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Dynamic Performances of Adjustable Speed AC Drives Part 1: Dynamic Modeling and Implementation of PWM-Fed Synchronous and Asynchronous Machines

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Abstract: This part of the paper is concern with the development of a mathematical model for the simulation of sysnchronous and asynchronous machine using three-phase coordinates. The phase coordinate method allows ready analysis of system unbalance, and the model is applicable to altenating current machines under these conditions. The paper deals with the implementation of AC machine and drives dynamic equations.

Key Words: Mathematical Model, Simulation and Dynamic Performance

Introduction

In the analysis of unbalanced three-phase networks, phase coordinate methods (Hoadley et al., 2001) may offer advantages over the traditional symmetrical component methods. The sysmmetrical component approach is elegant and simple when applied to a balanced system with unbalanced loads, but when there is unbalanced in the network itself, the method losses its decoupling effect and becomes cumbersome. In this case, the direct phase coordinate method becomes simpler.

The mathematical analysis of the transient response of AC machines requires the solution of differential equations and the methods used have invariably been based on a circuit approach, which avoids detailed reference to the electromagnetic phonemena internal to the machine. The traditional methods used for the analysis of electromechanical machines in the steady state deals seperately with each individual machine type by developing a theory applicable to a particular machine and disregard the fact that machines are not fundamentally different. Modern methods use a generalised approach since the principles of operation are the same for the majority of machines studied. This approach used, is predominantly mathematical treatment and does not provide the same physical insight into the operation of the machine as the electromagnetic approach. For a full and more complete understanding of the subject it is recommended that physical principles, Adkins (1964), be studied in unison with the generalised theory. Many excellent texts, Smith (1993) and Hancock (1974) are available which cover the theoretical aspects of the subject in detail. This paper describes the mathematical models of AC machines in direct phase quantities .

Implementation of AC Machines Modeling: Alternating current electrical machines consist of two electromagnetic interacting entities possessing the facility for relative motion between them. The theory is conditional on the balanced phase circuits of the polyphase machines and the analysis is based, for the machines considered here and shown in schematic form in Fig. 1, on the operational matrix equation (Yildir, 1995) (Peter Vas, 1990).

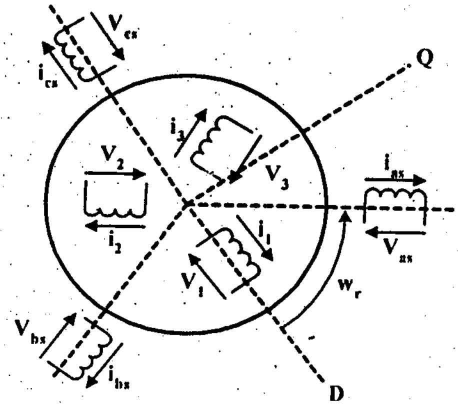
Induction Machine Equations: The voltage equations for a three phase induction machine with three symmetrical stator windings, and three symmetrical rotor windings as shown in Fig. 1, are given by eqn. 1. Where R_S is the resistance of stator winding, and R_r is the resistance of the rotor winding. p is the differential operand d/dt.

$$\begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \\ V_{ar} \\ V_{br} \\ V_{cr} \end{bmatrix} = \begin{bmatrix} R_{as} & & & & & \\ & R_{bs} & & & & \\ & & R_{cs} & & & \\ & & & R_{ar} & & \\ & & & & R_{br} & \\ & & & & & R_{cr} \end{bmatrix} \begin{bmatrix} I_{as} \\ I_{bs} \\ I_{cs} \\ I_{ar} \\ I_{br} \\ I_{cr} \end{bmatrix} + P \begin{bmatrix} \lambda_{as} \\ \lambda_{bs} \\ \lambda_{cs} \\ \lambda_{ar} \\ \lambda_{br} \\ \lambda_{cr} \end{bmatrix} \quad (1)$$

