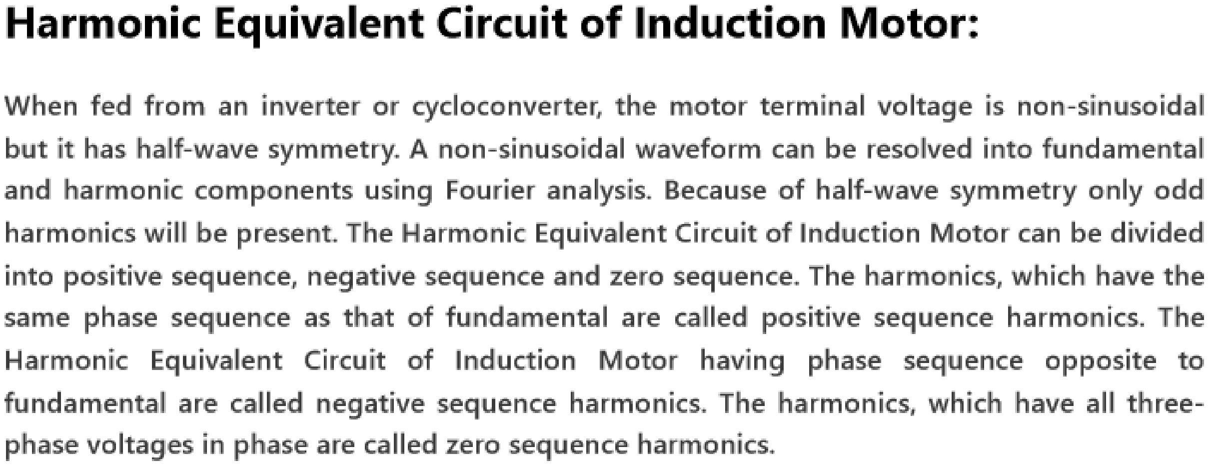
Industrial Drives and Applications (18EE741)

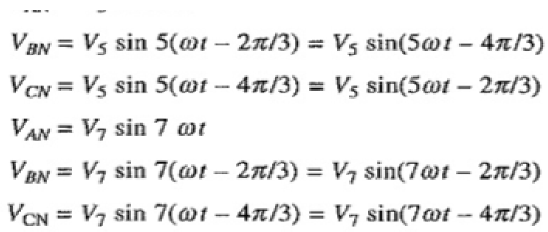
IAT-3 Solution

1. Explain the operation of Induction Motor fed from non-sinusoidal supply voltage.

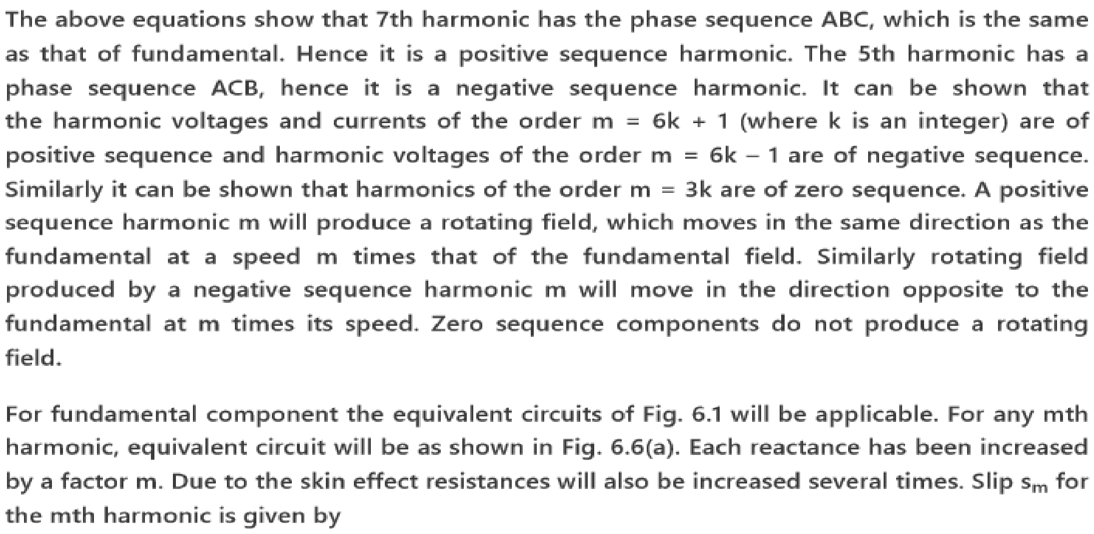


Harmonic Equivalent Circuit of Induction Motor:

When fed from an inverter or cycloconverter, the motor terminal voltage is non-sinusoidal but it has half-wave symmetry. A non-sinusoidal waveform can be resolved into fundamental and harmonic components using Fourier analysis. Because of half-wave symmetry only odd harmonics will be present. The Harmonic Equivalent Circuit of Induction Motor can be divided into positive sequence, negative sequence and zero sequence. The harmonics, which have the same phase sequence as that of fundamental are called positive sequence harmonics. The Harmonic Equivalent Circuit of Induction Motor having phase sequence opposite to fundamental are called negative sequence harmonics. The harmonics, which have all three-phase voltages in phase are called zero sequence harmonics.

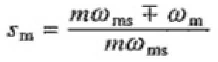


$$V_{BN} = V_5 \sin 5(\omega t - 2\pi/3) = V_5 \sin(5\omega t - 4\pi/3)$$
$$V_{CN} = V_5 \sin 5(\omega t - 4\pi/3) = V_5 \sin(5\omega t - 2\pi/3)$$
$$V_{AN} = V_7 \sin 7\,\omega t$$
$$V_{BN} = V_7 \sin 7(\omega t - 2\pi/3) = V_7 \sin(7\omega t - 2\pi/3)$$
$$V_{CN} = V_7 \sin 7(\omega t - 4\pi/3) = V_7 \sin(7\omega t - 4\pi/3)$$



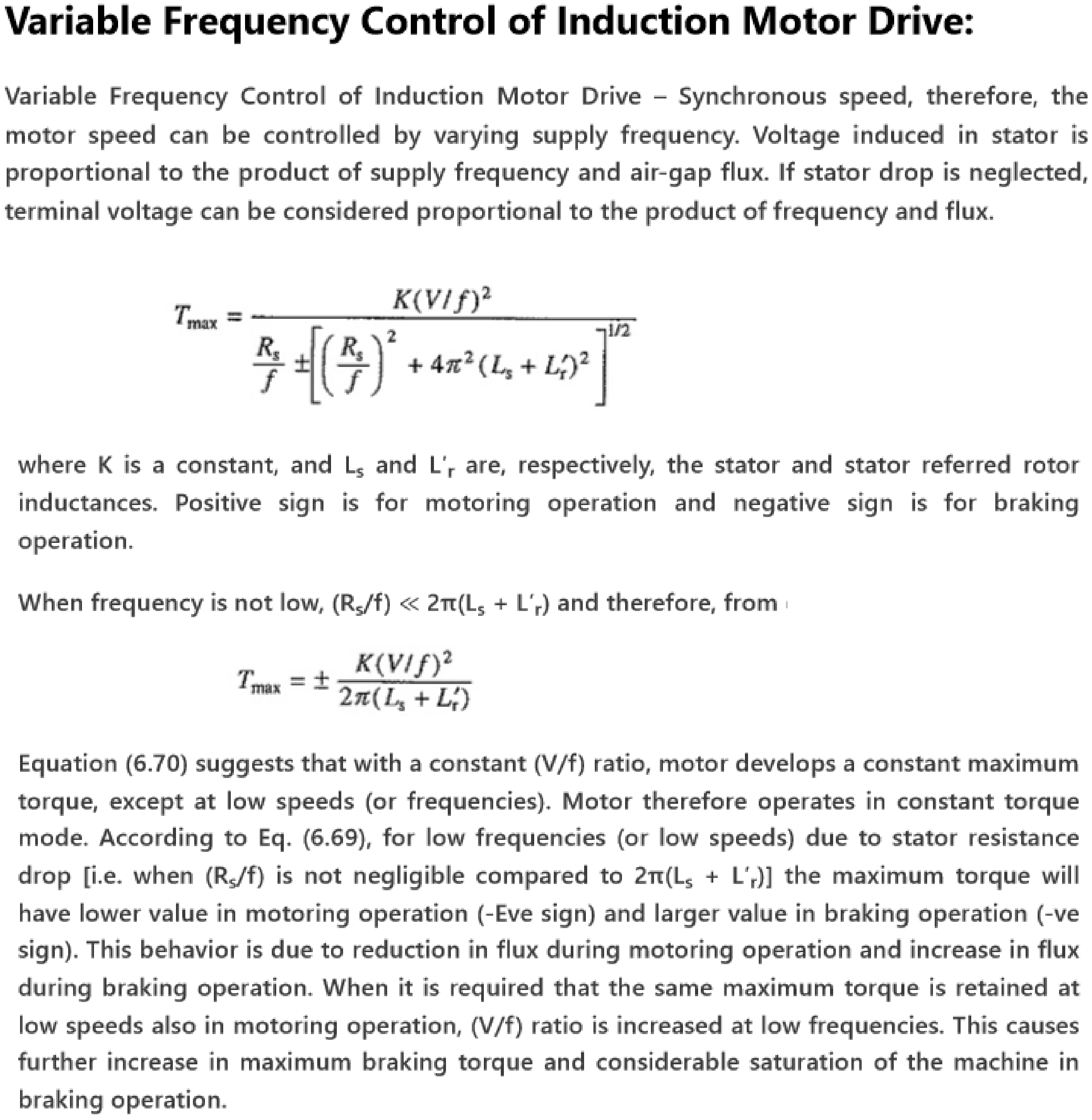
The above equations show that 7th harmonic has the phase sequence ABC, which is the same as that of fundamental. Hence it is a positive sequence harmonic. The 5th harmonic has a phase sequence ACB, hence it is a negative sequence harmonic. It can be shown that the harmonic voltages and currents of the order m = 6k + 1 (where k is an integer) are of positive sequence and harmonic voltages of the order m = 6k − 1 are of negative sequence. Similarly it can be shown that harmonics of the order m = 3k are of zero sequence. A positive sequence harmonic m will produce a rotating field, which moves in the same direction as the fundamental at a speed m times that of the fundamental field. Similarly rotating field produced by a negative sequence harmonic m will move in the direction opposite to the fundamental at m times its speed. Zero sequence components do not produce a rotating field.

