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 .

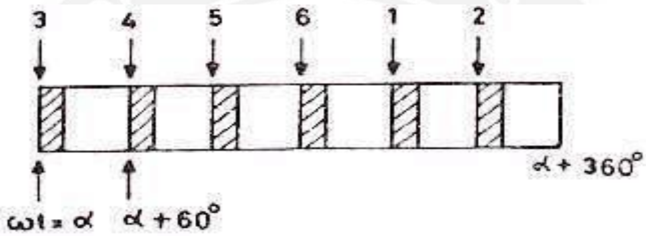

Figure 2.3.1 Timing diagram

[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 ($\mu>60^o$)

<u>i)Analysis of Two and Three Valve Conduction Mode:</u>

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.

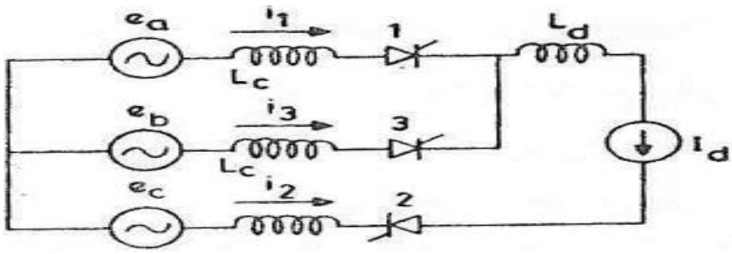

Figure 2.3.2 Equivelent circuit of 3 valve conduction

[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.

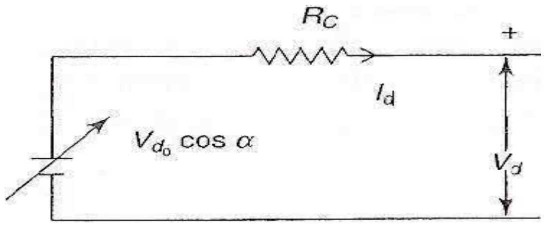

Figure 2.3.3 Equivalent circuit of a bridge converter

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

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

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

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

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

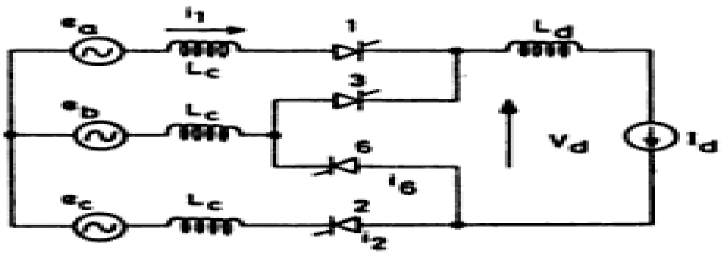

Figure 2.3.4 Equivalent circuit for four valve conduction

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

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

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

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

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