. The break-even distances are reducing with the progress made in the development of converting devices.

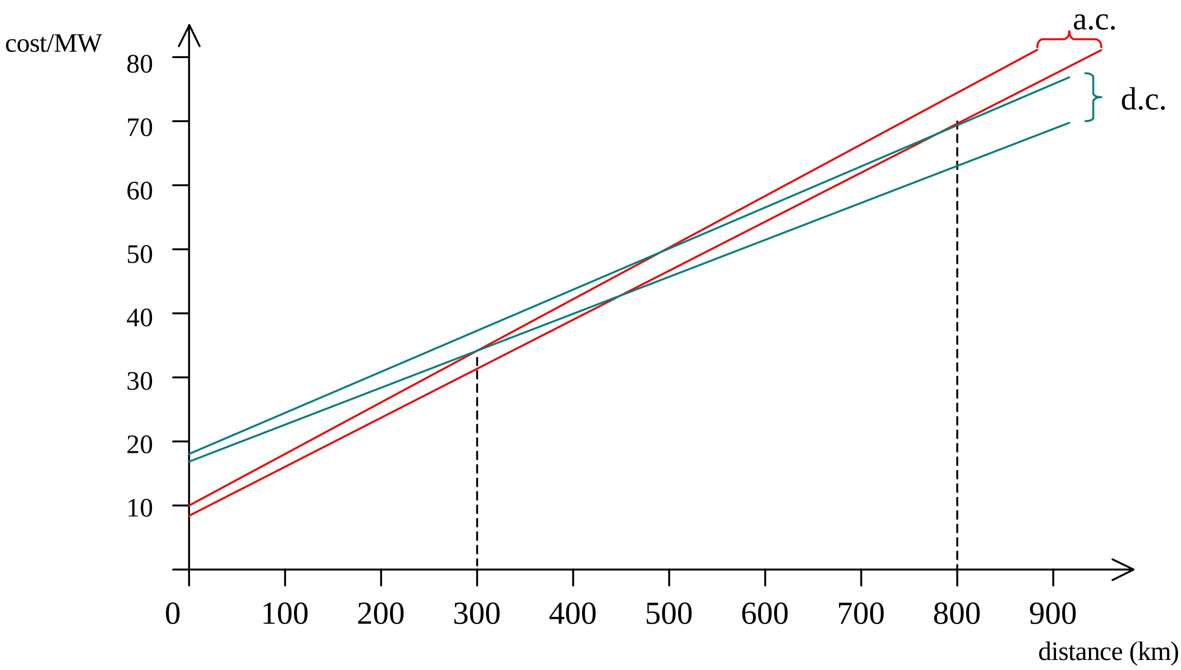


Figure 11.1 - Break-even distance for d.c. transmission

Figure 11.1 shows the comparative costs of d.c. links and a.c. links with distance, assuming a cost variation of ± 5% for the a.c. link and a variation of ± 10% for the d.c. link.

For cables, the break-even distance is much smaller than for overhead lines and is of the order of 25 km for submarine cables and 50 km for underground cables.

11.2 Convertor arrangements and operation

The three-phase six-valve bridge rectifier is almost exclusively used in high voltage direct current applications. This is shown in figure 11.2.

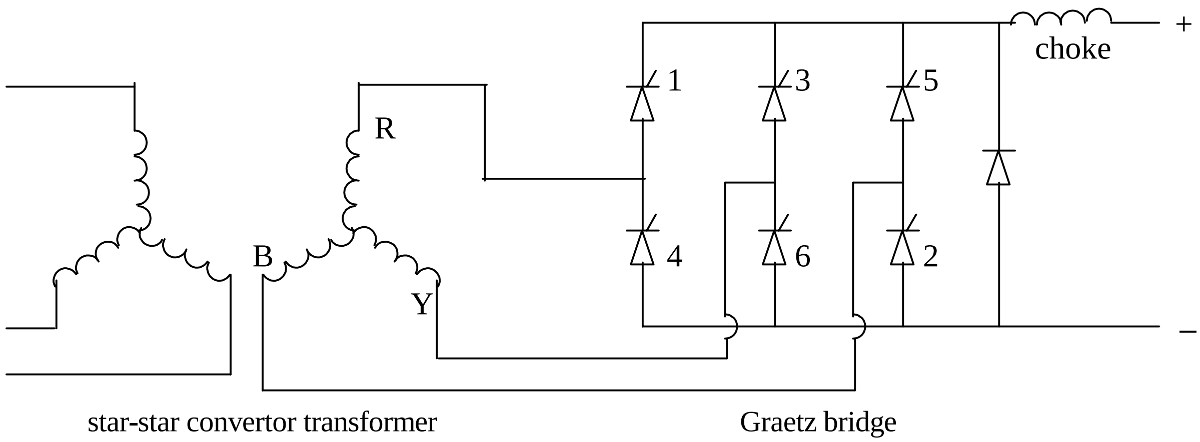


Figure 11.2 - Hexa-valve Bridge Convertor arrangement

The 6-valve bridge connection gives double the direct voltage as output compared to the simple 3-phase rectifier. The convertor transformer may either be wound star-star as shown, or as star-delta (or even as delta-star or delta-delta). The ripple of each of these connections is the same, but are phase shifted by 30^0 in output with respect to each other. To obtain a smoother output, two bridges (one star-star and the other star-delta) may be connected together to give the twelve pulse connection.

For the 6-valve bridge, with zero firing delay, the voltage waveforms across the thyristors are shown in figure 11.3. 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.

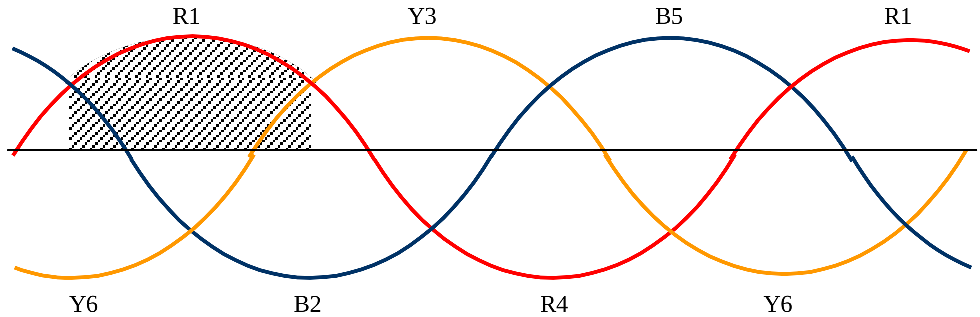


Figure 11.3 - Thyristor voltage waveforms ($\alpha = 0$)

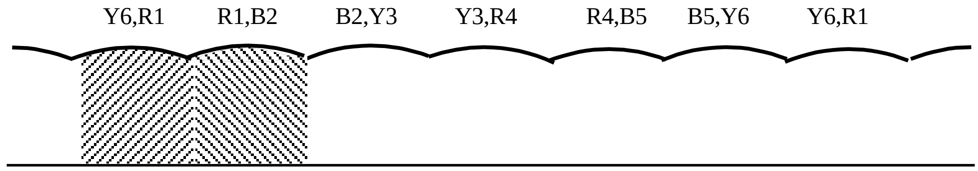


Figure 11.4 - d.c. output waveforms ($\alpha = 0$)

The corresponding d.c. output voltage waveforms are shown in figure 11.4.