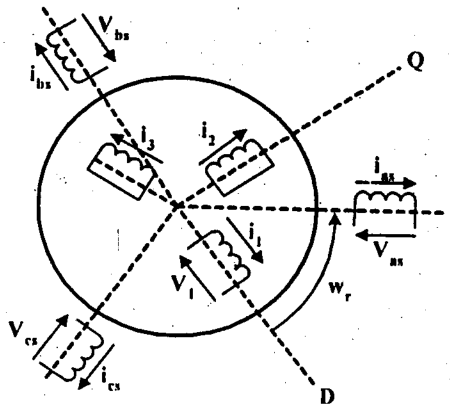
The flux linkage equations are given by eqn. 2

$$\begin{bmatrix} \lambda_{as} \\ \lambda_{bs} \\ \lambda_{cs} \\ \lambda_{ar} \\ \lambda_{br} \\ \lambda_{cr} \end{bmatrix} = \begin{bmatrix} L_{asas} & L_{asbs} & L_{ascs} & L_{asar} & L_{asbr} & L_{ascr} \\ L_{bsas} & L_{bsbs} & L_{bscs} & L_{bsar} & L_{bsbr} & L_{bscr} \\ L_{csas} & L_{csbs} & L_{cscs} & L_{csar} & L_{csbr} & L_{cscr} \\ L_{aras} & L_{arbs} & L_{arcs} & L_{arar} & L_{arbr} & L_{arcr} \\ L_{bras} & L_{brbs} & L_{brcs} & L_{brar} & L_{brbr} & L_{brcr} \\ L_{cras} & L_{crbs} & L_{crcs} & L_{crar} & L_{crbr} & L_{crcr} \end{bmatrix} \begin{bmatrix} I_{as} \\ I_{bs} \\ I_{cs} \\ I_{ar} \\ I_{br} \\ I_{cr} \end{bmatrix} \quad (2)$$

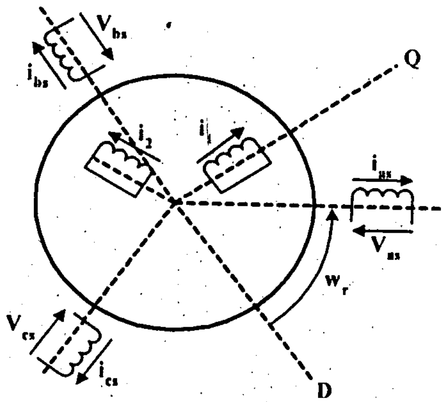
where subscripts as, bs, cs, ar, br, cr refer to stator and rotor quantities respectively (Krause and Thomas, 1965).



(a) 3-phase induction machine



(b) 3-phase synchronous machine



(c) 3-phase reluctance machine

Fig. 1a: Three phase Induction Machine
Fig. 1b: Three Phase synchronous Machine
Fig. 1c: Three phase Reluctance Machine

Synchronous Machine Equations: The voltage equations for a three phase salient-pole synchronous machine with three symmetrical stator windings, an excitation winding and two damper windings on the d- and q- axis of the rotor respectively, as shown in Fig. 1.b, are given by eqn 3. Where R_s is the resistance of stator winding, and R_{fd} , R_{kd}, R_{kq} are the resistances of the excitation winding, and d- and q- axis damper windings respectively.

$$\begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \\ V_{fd} \\ V_{kd} \\ V_{kq} \end{bmatrix} = \begin{bmatrix} R_{as} & & & & & \\ & R_{bs} & & & & \\ & & R_{cs} & & & \\ & & & R_{fd} & & \\ & & & & R_{kd} & \\ & & & & & R_{kq} \end{bmatrix} \begin{bmatrix} I_{as} \\ I_{bs} \\ I_{cs} \\ I_{fd} \\ I_{kd} \\ I_{kq} \end{bmatrix} + P \begin{bmatrix} \lambda_{as} \\ \lambda_{bs} \\ \lambda_{cs} \\ \lambda_{fd} \\ \lambda_{kd} \\ \lambda_{kq} \end{bmatrix} \quad (3)$$

