Module 2

AC to DC Converters

Lesson 15

Effect of Source Inductance on the Performance of AC to DC Converters

Instructional Objectives

On completion the student will be able to

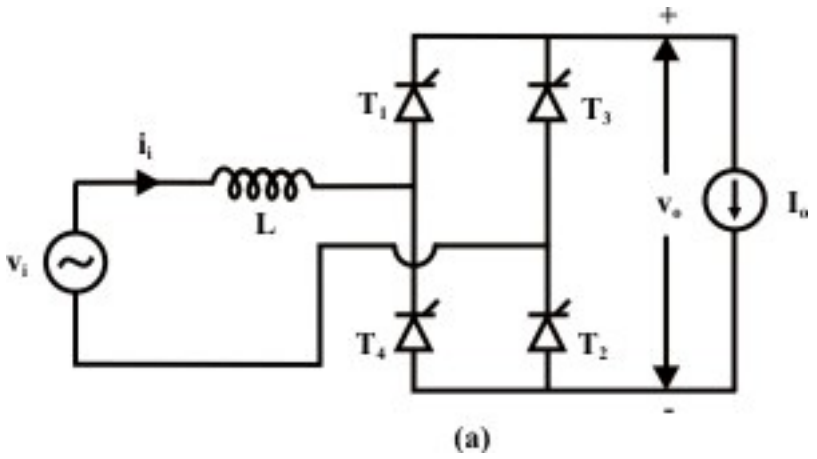
- Draw the voltage and current waveforms associated with a converter taking into account the effect of source inductance.
- Find the average output voltage of the converter as a function of the firing angle and overlap angle.
- Estimate overlap angles under a given operating condition and hence determine the turn off time available for the thyristors.
- Draw the dc equivalent circuit of a converter and parameterize it.
- Find out the voltage stress on the thyristors due to commutation overlap.

15.1 Introduction

In the previous lessons the input ac power sources supplying an ac to dc power converter have been assumed to be ideal with no source impedance. Although this assumption simplifies the analysis of the converters, in most practical situations, they are not fully justified. Most ac dc converters are supplied from transformers. The series impedance of the transformer can not always be neglected. Even if no transformer is used, the impedance of the feeder line comes in series with the source. In most cases this impedance is predominantly inductive with negligible resistive component. The presence of source inductance does have significant effect on the performance of the converter. With source inductance present the output voltage of a converter does not remain constant for a given firing angle. Instead it drops gradually with load current. The converter output voltage and input current waveforms also change significantly. In this lesson a quantitative analysis of these effects will be taken up in some detail.

15.2 Single phase fully controlled converter with source inductance

Fig. 15.1(a) shows a single phase fully controlled converter with source inductance. For simplicity it has been assumed that the converter operates in the continuous conduction mode. Further, it has been assumed that the load current ripple is negligible and the load can be replaced by a dc current source the magnitude of which equals the average load current. Fig. 15.1(b) shows the corresponding waveforms. It is assumed that the thyristors T_3 and T_4 were conducting at $t = 0$. T_1 and T_2 are fired at $\omega t = \alpha$. If there were no source inductance T_3 and T_4 would have commutated as soon as T_1 and T_2 are turned ON. The input current polarity would have changed instantaneously. However, if a source inductance is present the commutation and change of input current polarity can not be instantaneous. Therefore, when T_1 and T_2 are turned ON T_3 T_4 does not commutate immediately. Instead, for some interval all four thyristors continue to conduct as shown in Fig. 15.1(b). This interval is called "overlap" interval.