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 ripple of course increases with the delay angle and has a value of about 30% at $\alpha = \pi/2$.

With the 12 pulse bridge, the r.m.s. ripple is of the order of 1.03% of the d.c. value (for $\alpha = 0$ and $\gamma = 0$), and increases to about 15% at $\alpha = \pi/2$.

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 $\alpha = 0$, $\gamma = 0$, then the direct voltage output is given by equation (11.1).

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

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

$$V_{do} = \frac{3\sqrt{2}}{\pi}\,.\,E = 1.350\;E \qquad (11.1)$$

11.2.1 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 11.5.

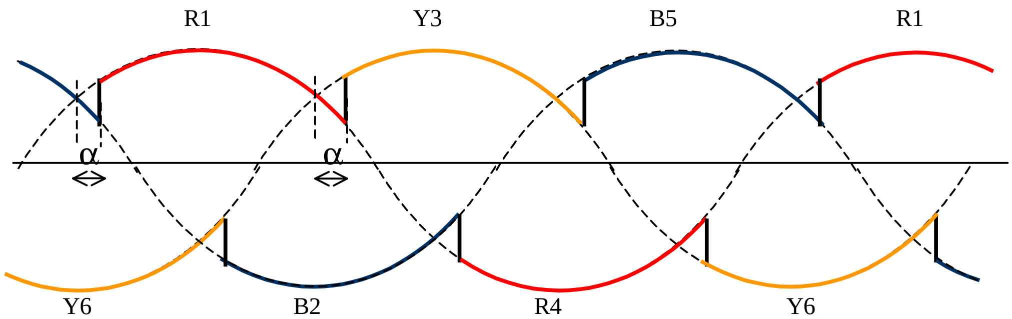


Figure 11.5 - Thyristor voltage waveforms (with delay α)

In this case, the magnitude of the direct voltage output is given by the equation (11.2).

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

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

$$V_d = \frac{3\sqrt{2}}{\pi}\,E\cos\alpha = V_{do}\cos\alpha \qquad (11.2)$$

11.2.2 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, the voltage at the electrode follows mean voltage of the 2 conducting thyristors on the same side. This is shown in figure 11.6.

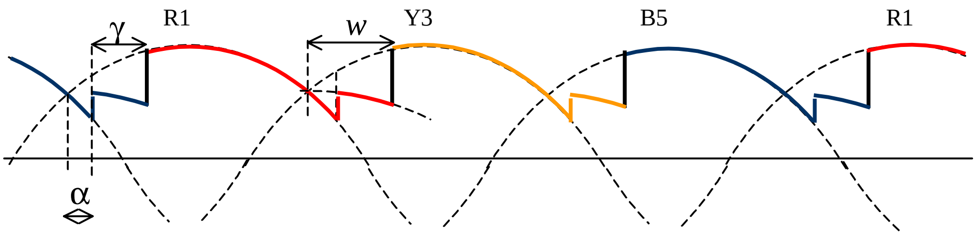


Figure 11.6 - commutation between 2 thyristors

With both the delay angle and commutation being present, the magnitude of the direct voltage may be determined from equation (11.3) as follows.

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

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

$$V_d = \frac{V_{do}}{2}\left[\cos\alpha+\cos(\alpha+\gamma)\right] \qquad (11.3)$$

An alternate method of derivation of the result is based on comparison of similar areas on the waveform. Figure 11.7 gives the necessary information.

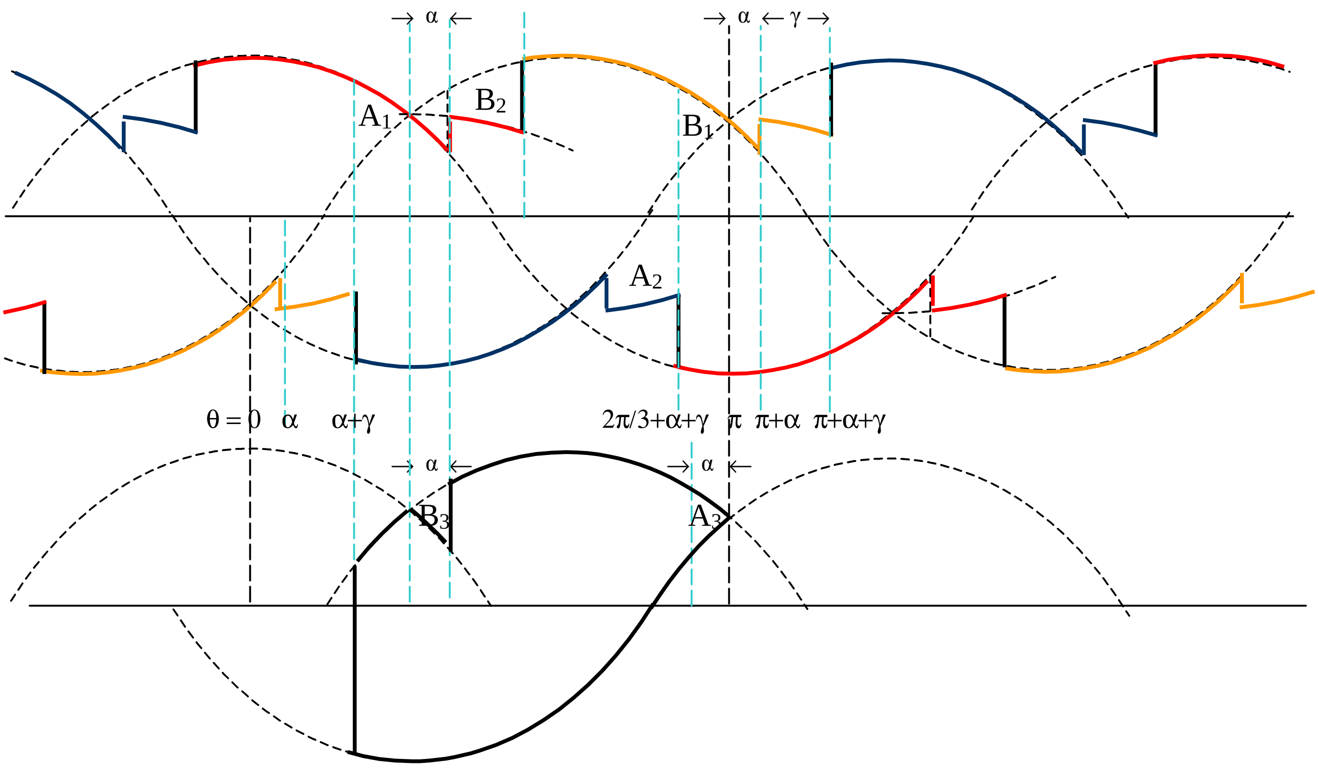


Figure 11.7 - Graphical analysis of waveform

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 A_1 can be replaced by area B_1. Similarly, area A_2 can be replaced by area B_2 and area A_3 by area B_3. 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 $\sqrt{2}$ E is the peak value of the line voltage.