The flux linkage equations are given by eqn. 4

$$\begin{bmatrix} \lambda_{as} \\ \lambda_{bs} \\ \lambda_{cs} \\ \lambda_{fd} \\ \lambda_{kd} \\ \lambda_{kq} \end{bmatrix} = \begin{bmatrix} L_{asas} & L_{asbs} & L_{ascs} & L_{asar} & L_{asbr} & L_{ascr} \\ L_{bsas} & L_{bsbs} & L_{bscs} & L_{bsar} & L_{bsbr} & L_{bscr} \\ L_{csas} & L_{csbs} & L_{cscs} & L_{csar} & L_{csbr} & L_{cscr} \\ L_{fdas} & L_{fdbs} & L_{fdcs} & L_{fdfd} & L_{fdkd} & L_{fdkq} \\ L_{kdas} & L_{kdbs} & L_{kdcs} & L_{kdfd} & L_{kdkd} & L_{kdkq} \\ L_{kqas} & L_{kqbs} & L_{kqcs} & L_{kqfd} & L_{kqkd} & L_{kqkq} \end{bmatrix} \begin{bmatrix} I_{as} \\ I_{bs} \\ I_{cs} \\ I_{fd} \\ I_{kd} \\ I_{kq} \end{bmatrix} \quad (4)$$

where subscripts as, bs, cs, fd, kd, kq refer to the three stator windings, excitation and d- and q- axis damper quantities respectively.

Reluctance Machine Equations: The voltage equations for a three phase salient-pole reluctance machine with three symmetrical stator windings, an excitation winding and two damper windings on the d- and q- axis of the rotor respectively, as shown in fig.1.c, are given by eqn. 5. Where R_s is the resistance of stator winding , R_{kd}, R_{kq} are the resistances of the d- and q- axis damper windings respectively.

$$\begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \\ V_{kd} \\ V_{kq} \end{bmatrix} = \begin{bmatrix} R_{as} & & & & \\ & R_{bs} & & & \\ & & R_{cs} & & \\ & & & R_{kd} & \\ & & & & R_{kq} \end{bmatrix} \begin{bmatrix} I_{as} \\ I_{bs} \\ I_{cs} \\ I_{kd} \\ I_{kq} \end{bmatrix} + p \begin{bmatrix} \lambda_{as} \\ \lambda_{bs} \\ \lambda_{cs} \\ \lambda_{kd} \\ \lambda_{kq} \end{bmatrix} \quad (5)$$

the flux linkage equations are given by eqn. 6

$$\begin{bmatrix} \lambda_{as} \\ \lambda_{bs} \\ \lambda_{cs} \\ \lambda_{kd} \\ \lambda_{kq} \end{bmatrix} = \begin{bmatrix} L_{asas} & L_{asbs} & L_{asbs} & L_{askd} & L_{askq} \\ L_{bsas} & L_{bsbs} & L_{bscs} & L_{bskd} & L_{bskq} \\ L_{csas} & L_{csbs} & L_{cscs} & L_{cskd} & L_{cskq} \\ L_{kdas} & L_{kdbs} & L_{kdcs} & L_{kdkd} & L_{kdkq} \\ L_{kqas} & L_{kqbs} & L_{kqcs} & L_{kdkq} & L_{kqkq} \end{bmatrix} \begin{bmatrix} I_{as} \\ I_{bs} \\ I_{cs} \\ I_{kd} \\ I_{kq} \end{bmatrix} \quad (6)$$

where subscripts as, bs, cs, kd, kq refer to the three stator windings, d- and q- axis damper quantities respectively.

Electrical Machines in a Three-Phase Frame of Reference: When electrical machines are expressed in three-phase axes, many of the inductances are functions of rotor speed and time as shown in the following:

Induction Machines

Stator Inductances: If it is assumed that the air gap of an induction machine is uniform and the stator and rotor windings are sinusoidally distributed, all stator self inductances are identical

$$L_{asas} = L_{bsbs} = L_{cscs} = L_{ls} + L_{ms} \quad (7)$$

L_{ls} is the stator leakage inductance and identical for all three phases. L_{ms} is the stator magnetising inductance . The mutual inductance between any two stator windings is the same due to symmetry

$$L_{bscs} = L_{csbs} = -0.5L_{ms} \quad (8)$$

$$L_{brcr} = L_{crbr} = -0.5L_{mr} \quad (9)$$

$$L_{crar} = L_{arcr} = -0.5L_{mr} \quad (10)$$

(ii) Rotor Inductances

In the same manner to that given for the stator , the rotor self-inductances are

$$L_{arar} = L_{brbr} = L_{crcr} = L_{lr} + L_{mr} \quad (11)$$

and mutual inductances are

$$L_{arbr} = L_{brar} = -0.5L_{mr} \quad (12)$$

$$L_{brcr} = L_{crbr} = -0.5L_{mr} \quad (13)$$

$$L_{crar} = L_{arcr} = -0.5L_{mr} \quad (14)$$

Mutual Inductances between Stator and Rotor Windings: The mutual inductance between a stator winding and any rotor winding varies sinusoidally with the rotor position .