(a)

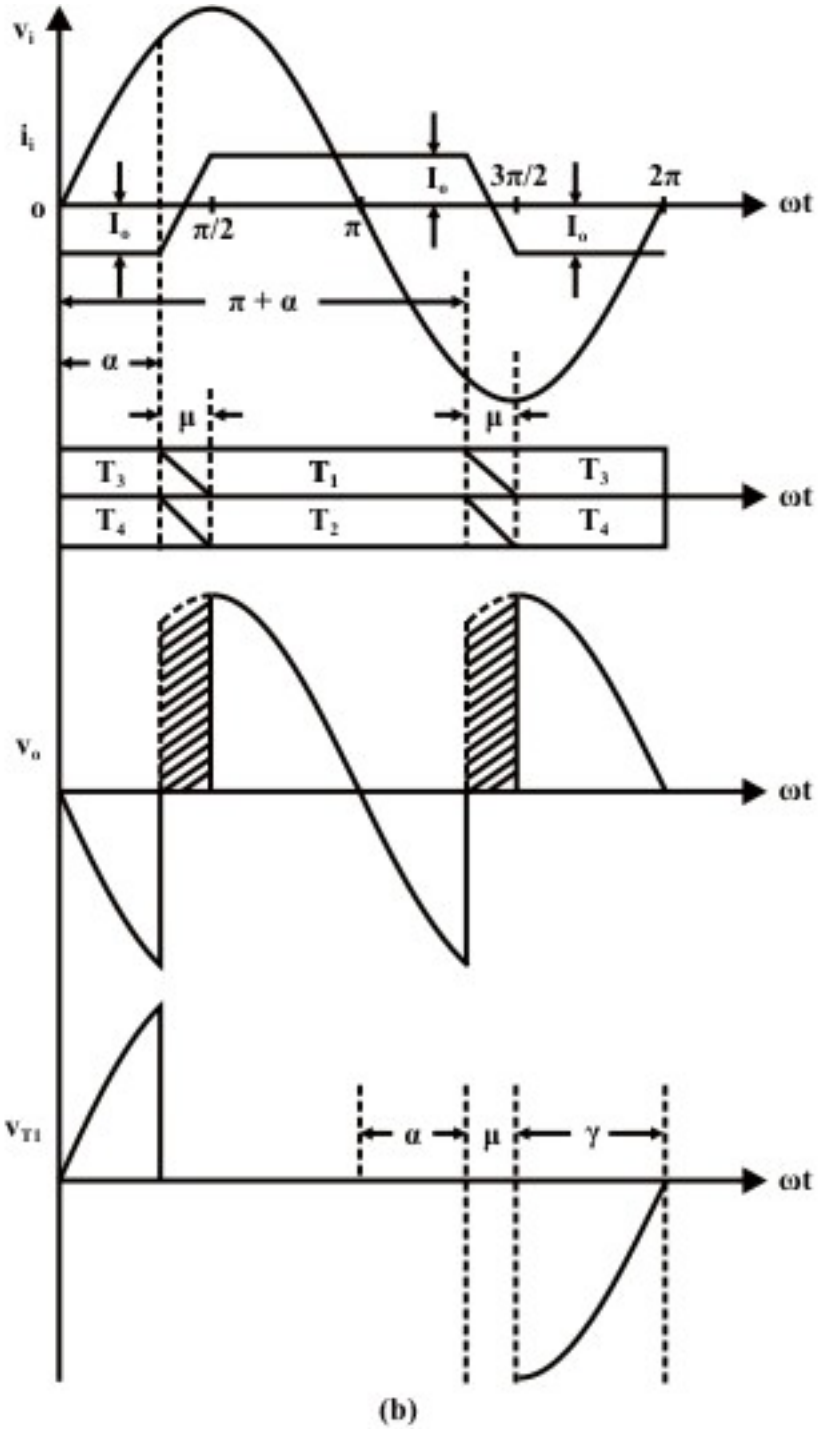


Fig. 15.1: Operation of single phase fully controlled converter with source inductance
(a) circuit diagram,
(b) waveforms.

During this period the load current freewheels through the thyristors and the output voltage is clamped to zero. On the other hand, the input current starts changing polarity as the current through T_1 and T_2 increases and T_3 T_4 current decreases. At the end of the overlap interval the current through T_3 and T_4 becomes zero and they commutate, T_1 and T_2 starts conducting the full load current. The same process repeats during commutation from T_1 T_2 to T_3T_4 at $\omega t = \pi + \alpha$.