Simplification gives the desired result as in equation (11.3).

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

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

Commutation is a result of the a.c. system inductance L_c, which does not allow the current through a thyristor to extinguish suddenly. Thus the larger the current the larger the commutation angle γ.

If the extinction angle for rectifier operation w is defined as $w = \alpha + \gamma$, then V_d can be written as in equation 11.4.

Consider the commutation between thyristors 1 & 3 in the bridge circuit shown in figure 11.8. Let i_c be the commutation current. The commutation current is produced by the voltage e_c which is the line voltage between phases 1 and 2.

$$V_d = \tfrac{1}{2}\left[\cos\alpha + \cos w\right] \qquad (11.4)$$

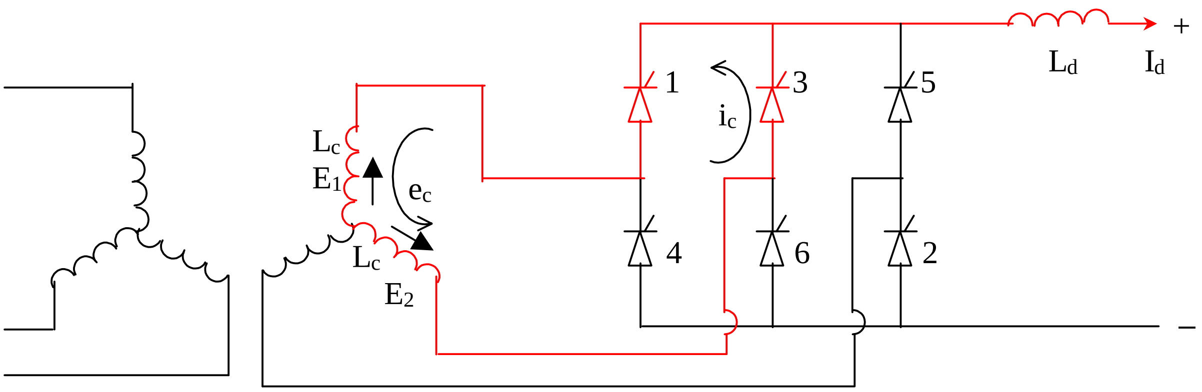


Figure 11.8 - Circuit for analysis of commutation

$$e_c = E_2 - E_1 = \frac{E\sqrt{2}}{\sqrt{3}}\left[\cos\left(\omega t + \frac{\pi}{3}\right) - \cos\left(\omega t - \frac{\pi}{3}\right)\right]$$

$$= \sqrt{2}\,E \sin\omega t$$

This can also be written in the following form, with $i_c = 0$ at the start of commutation and $i_c = I_d$ at the end of commutation.

$$e_c = 2\,L_c \frac{d\,i_c}{d\,t}$$

This equation may be integrated as follows to give equation 11.5.

$$\tfrac{1}{2}\int_{\alpha}^{w=\alpha+\gamma} e_c\, d(\omega t) = \omega\, L_c \int_0^{I_d} d\, i_c$$

$$\tfrac{1}{2}\int_{\alpha}^{w} \sqrt{2}\, E \sin \omega t\, d(\omega t) = \omega\, L_c\, I_d$$

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

$$\cos\alpha - \cos w = \frac{\sqrt{2}\,\omega\, L_c}{E} I_d \qquad (11.5)$$

$$\cos\alpha + \cos w = \frac{2V_d}{V_o} \qquad (11.6)$$

Equation 11.4 can also be written of the form of equation (11.6).

From equations (11.5) and (11.6) **w** may be eliminated to give the equation (11.7).

$$\cos\alpha = \frac{V_d}{V_0} + \frac{\omega\, L_c}{\sqrt{2}\, E} I_d$$

$$\because V_0 = \frac{3\sqrt{2}\, E}{\pi}, \quad \cos\alpha = \frac{V_d}{V_0} + \frac{3\,\omega\, L_c}{\pi\, V_0}$$

$$\therefore\ V_d = V_0 \cos\alpha - \frac{3\,\omega\, L_c}{\pi} I_d \qquad (11.7)$$

It can also be shown that equation (11.7) can be rewritten in terms of the extinction angle w instead of the ignition angle α as in equation (11.8).

$$V_d = V_0 \cos w + \frac{3\,\omega\, L_c}{\pi} I_d \qquad (11.8)$$

Equation (11.7) suggests that the convertor may be represented by a no load d.c. output voltage $\mathbf{V_o \cos \alpha}$

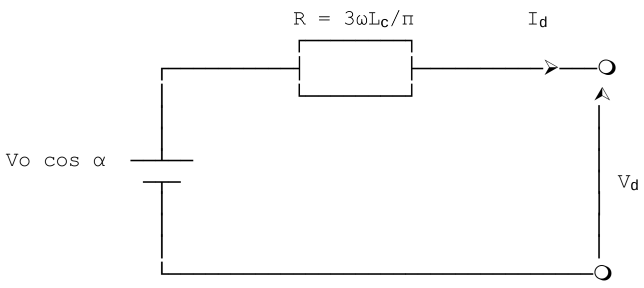


Figure 11.9 - Equivalent circuit for Rectifier

and a series fictitious resistance $\mathbf{3\omega L_c/\pi}$ as shown in figure 11.9. The fictitious resistor does not however consume any active power.

11.2.3 Current Waveforms

If Commutation is not considered, the current waveforms through each thyristor (assuming a very high value of inductance L_d in the d.c. circuit to give complete smoothing) is a rectangular pulse lasting exactly one-third of a cycle. This is shown in figure 11.10 for the cases without delay and with delay.