For fundamental component the equivalent circuits of Fig. 6.1 will be applicable. For any mth harmonic, equivalent circuit will be as shown in Fig. 6.6(a). Each reactance has been increased by a factor m. Due to the skin effect resistances will also be increased several times. Slip s_m for the mth harmonic is given by



$$s_m = \frac{m\omega_{ms} \mp \omega_m}{m\omega_{ms}}$$

2. Explain variable frequency control of Induction Motor from voltage sources.



Variable Frequency Control of Induction Motor Drive:

Variable Frequency Control of Induction Motor Drive – Synchronous speed, therefore, the motor speed can be controlled by varying supply frequency. Voltage induced in stator is proportional to the product of supply frequency and air-gap flux. If stator drop is neglected, terminal voltage can be considered proportional to the product of frequency and flux.

$$T_{\max} = \frac{K(V/f)^2}{\frac{R_s}{f} \pm \left[\left(\frac{R_s}{f}\right)^2 + 4\pi^2 (L_s + L_r')^2\right]^{1/2}}$$

where K is a constant, and L_s and L'_r are, respectively, the stator and stator referred rotor inductances. Positive sign is for motoring operation and negative sign is for braking operation.

When frequency is not low, $(R_s/f) \ll 2\pi(L_s + L'_r)$ and therefore, from

$$T_{\max} = \pm \frac{K(V/f)^2}{2\pi(L_s + L_r')}$$

Equation (6.70) suggests that with a constant (V/f) ratio, motor develops a constant maximum torque, except at low speeds (or frequencies). Motor therefore operates in constant torque mode. According to Eq. (6.69), for low frequencies (or low speeds) due to stator resistance drop [i.e. when (R_s/f) is not negligible compared to $2\pi(L_s + L'_r)$] the maximum torque will have lower value in motoring operation (-Eve sign) and larger value in braking operation (-ve sign). This behavior is due to reduction in flux during motoring operation and increase in flux during braking operation. When it is required that the same maximum torque is retained at low speeds also in motoring operation, (V/f) ratio is increased at low frequencies. This causes further increase in maximum braking torque and considerable saturation of the machine in braking operation.

3. Explain the starting of Induction motors by the following method: (i) Reactor Starter (ii) Rotor Resistance Starter

Reactor Starter:

Starting current can also be reduced by connecting a three-phase reactor in series with stator.