From Fig. 15.1(b) it is clear that, commutation overlap not only reduces average output dc voltage but also reduces the extinction angle γ which may cause commutation failure in the inverting mode of operation if α is very close to 180º. In the following analysis an expression of the overlap angle "μ" will be determined.

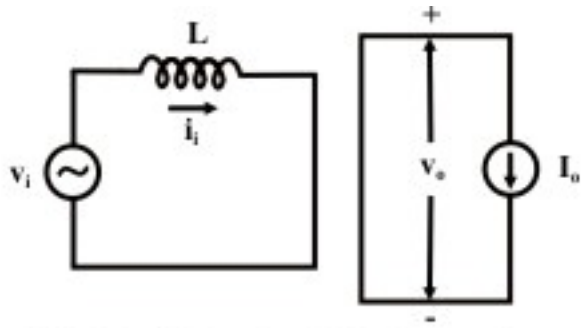


Fig. 15.2: Equivalent circuit during overlap period.

From the equivalent circuit of the converter during overlap period

$$L\frac{di_i}{dt} = v_i \qquad \text{for} \qquad \alpha \le \omega t \le \alpha + \mu \tag{15.1}$$

$$i_i(\omega t = \alpha) = - I_0 \tag{15.2}$$

$$\therefore \quad i_i = I - \frac{\sqrt{2}V_i}{\omega L}\cos\omega t \tag{15.3}$$

$$i_i\big|_{\omega t = \alpha} = I - \frac{\sqrt{2}V_i}{\omega L}\cos\alpha = - I_0 \tag{15.4}$$

$$\therefore \quad I = \frac{\sqrt{2}V_i}{\omega L}\cos\alpha - I_0 \tag{15.5}$$

$$\therefore \quad i_i = \frac{\sqrt{2}V_i}{\omega L}(\cos\alpha - \cos\omega t) - I_0 \tag{15.6}$$

at $\omega t = \alpha + \mu \quad i_i = I_0$

$$\therefore \quad I_0 = \frac{\sqrt{2}V_i}{\omega L}(\cos\alpha - \cos(\alpha + \mu)) - I_0 \tag{15.7}$$

$$\therefore \quad \cos\alpha - \cos(\alpha + \mu) = \frac{\sqrt{2}\omega L}{V_i} I_0 \tag{15.8}$$

$$V_0 = \frac{I}{\pi}\int_{\alpha}^{\alpha+\pi} v_i \, d\omega t \tag{15.9}$$

or
$$V_0 = \frac{I}{\pi}\int_{\alpha+\mu}^{\alpha+\pi} \sqrt{2}v_i \sin\omega t \, d\omega t$$

$$= \frac{\sqrt{2}v_i}{\pi}\left[\cos(\alpha + \mu) - \cos(\pi + \alpha)\right]$$

$$= \frac{\sqrt{2}v_i}{\pi}\left[\cos\alpha + \cos(\alpha + \mu)\right] \tag{15.10}$$

$$\therefore \quad V_0 = 2\sqrt{2}\frac{v_i}{\pi}\cos\alpha - \frac{\sqrt{2}v_i}{\pi}\left[\cos\alpha - \cos(\alpha + \mu)\right]$$

$$= \frac{2\sqrt{2}}{\pi}v_i\cos\alpha - \frac{2}{\pi}\omega L\, I_0 \tag{15.11}$$