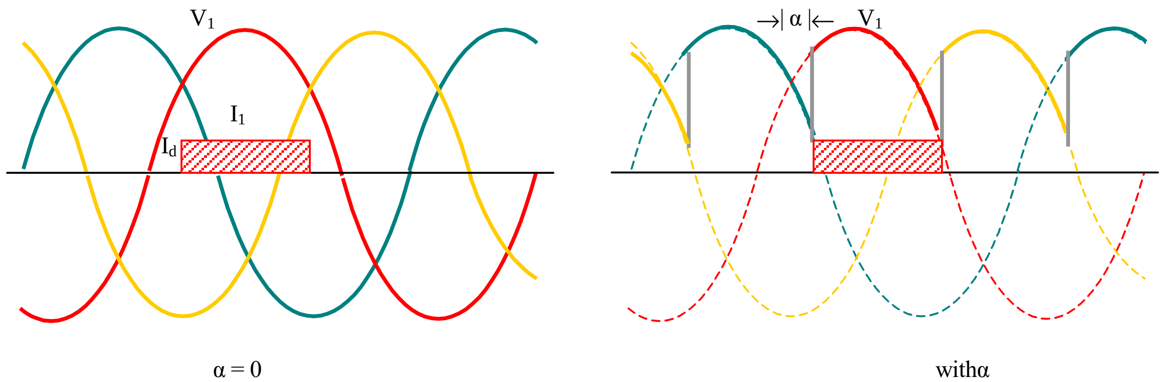


Figure 11.10 - Thyristor current waveforms (γ)

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 11.11.

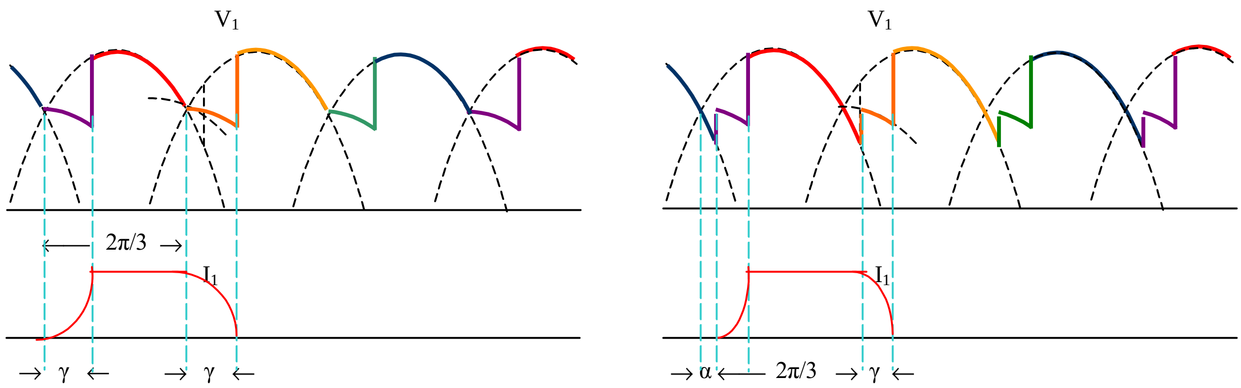


Figure 11.11 - Thyristor current waveforms

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 11.12.

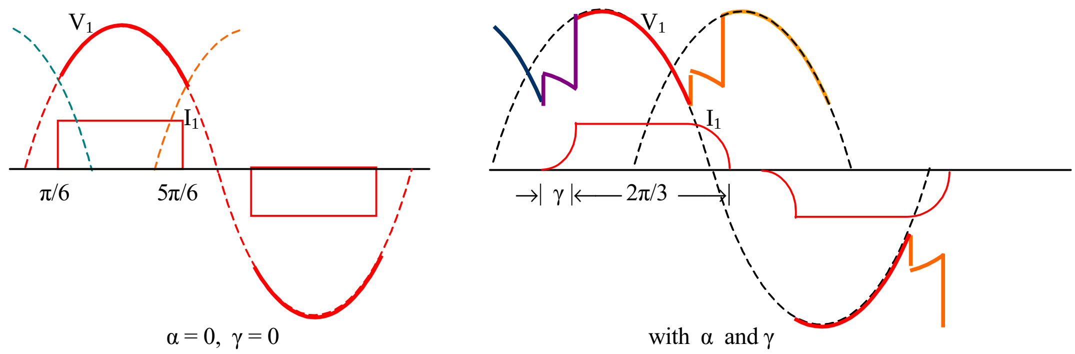


Figure 11.12 - Current waveforms on transformer secondary

If commutation angle is not considered, we can easily calculate the r.m.s. value of the a.c. current on the transformer secondary I_s as in equation (11.9).

$$I_s = \sqrt{\frac{1}{\pi} \cdot \frac{2\pi}{3} \cdot I_d{}^2} = \sqrt{\tfrac{2}{3}}\, I_d = 0.8165\, I_d \qquad (11.9)$$

Usually harmonic filters are provided on the a.c. system, so that only the fundamental component need to be supplied/absorbed from the a.c. system. From Fourier analysis, it can be shown that the fundamental component is given as follows, resulting in equation (11.10).

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

$$I = \frac{\sqrt{2}}{\pi} I_d \, 2 \sin \frac{\pi}{3} = \frac{\sqrt{6}}{\pi} I_d = 0.78\, I_d \qquad (11.10)$$

If filters were not provided, it can be shown, using the Fourier series analysis, that the r.m.s. ripple on the a.c. system would be 0.242 I_d (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 a.c. side, the current lags the voltage due to the presence of the delay angle α and the commutation angle γ. Thus since only active power is transmitted in a d.c. link, the convertor must consume the reactive power.

11.2.4 Power factor cos φ

Since the convertor consumes reactive power, there will be a power factor associated with the convertor on the a.c. side. This can be calculated as follows.

Active power supplied to d.c. link = $V_d I_d$

Active power supplied from a.c. system = $\sqrt{3}\, E\, I \cos \varphi$

Since the convertor does not consume any active power, there must be power balance.

$$V_d I_d = \sqrt{3}\, E\, I \cos \varphi$$

From this the power factor can be calculated as follows.

$$\cos \phi = \frac{V_d I_d}{\sqrt{3}\, E\, I}$$

$$\cos \phi = \frac{\frac{1}{2} V_0 (\cos \alpha + \cos w) \frac{\pi}{\sqrt{6}} I}{\sqrt{3} \frac{\pi}{3\sqrt{2}} V_0 I}$$

This gives the result as in equation (11.11).

$$\cos \varphi = \tfrac{1}{2} (\cos \alpha + \cos w) = \tfrac{1}{2} [\cos \alpha + \cos(\alpha+\gamma)] \qquad (11.11)$$

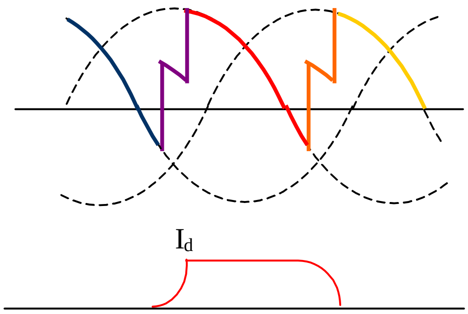
In the absence of commutation, this reduces to the simple relationship

$$\cos \varphi = \cos \alpha$$

Which means that α is the power factor angle in the absence of commutation. The presence of commutation reduces the effective power factor by increasing the effective angle.