When motor reaches full speed, the reactor is bypassed. Figure 6.9 shown such a scheme. CB_m is closed to start the machine. After full speed is reached CB_s is closed to short the reactor. It is advantageous to connect reactor at the neutral end of stator winding. This minimizes its voltage rating and also maintains its voltage and the voltage of breaker CB_s at neutral potential during normal motor operation.

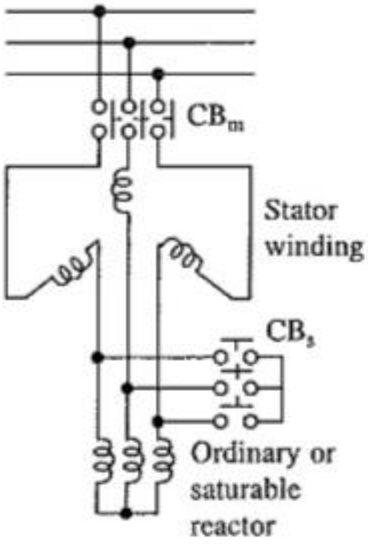
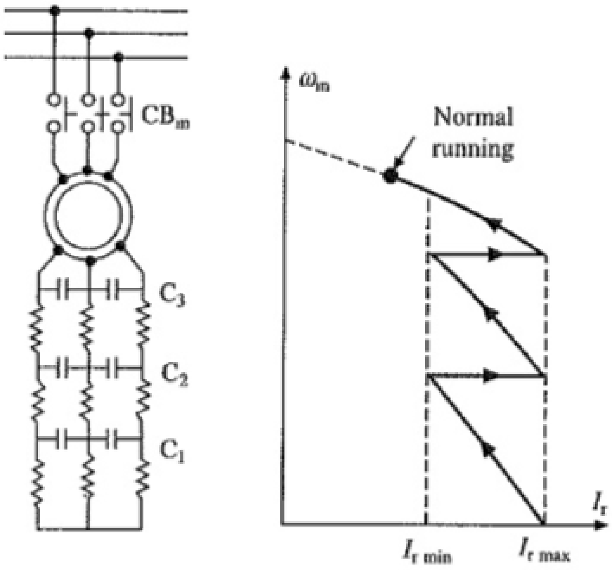


Fig. Reactor starting

Rotor Resistance Starter:

Wound-rotor motors are generally started by connecting external resistors in the rotor circuit (Fig. 6.12(a)). The highest value of resistance is chosen to limit current at zero speed within the safe value. As the motor accelerates, sections in the external resistor are cut out one-by-one by closing contacts C_1, C_2 and C_3 so as to limit the rotor current between specified maximum and minimum values (Fig. 6.12(b)).



(a) (b)

Fig. Rotor resistance starting

4. Explain the Braking of Induction motor by (i) Plugging (ii) Regenerative Braking

Regenerative Braking:

The power input to an induction motor is given by

$$P_{in} = 3VI_s \cos \phi_s$$

where Φ_s is the phase angle between stator phase voltage V and the stator phase current I_s. For motoring operation $\Phi_s < 90°$. If the rotor speed becomes greater than synchronous speed, relative speed between the rotor conductors and air-gap rotating field reverses. This reverses the rotor induced emf, rotor current and component of stator current which balances the rotor ampere turns. Consequently, angle Φ_s becomes greater than 90° and power flow reverses, giving regenerative braking. Magnetizing current required to produce air-gap flux is obtained from the source. Equations (6.1)-(6.13) are applicable, except that slip is negative. The nature of speed-torque characteristic is shown in Fig. 6.13.