Equation 15.11 can be represented by the following equivalent circuit

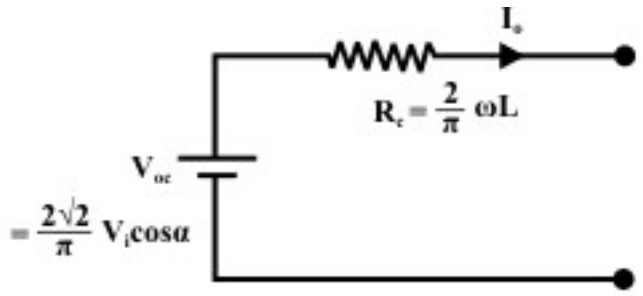
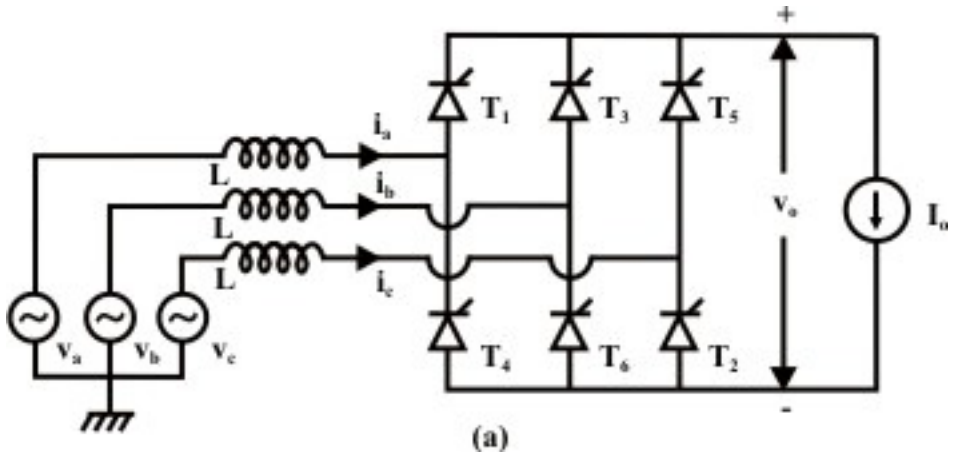


Fig. 15.3: Equivalent circuit representation of the single phase fully controlled rectifier with source inductance.

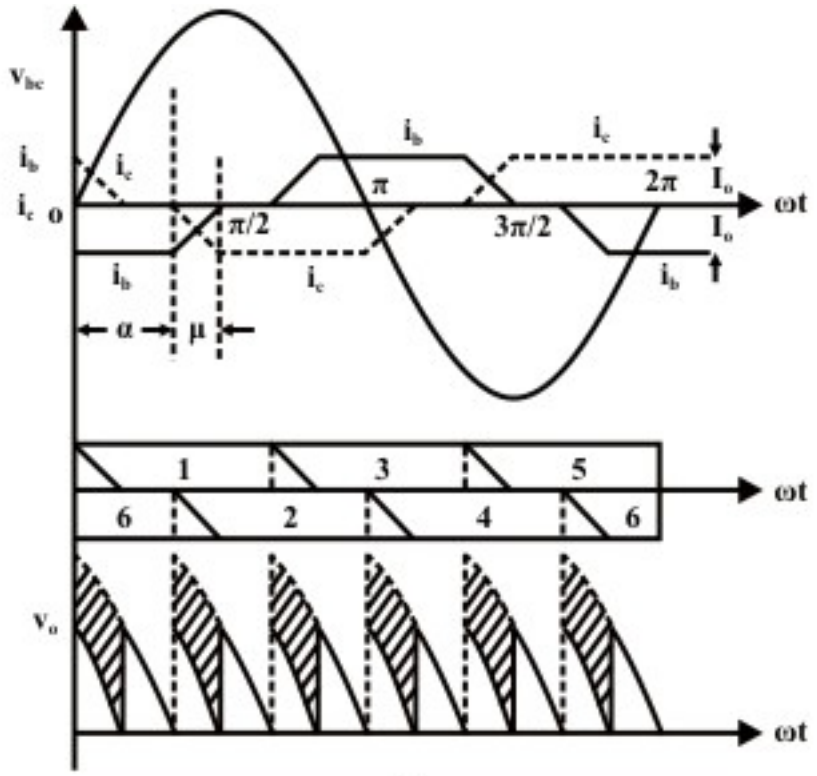
The simple equivalent circuit of Fig. 15.3 represents the single phase fully controlled converter with source inductance as a practical dc source as far as its average behaviour is concerned. The open circuit voltage of this practical source equals the average dc output voltage of an ideal converter (without source inductance) operating at a firing angle of α. The voltage drop across the internal resistance "R_C" represents the voltage lost due to overlap shown in Fig. 15.1(b) by the hatched portion of the v_0 waveform. Therefore, this is called the "Commutation resistance". Although this resistance accounts for the voltage drop correctly there is no power loss associated with this resistance since the physical process of overlap does not involve any power loss. Therefore this resistance should be used carefully where power calculation is involved.