With $\gamma = 0$, the active power transmitted is $\sqrt{3}$ E I cos α, and is zero in value when $\alpha = 90^o$.

Thus if a high inductance is connected with the load, the limit of power transfer under rectification is $\alpha = 90^o$. However, if no inductance were present with the load (i.e. $L_d=0$) then the voltage and the current waveforms would become identical in shape (since the load is purely resistive). Under these conditions, the voltage cannot go negative at any instant of time, since the current cannot flow in the opposite direction through the thyristors. The power transmitted would then become zero only at $\alpha = 120^o$. Figure 11.13 shows typical output current and voltage waveforms.



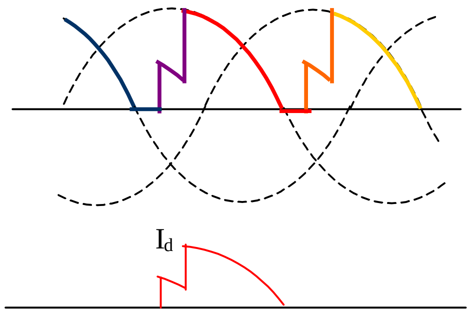


Figure 11.13 - Typical d.c. output waveforms

11.2.5 Current waveforms on a.c. system

In section 11.3.3 it was seen that the current waveform on the secondary side of the convertor transformer was as shown in figure 11.14

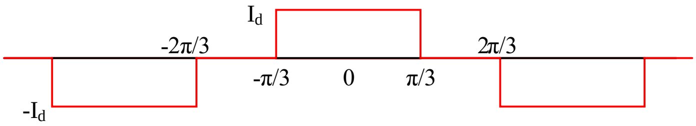


Figure 11.14 - Current waveform on a.c. system

The same current waveform appears on the primary side of the convertor transformer (a.c. system) when the winding connection is star-star, if no filters are present. If filters are present they would filter out some of the harmonics and make the a.c system currents more or less sinusoidal.

When the convertor transformer is delta-star connected, the corresponding primary current waveforms would be as shown in figure 11.15.

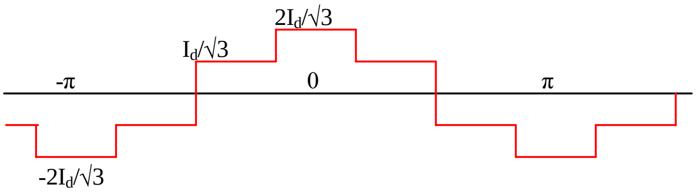


Figure 11.15 - Primary current waveform

Each of the waveforms shown in figures 11.14 and 11.15 contain the same harmonics ($6k\pm1$) with their amplitudes inversely proportional to the harmonic number. The polarities of some of the components of the two waveforms are opposite, so that when a star-star and delta-star convertor bridge are connected in cascade, only the ($12k\pm1$) harmonics remain. Thus less filtering is required. Further when commutation is present, the harmonic amplitudes reduce due to smoothing action.

Note: During normal operation of the convertor as a rectifier, the delay angle α is small (about 10^0), while the commutation angle is comparatively larger (about 20^0).

11.2.6 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 the angle of advance. Similarly the extinction angle is also defined as $\delta = \pi$ - w. The definition of the commutation angle γ is unchanged. Thus $\beta = \gamma + \delta$.

It must be noted, that unlike with rectification which can be operated with $\alpha = 0$, inversion cannot be carried out with $\beta = 0$, since a minimum angle δ_0 is required for deionisation of the arc and regaining grid control.

Thus we have the practical relationship $\delta_0 < \beta < \pi/2$. Practical values of δ_0 lie between 1^0 and 8^0.

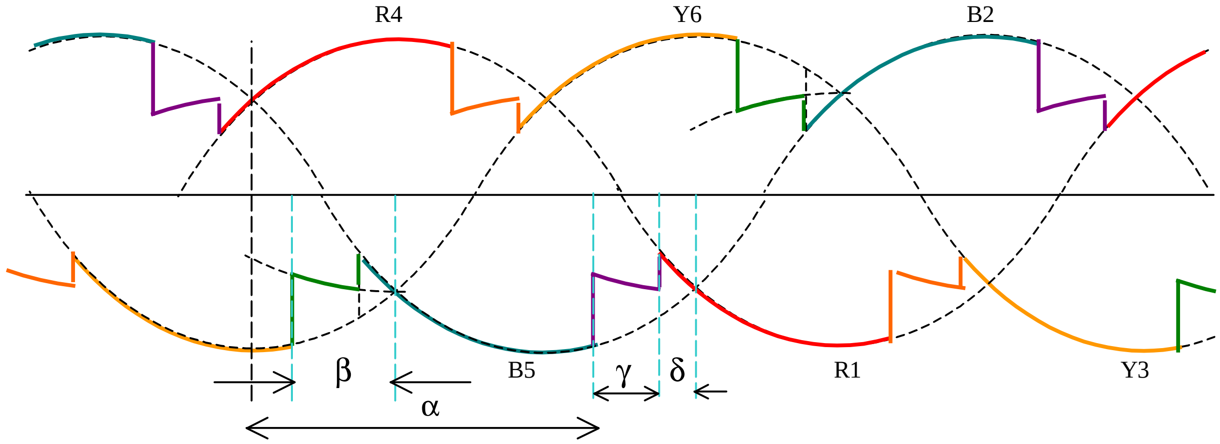


Figure 11.16 - Thyristor voltage waveforms for inversion

Inversion cannot of course be carried out without a d.c. power source. Further, to obtain the necessary frequency for the a.c. on inversion, the commutation voltage is obtained from either synchronous machines or from the a.c. system fed. In isolated systems, L C circuits may also be sometimes used for the purpose. Figure 11.16 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 has the form shown in figure 11.17.