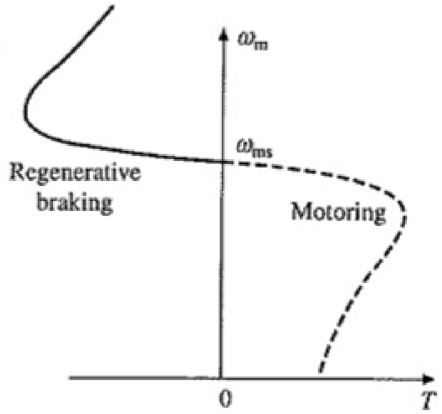


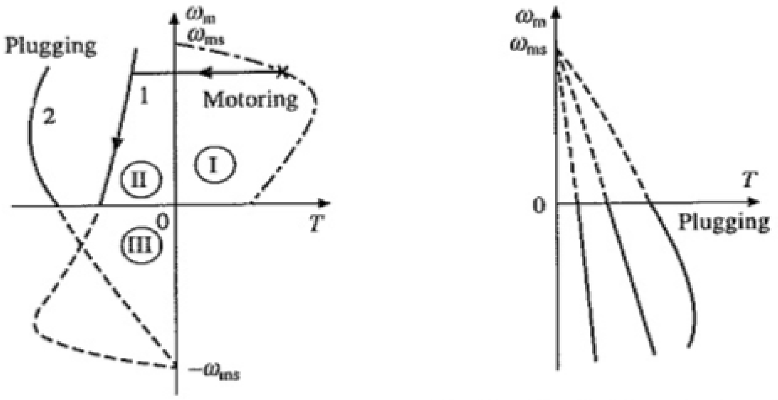
Fig. 6.13 Regenerative braking

Plugging or Reverse Voltage Braking:

When phase sequence of supply of the motor running at a speed is reversed, by interchanging connections of any two phases of stator with respect to supply terminals, operation shifts from motoring to plugging as shown in Fig. 6.14. Plugging characteristics are actually extension of motoring characteristics for negative phase sequence from quadrant III to II. Reversal of phase sequence reverses the direction of rotating field. If the slip for plugging is denoted by s_n, then

$$s_n = \frac{-\omega_{ms} - \omega_m}{-\omega_{ms}} = 2 - s \qquad (6.27)$$

Motor performance can be calculated from Eqs. (6.4)-(6.10) when s is replaced by s_n or (2 — s). Since at the instant of switchover to plugging, slip can be upto 2, the rotor induced voltage can be twice of its value at zero speed. Consequently, motor current is large, although braking torque is low. In case of wound-rotor motors, a resistance equal to twice the starter resistance is inserted in the rotor to limit braking current to starting value. This also increases braking torque as shown by curve 2 (Fig. 6.14).



(a) 1 : Natural characteristic
2 : With external resistance in rotor

(a) Plugging in IV quadrant with large external resistance in rotor

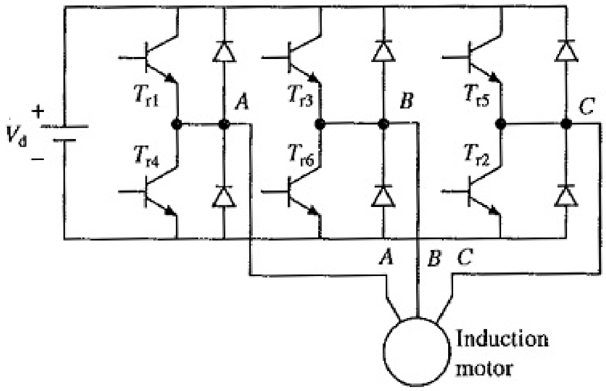
Fig. 6.14 Plugging

As shown in Fig. 6.14, torque is not zero at zero speed. When used for stopping motor, it is necessary that the motor should be disconnected from supply at or near zero speed. This makes it necessary to use an additional device for detecting zero speed and disconnecting motor from supply. This Braking of Induction Motor Drive is suitable for reversing the motor. As motor is already-connected for operation in reverse direction and torque is not zero at zero or any other speed, motor smoothly decelerates and then accelerates in the reverse direction.

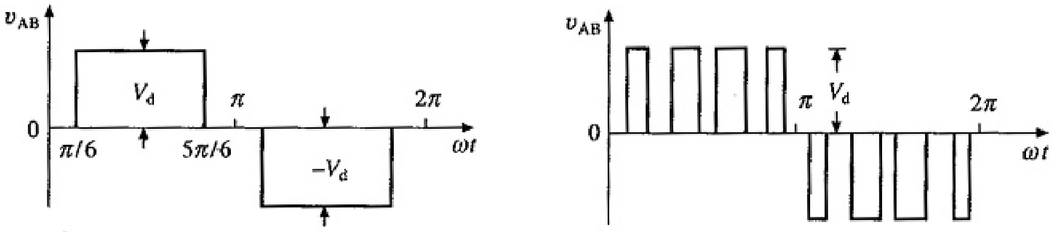
5. Explain VSI control of Induction Motor Drives

VSI Induction Motor Drives:

Voltage Source Inverter Control of Induction Motor allows a variable frequency supply to be obtained from a dc supply. Fig. 6.37(a) shows a VSI employing transistors. Any other self-commutated device can be used instead of a transistor. Generally MOSFET is used in low voltage and low power inverters, IGET (insulated gate bipolar transistor) and power transistors are used up to medium power levels and GTO (gate turn off thyristor) and IGCT (insulated gate commutated thyristor) are used for high power levels.