15.3 Three phase fully controlled converter with source inductance

In lesson 13 the three phase fully controlled converter was analyzed with ideal source with no internal impedance. When the source inductance is taken into account, the qualitative effects on the performance of the converter is similar to that in the case of a single phase converter. Fig. 15.4(a) shows such a converter. As in the case of a single phase converter the load is assumed to be highly inductive such that the load can be replaced by a current source.



(a)



(b)

Fig. 15.4: Operation of 3 phase fully controlled converter with source inductance
(a) circuit diagram
(b) wave forms

As in the case of a single phase converter, commutations are not instantaneous due to the presence of source inductances. It takes place over an overlap period of "μ_1" instead. During the overlap period three thyristors instead of two conducts. Current in the outgoing thyristor gradually decreases to zero while the incoming thyristor current increases and equals the total load current at the end of the overlap period. If the duration of the overlap period is greater than 60º four thyristors may also conduct clamping the output voltage to zero for sometime. However, this situation is not very common and will not be discussed any further in this lesson. Due to the conduction of two devices during commutation either from the top group or the bottom group the instantaneous output voltage during the overlap period drops (shown by the hatched portion of Fig. 15.4 (b)) resulting in reduced average voltage. The exact amount of this reduction can be calculated as follows.

In the time interval $\alpha < \omega t \leq \alpha + \mu$, T_6 and T_2 from the bottom group and T_1 from the top group conducts. The equivalent circuit of the converter during this period is given by the circuit diagram of Fig. 15.5.

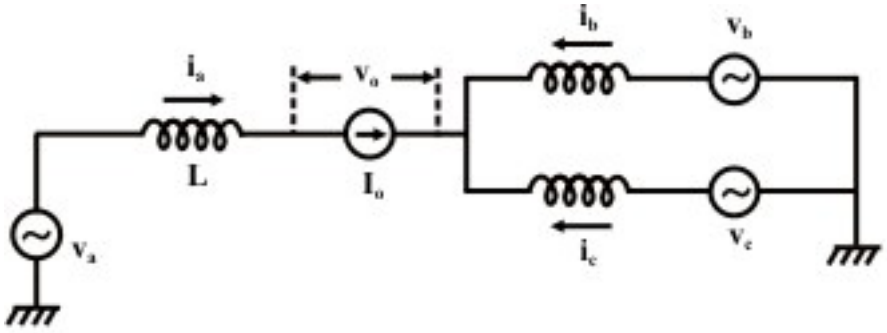


Fig. 15.5: Equivalent circuit during commutation from T_6 to T_2.

Therefore, in the interval $\alpha < \omega t \leq \alpha + \mu$

$$v_b = L\frac{di_b}{dt} - L\frac{di_c}{dt} + v_c \tag{15.12}$$

or, $$v_{bc} = L\frac{d}{dt}(i_b - i_c) \tag{15.13}$$

but $i_b + i_c + I_o = 0 \quad \therefore \quad \frac{di_b}{dt} = -\frac{di_c}{dt}$ (15.14)

$$\therefore \quad 2L\frac{d}{dt}i_b = v_{bc} = \sqrt{2}V_L \sin\omega t \tag{15.15}$$

$$\therefore \quad i_b = C - \frac{\sqrt{2}V_L}{2\omega L}\cos\omega t \tag{15.16}$$

at $\omega t = \alpha$, $i_b = -I_0 \quad \therefore \quad C = \frac{\sqrt{2}V_L}{2\omega L}\cos\alpha - I_0$ (15.17)

$$\therefore \quad i_b = \frac{\sqrt{2}V_L}{2\omega L}(\cos\alpha - \cos\omega t) - I_0 \tag{15.18}$$

at $\omega t = \alpha + \mu$, $i_b = 0$

$$\therefore \quad \frac{\sqrt{2}V_L}{2\omega L}(\cos\alpha - \cos(\alpha + \mu)) = I_0 \tag{15.19}$$