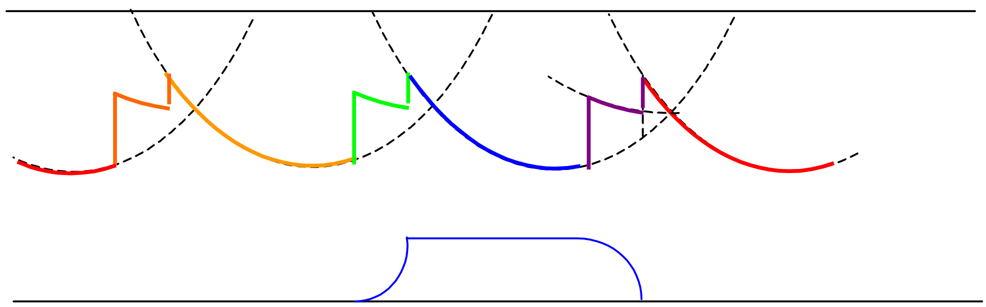


Figure 11.17 - Direct voltage waveform & thyristor current waveform

The equations derived earlier for the convertor are valid. However, they are usually written in terms of the variables β and δ instead of αand w. Thus the equation $V_d = ½ V_0 [\cos α + \cos (α+γ)]$ becomes

$$V_d = ½ V_0 [\cos (π - β) + \cos (π - δ)]$$

or $$(-) V_d = ½ V_0 [\cos β + \cos δ] = V_0 \cos β + (3ωL_c/π) I_d$$

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

$$(-) V_d = V_0 \cos δ - (3ωL_c/π) I_d$$

As in the case of rectification, it can be shown that for inversion

$$\cos δ - \cos β = \sqrt{3}ωL_c/E . I_d \quad \text{and} \quad I = \sqrt{6}/π I_d$$

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

$$\cos φ = ½ (\cos δ + \cos β)$$

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

11.3 Control Characteristics

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.

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

The Natural Voltage Characteristic corresponds to zero delay angle α = 0. This has the characteristic equation given by $V_d = V_0 - (3ωL_c/π) I_d$. The Constant Ignition Angle control is a similar characteristic which is parallel to the NV characteristic with a controllable intercept $V_0 \cos α$. These are shown in figure 11.18.

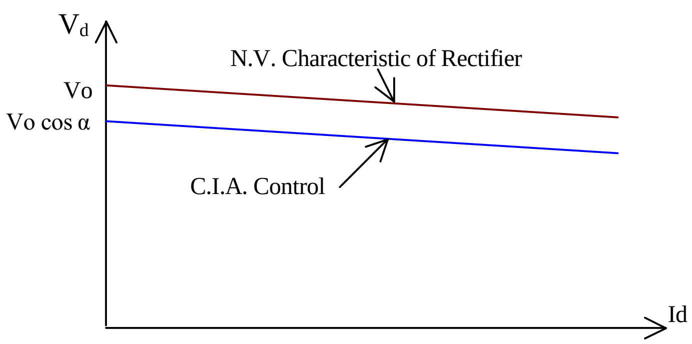


Figure 11.18 - N.V. Ch. & C.I.A. Control of Rectifier

11.3.2 Constant Extinction Angle (CEA) control

The Invertor is usually operated at constant extinction angle. This has the characteristic equation given by $V_d = V_0 \cos δ - (3ωL_c/π) I_d$. This is shown in figure 11.19.

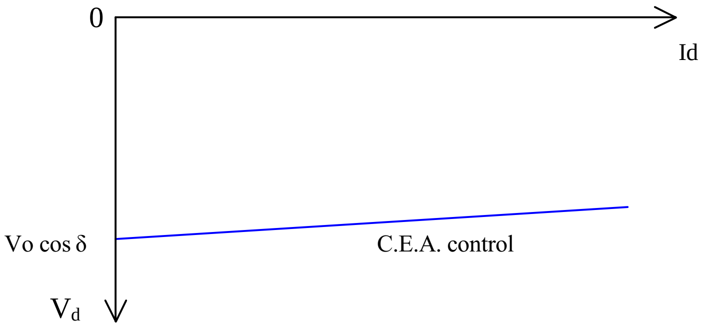


Figure 11.19 - N.V. Characteristic & C.I.A. Control of Rectifier

11.3.3 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.

11.3.4 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 11.20 for a single convertor.

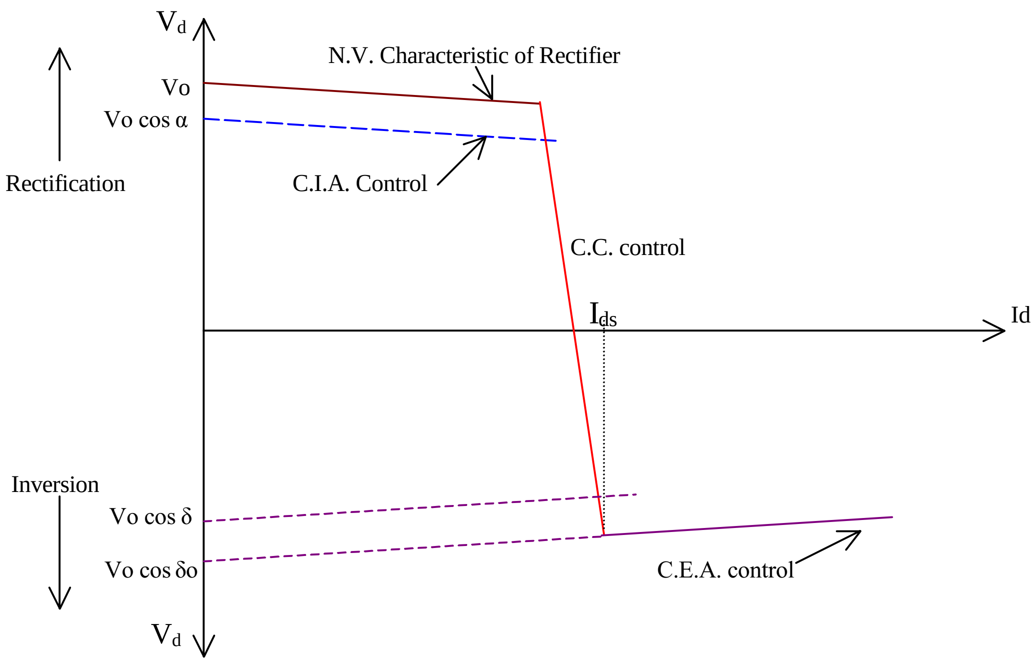


Figure 11.20 - Complete characteristic of Convertor

Note: The constant current controller adjusts the firing angle α so that the current is maintained at a set value, even for short-circuits on the d.c. line. The C.C. control is present in the invertor too, although the invertor is not usually operated in that region. The rectifier is normally operated in the C.C. region while the invertor is operated in the C.E.A. region.

11.3.5 Compounding of Convertors

Figure 11.21 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 11.22.