(a) Transistor inverter-fed induction motor drive



(b) Stepped wave inverter line voltage waveform

(c) PWM inverter line voltage waveform

Fig. 6.37 VSI fed induction motor drives:

Voltage Source Inverter Control of Induction Motor can be operated as a stepped wave inverter or a pulse-width modulated (PWM) inverter. When operated as a stepped wave inverter, transistors are switched in the sequence of their numbers with a time difference of T/6 and each transistor is kept on for the duration T/2, where T is the time period for one cycle. Resultant line voltage waveform is shown in Fig. 6.37(b). Frequency of inverter operation is varied by varying T and the output voltage of the inverter is varied by varying dc input voltage. When supply is dc, variable dc input voltage is obtained by connecting a chopper between dc supply and inverter (Fig. 6.38(a)). When supply is ac, variable dc input voltage is obtained by connecting a controlled rectifier between ac supply and inverter (Fig. 6.38(b)). A large electrolytic filter capacitor C is connected in dc link to make inverter operation independent of rectifier or chopper and to filter out harmonics in dc link voltage.

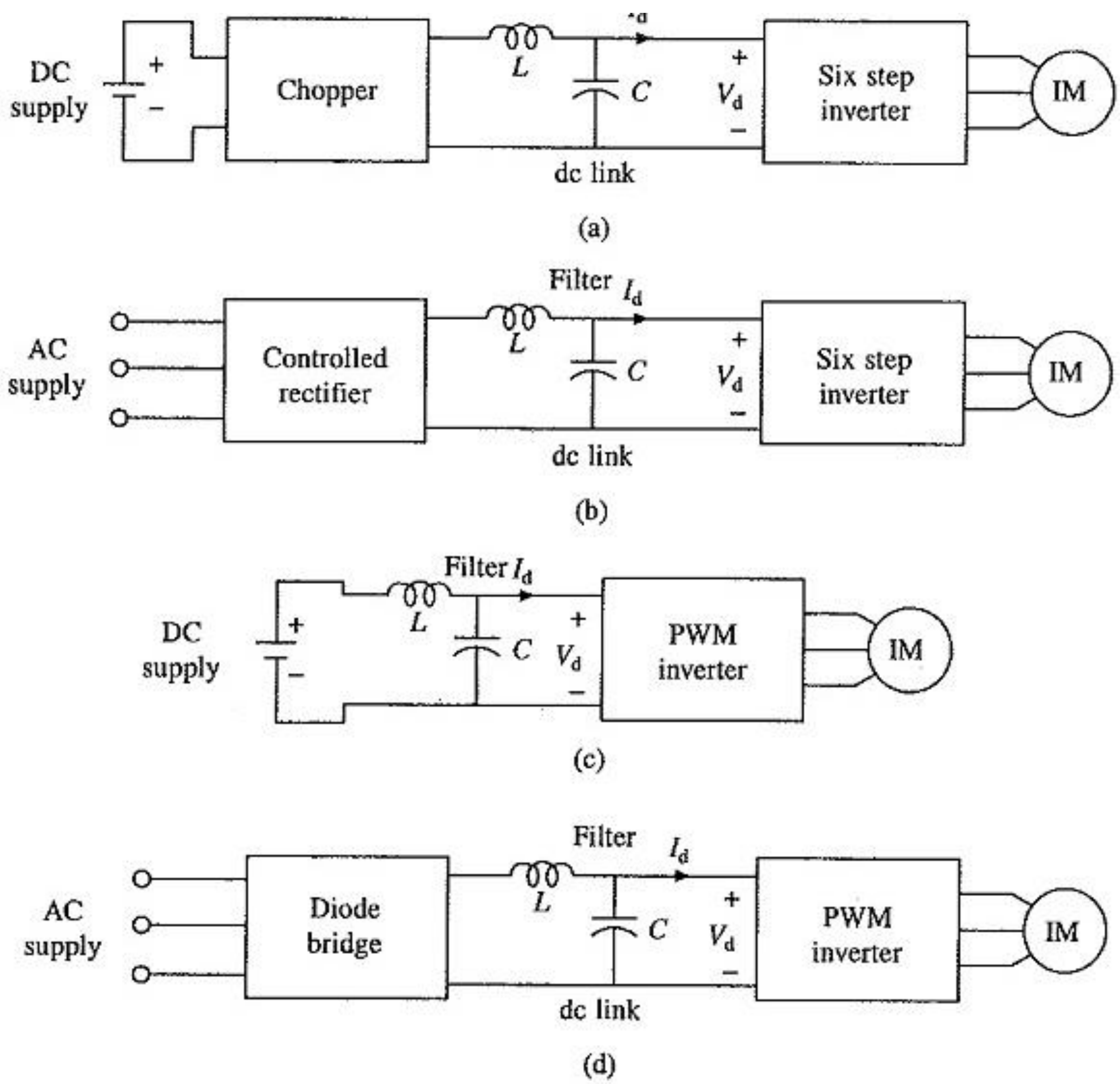


Fig. VSI controlled IM drives

6. Explain the performance of 3Φ Induction Motor with unbalanced source voltage with the help of relevant equations.

Unbalanced Source Voltages Operations:

As Supply voltage may sometimes become unbalanced, it is useful to know the effect of Unbalanced Source Voltages Operations on motor performance. Further, motor terminal voltage may be unbalanced intentionally for speed control or starting as described later.
A three-phase set of Unbalanced Source Voltages Operations (V_a,V_b and V_c) can be resolved into three-phase balanced positive sequence (V_p), negative sequence (V_n) and zero sequence (V_0) voltages, using symmetrical component relations:

$$V_{\mathrm{p}} = \frac{1}{3}(V_{\mathrm{a}} + \alpha V_{\mathrm{b}} + \alpha^2 V_{\mathrm{c}})$$