Or, $$\cos\alpha - \cos(\alpha + \mu) = \frac{\sqrt{2}\omega L}{V_L}I_0 \tag{15.20}$$

Equation 15.20 holds for $\mu \leq 60^o$. It can be shown that for this condition to be satisfied

$$I_0 \leq \frac{V_L}{\sqrt{2}\omega L}\cos\left(\alpha - \frac{\pi}{3}\right) \tag{15.21}$$

To calculate the dc voltage

For $\alpha \leq \omega t \leq \alpha + \mu$

$$v_0 = v_a - v_b + L\frac{di_b}{d_t} = \frac{3}{2}v_a \tag{15.22}$$

for $\alpha + \mu \leq \omega t \leq \alpha + \frac{\pi}{3} \qquad v_0 = v_{ac}$

$$\therefore \quad V_0 = \frac{3}{\pi}\left[\int_{\alpha}^{\alpha+\mu}\frac{3}{2}v_a\, d\omega t + \int_{\alpha+\mu}^{\alpha+\frac{\pi}{3}}v_{ac}\, d\omega t\right]$$

$$= \frac{3}{\pi}\left[\int_{\alpha}^{\alpha+\mu}\left(v_{ac} + \frac{3}{2}v_a - v_{ac}\right) + \int_{\alpha+\mu}^{\alpha+\frac{\pi}{3}} v_{ac}\, d\omega t\right]$$

$$= \frac{3}{\pi}\left[\int_{\alpha}^{\alpha+\frac{\pi}{3}} v_{ac}\, d\omega t + \int_{\alpha}^{\alpha+\mu}\left(\frac{v_a}{2} + v_c\right) d\omega t\right]$$

$$= \frac{3\sqrt{2}}{\pi} V_L \cos\alpha - \frac{3}{2\pi}\int_{\alpha}^{\alpha+\mu} v_{bc}\, d\omega t \qquad (15.23)$$

or $$V_0 = \frac{3\sqrt{2}}{\pi} V_L \cos\alpha - \frac{3\sqrt{2}V_L}{2\pi}\int_{\alpha}^{\alpha+\mu} \sin\omega t\, d\omega t$$

$$= \frac{3\sqrt{2}}{\pi} V_L \cos\alpha - \frac{3\sqrt{2}V_L}{2\pi}\left[\cos\alpha - \cos(\alpha+\mu)\right] \qquad (15.24)$$

Substituting Equation 15.20 into 15.24

$$V_0 = \frac{3\sqrt{2}}{\pi} V_L \cos\alpha - \frac{3}{\pi}\omega L\, I_0 \qquad (15.25)$$

Equation 15.25 suggests the same dc equivalent circuit for the three phase converter with source inductance as shown in Fig. 15.3 with

$$V_{OC} = \frac{3\sqrt{2}}{\pi} V_L \cos\alpha \qquad \text{and commutation resistance} \quad R_C = \frac{3}{\pi}\omega L .$$

It should be noted that R_C is a "loss less" resistance, since the overlap process does not involve any active power loss.

Exercise 15.1

1. Fill in the blank(s) with appropriate word(s)

i. The internal impedance of an ac source supplying a converter is largely _____ in nature.

ii. Due to the presence of source _____ commutation in a converter is not _____.

iii. The period over which the commutation process continues is called the _____ period.

iv. Length of the overlap period depends on the valve of the source inductance and load _____.

v. In a single phase converter _____ thyristors conduct during the overlap period.

vi. In a three phase converter _____ thryistors conduct during the overlap period provided the overlap angle is less than _____ degrees.

vii. The average output voltage of a ac-dc converter _____ as a result of commutation overlap.

viii. In the dc equivalent circuit of a converter the input ac source inductor appears as a loss less resistance called the _____ resistance.

ix. Commutation overlap decreases the _____ angle of a converter and may cause commutation failure during _____ mode of operation.

x. Commutation overlap introduces _____ in the supply voltage waveform.