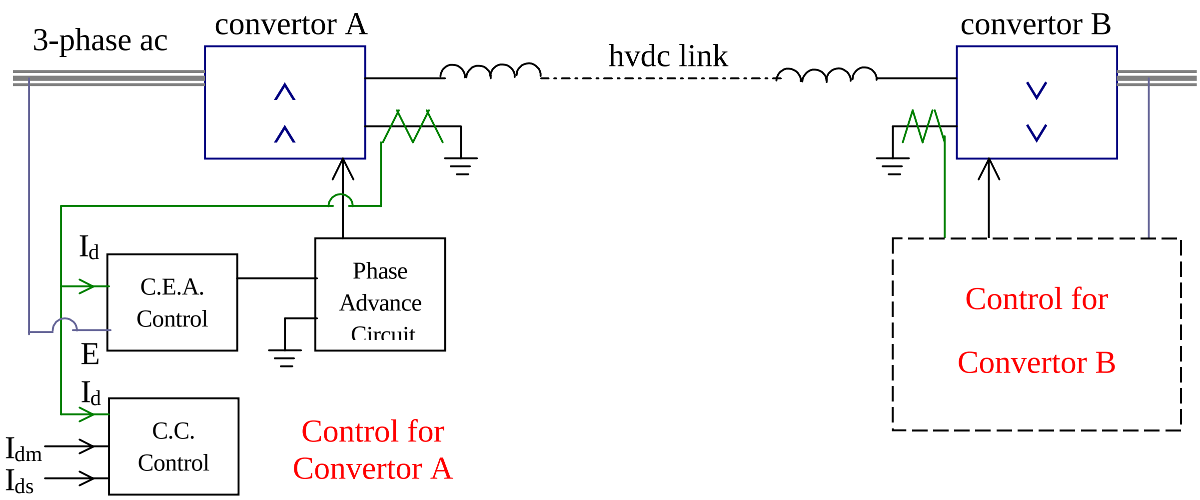


Figure 11.21 - Compounding of Convertors

The margin setting I_{dm} between the current setting I_{ds} 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 I_{dm}.

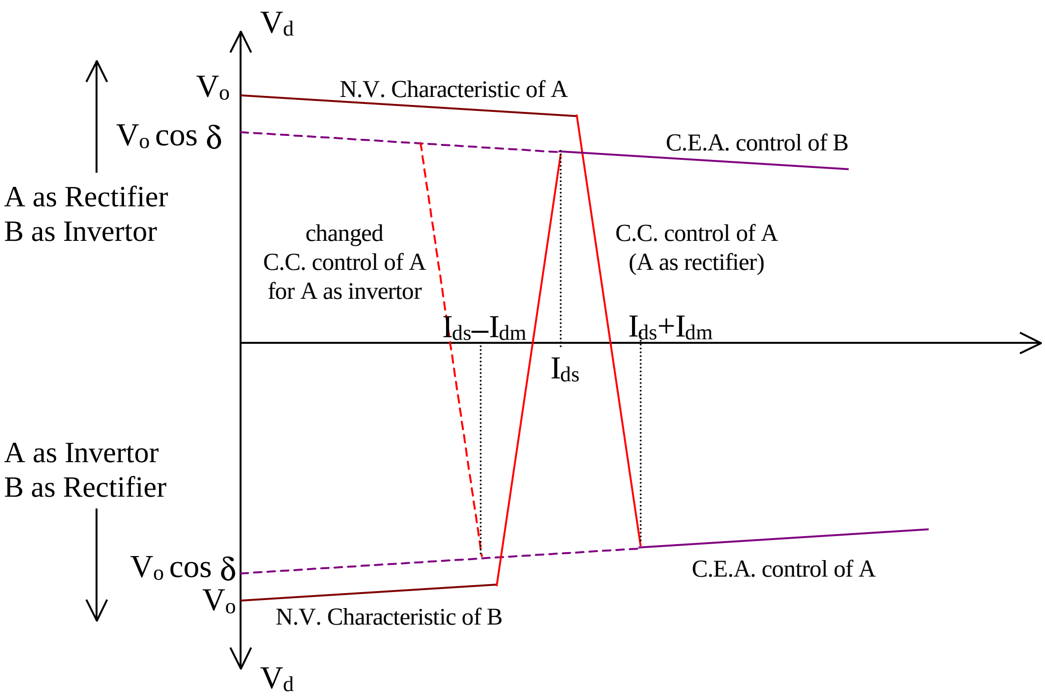


Figure 11.22 - Compounded characteristic of Convertors

The usual operating point for power transfer is the intersection of the CC control of the rectifier and the CEA control of the invertor. (For comparison, the characteristics of convertor B has 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 invertor, as V_o of the two ends are not necessarily equal.

With convertor A operating as rectifier, and convertor B operating as invertor, the steady state current under all circumstances will remain within the upper limit (I_{ds} + I_{dm}) and the lower limit I_{ds}. 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 invertor. The reversal of power occurs as a result of the reversal of polarity of the voltage.

11.3.6 Per Unit Convertor Chart

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

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

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

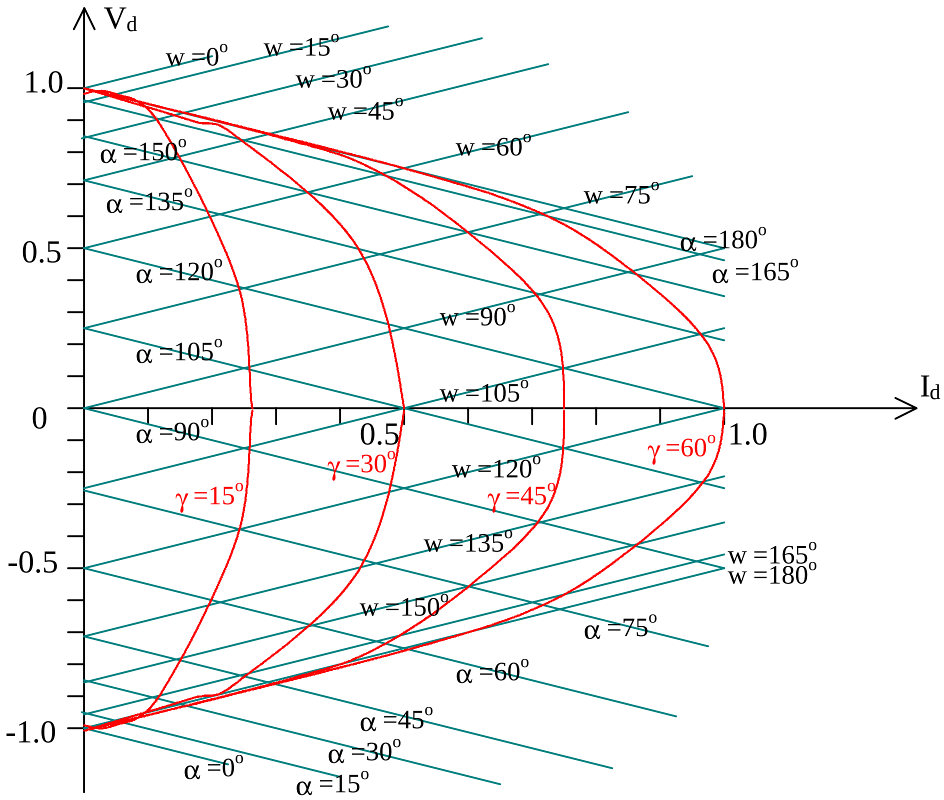


Figure 11.23 - Per unit convertor chart

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 V_{do}. There is no such natural current base. Thus it is convenient to select the constant appearing in equation (11.5) for current as the base quantity. Thus the selected base quantities are as given in equation (11.15).

$$V_{base} = \frac{3\sqrt{2}\,E}{\pi}, \quad I_{base} = \frac{E}{\sqrt{2}\,\omega\,L_c} \tag{11.15}$$

With these base quantities, the per unit voltage $\mathbf{V_d}$ and per unit current $\mathbf{I_d}$ are given as follows.