A three-phase set of Unbalanced Source Voltages Operations (V_a,V_b and V_c) can be resolved into three-phase balanced positive sequence (V_p), negative sequence (V_n) and zero sequence (V_0) voltages, using symmetrical component relations:

$$\begin{aligned} V_{\mathrm{p}} &= \frac{1}{3}(V_{\mathrm{a}} + \alpha V_{\mathrm{b}} + \alpha^2 V_{\mathrm{c}}) \\ V_{\mathrm{n}} &= \frac{1}{3}(V_{\mathrm{a}} + \alpha^2 V_{\mathrm{b}} + \alpha V_{\mathrm{c}}) \qquad (6.16) \\ V_0 &= \frac{1}{3}(V_{\mathrm{a}} + V_{\mathrm{b}} + V_{\mathrm{c}}) \end{aligned}$$

where

$$\alpha = e^{j120^\circ} = \cos 120^\circ + j \sin 120^\circ \qquad (6.17)$$

Positive sequence voltages have the same phase sequence as original system, and negative sequence voltages have opposite phase sequence. It will be assumed here that machine does not have a neutral connection. In the absence of a neutral connection, zero sequence line voltage becomes zero.

Motor performance can be calculated for positive and negative sequence voltages separately. Resultant performance is obtained by the principle of superposition by assuming motor to be a linear system.

Positive sequence voltages produce an air-gap flux wave which rotates at synchronous speed in the forward direction. For a forward rotor speed ω_m, slip s is given by Eq. (6.1). For positive sequence voltages, equivalent circuits are same as shown in Fig. 6.1, except that V is replaced by V_p. The positive sequence rotor current and torque are obtained by replacing V by V_p, in Eqs. (6.4) and (6.10). Thus

$$I'_{rp} = \frac{V_p}{\left(R_s + \frac{R'_r}{s}\right) + j\,(X_s + X'_r)}$$

$$T_p = \frac{3}{\omega_{ms}} \left[\frac{V_p^2 R'_r / s}{\left(R_s + \frac{R'_r}{s}\right)^2 + (X_s + X'_r)^2} \right] \tag{6.18}$$

Negative sequence voltages produce an air-gap flux wave which rotates at synchronous speed in the reverse direction. The slip is

$$s_n = \frac{-\omega_{ms} - \omega_m}{-\omega_{ms}}$$

Substitution from Eq. (6.3) gives