Answer: (i) inductive; (ii) inductance, instantaneous; (iii) overlap; (iv) current ; (v) four; (vi) three, sixty; (vii) decreases; (viii) commutation; (ix) inverter, (x) notches.

2. A 220V, 1450 RPM, 100A separately excited dc motor has an armature resistance to 0.1Ω. It is supplied from a 3 phase fully controlled converter connected to a 3 phase 50 Hz ac source. The ac source has an inductive reactance of 0.5Ω at 50 Hz. The line voltage is adjusted such that at $\alpha = 0$; the motor operates at rated speed and torque. The motor is to be braked regeneratively in the reverse direction at rated speed using the converter. What is the maximum braking torque the motor will be able to produce under this condition without causing commutation failure?

Answer: Under rated operating condition, the motor terminal voltage is 220V and it draws 100 Amps current. Therefore from eqn. 15.25.

$$220 = \frac{3\sqrt{2}}{\pi} V_L - \frac{3}{\pi} \times .5 \times 100$$

or $V_L = 198$ volts $\qquad E_b\big|_{\text{rated speed}} = 220 - 100 \times 0.1 = 210\text{V}$

Under regenerative braking in the reverse direction at rated speed

$$\frac{3\sqrt{2}}{\pi} \times 198 \cos\alpha - \left(\frac{3}{\pi} \times 0.5 + 0.1\right) I_o = -210\text{V}$$

Also from equation 15.20

$$\cos\alpha - \cos(\alpha + \mu) = \frac{\sqrt{2} \times 0.5\ I_o}{198}$$

At the limiting condition of commutation failure

$$\alpha + \mu \approx 180^o$$

$$\therefore\ \cos\alpha = \frac{I_o}{198\sqrt{2}} - 1$$

$$\therefore\ \frac{3}{\pi} I_o - \frac{3\sqrt{2}}{\pi} \times 198 - \left(\frac{3}{\pi} \times 0.5 + 0.1\right) I_o = -210$$

or $0.377\ I_o = 57.4 \qquad \therefore\ I_o = 152.24$ Amps

$\therefore$ Maximum braking torque will be approximately 150% of the rated motor torque.

References

1. Muhammad H. Rashid; “Power Electronics, Circuits, Devices and Applications” Second Edition, Prentice – Hall of India, New Delhi, 1994.
2. P.C. Sen; “Power Electronics”, Tata McGrawhill publishing company limited, 1995.
3. “Power Electronics, Converters, Applications and Design”; Mohan, Undeland, Robbins; John Willey and Sons Inc, Third Edition, 2003.

Lesson Summary

- Ac power sources supplying an ac-dc converter have internal impedances which are not always negligible.
- The internal impedance of an ac source is predominantly inductive with negligible resistive component.
- Due to the presence of the source inductance in the ac line the thyristors in a ac-dc converter can not commutate instantaneously.
- The period over which the commutation process continuous is called the overlap period.
- The length of the overlap period increases with increasing source inductance and load current.
- In a single phase converter all four thyristors conduct during the overlap period.
- In a three phase converter, three thyristors conduct during the overlap period provided it is less than 60º.
- The average output voltage of a converter decreases as a result of commutation overlap.
- The voltage drop due to commutation overlap can be represented as a drop across a commutation resistance the value of which is proportional to the ac line reactance per phase.
- The commutation resistance is “loss less” since the actual process of overlap does not involve any real power loss.
- Commutation overlap reduces the margin angle (γ) of a converter and may cause commutation failure.
- Commutation overlap introduces “notches” in the ac supply voltage waveform which may affect other equipment connect to the same power source.