$\mathbf{V_d} = \frac{1}{2}(\cos\alpha + \cos w)$ and $\mathbf{I_d} = \cos\alpha - \cos w$

which give the simple per unit characteristic equations (11.16) and (11.17).

$$\mathbf{V_d} + 0.5\,\mathbf{I_d} = \cos\alpha \tag{11.16}$$

$$\mathbf{V_d} - 0.5\,\mathbf{I_d} = \cos w \tag{11.17}$$

In the chosen per unit system, constant delay angle control (or the natural voltage characteristic) correspond to straight lines with slope (-) 0.5 on the per unit voltage-current chart. Similarly constant extinction angle control correspond to straight lines with slope (+) 0.5.

For inversion, the corresponding equations are as follows.

$$\mathbf{V_d} + 0.5\,\mathbf{I_d} = \cos(\pi - \beta) = (-)\cos\beta$$
$$\mathbf{V_d} - 0.5\,\mathbf{I_d} = \cos(\pi - \delta) = (-)\cos\delta$$

Since voltages are measured in the opposite direction for inversion, these equations may be rewritten in their more usual form as in equations (11.18) and (11.19).

$$(-)\,\mathbf{V_d} - 0.5\,\mathbf{I_d} = \cos\beta \tag{11.18}$$
$$(-)\,\mathbf{V_d} + 0.5\,\mathbf{I_d} = \cos\delta \tag{11.19}$$

From the characteristics, the constant commutation angle characteristic may be obtained by subtraction as follows.

$$\gamma = \beta - \delta \quad \text{or} \quad \gamma = w - \alpha$$

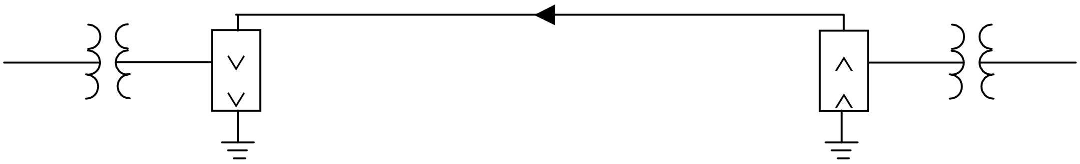
The constant γ characteristics can be shown to be ellipses ($\gamma < 60^0$). The per unit operating chart of the convertor is shown in figure 11.23.

11.4 Classification of d.c. links

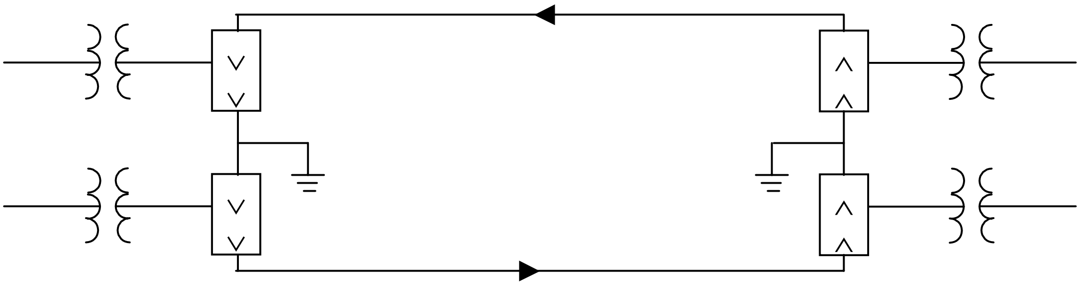
D.C. links are classified into **Monopolar** links, **Bipolar** links, and **Homopolar** links.

In the case of the monopolar link there is only one conductor and the ground serves as the return path. The link normally operates at negative polarity as there is less corona loss and radio interference is reduced. Figure 11.23 (a) shows a monopolar link.

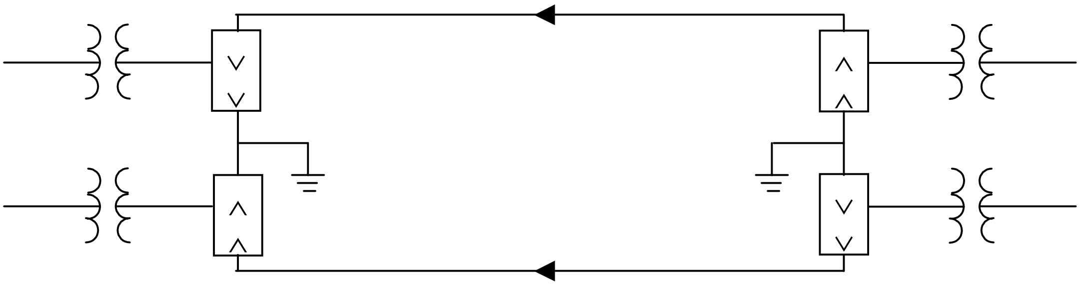
The bipolar links have two conductors, one operating at positive polarity and the other operating at negative polarity. The junction between the two convertors may be grounded at one or both ends. The ground does not normally carry a current. However, if both ends are grounded, each link could be independently operated when necessary. This is shown in figure 11.23 (b).



(a) monopolar link



(b) bipolar link



(c) homopolar link

Figure 11.24 - Kinds of d.c. links

The homopolar links have two or more conductors having the same polarity (usually negative) and always operate with ground path as return.

11.4.1 Harmonics and Filters

As was mentioned earlier, the harmonics present on the a.c. system are (6k±1). Thus the a.c. harmonic filters are tuned to the 5th, 7th, 11th, and 13th harmonics to reduce the harmonic content in the voltages and currents in the a.c. network to acceptable levels. Higher harmonics would not penetrate very far into the a.c. system. The harmonics are mainly present in the a.c. current as the a.c. voltage is heavily dependant on the a.c. system itself.

The Harmonics present on the d.c. side are mainly on output voltage. These are in multiples of 6 as the waveform repeats itself 6 times. The d.c. current is smoothed by the smoothing reactors.