$$L_{asar} = L_{bsbr} = L_{cscr} = L_{msr}\cos\theta_a \quad (15)$$

$$L_{ascr} = L_{bsar} = L_{csbr} = L_{msr}\cos\theta_b \quad (16)$$

$$L_{asbr} = L_{bscr} = L_{csar} = L_{msr}\cos\theta_c \quad (17)$$

where

$$\theta_a = \theta_r \quad (18)$$

$$\theta_b = \theta_r - 120^0 \quad (19)$$

$$\theta_c = \theta_r + 120^0 \quad (20)$$

By implication the derivatives of these inductances with respect to time are present in the equations for the machine .

Synchronous Machines

Stator Self Inductances: The maximum self-inductance of any stator winding is obtained when the field axis is in line with phase axis , and the minimum value is obtained when the quadrature axis coincides with the phase axis . The inductance varies periodically due to the winding arrangement and the symmetry of the rotor structure. Moreover, to take into account the assumption of sinusoidal winding distribution, the self-inductances of stator may be expressed as,

Where

$$L_{asas} = L_{a0} + L_{a2}\cos 2\theta_a \quad (21)$$

$$L_{bsbs} = L_{a0} + L_{a2}\cos 2\theta_b \quad (22)$$

$$L_{cscs} = L_{a0} + L_{a2}\cos 2\theta_c \quad (23)$$

$$L_{ao} = (L_d + L_q + L_{ls})/3 \quad (24)$$

$$L_{a2} = (L_d - L_q)/3 \quad (25)$$

$$\theta_a = \theta_r \quad (26)$$

$$\theta_b = \theta_r - 120^0 \quad (27)$$

$$\theta_c = \theta_r + 120^0 \quad (28)$$

l_{ls} is the stator leakage inductance and identical for all three phases. L_d is the d-axis self-inductance and is defined as the sum of stator leakage inductance and d-axis magnetizing inductance. L_q is the q-axis self-inductance and is defined as the sum of stator leakage inductance and q-axis magnetizing inductance. θ_r is the rotor displacement in electrical degrees.

Stator Mutual Inductances: The mutual inductance between any two stator windings is composed of two parts, one is the component of mutual flux that does not link the rotor and is therefore independent of rotor position and the other varies with rotor position. The former part is always negative because of the winding arrangement. The mutual inductances between stator windings may be expressed as,

$$L_{asbs} = L_{bsas} = L_{b0} + L_{a2}\mathrm{Cos}2\theta_c \quad (29)$$

$$L_{bscs} = L_{csbs} = -L_{b0} + L_{a2}\mathrm{Cos}2\theta_a \quad (30)$$

$$L_{csas} = L_{ascs} = -L_{b0} + L_{a2}\mathrm{Cos}2\theta_b \quad (31)$$

where

$$L_{b0} = (L_d + L_q - 2L_{1s})/6 \quad (32)$$

The amplitude of the sinusoidal part of the inductances are identical to each other and to that of the self-inductances because of the rotor saliency.

Rotor Inductances: Since the stator surface has been considered smooth, the rotor inductances are all constants. It is also apparent that the mutual inductances between the direct axis windings and the quadrature axis windings are all zeros (the cross-field effect is not considered.) The rotor self inductances are

$$L_{kdkd} = L_{lkd} + L_{fdkd} \quad (33)$$

$$L_{kqkq} = L_{lkq} + L_{mkq} \quad (34)$$

L_{lfd}, L_{lkd}, L_{lkq} are leakage inductances of the excitation winding, d-axis damping winding, and q-axis damping winding respectively. The mutual inductances between rotor windings are.

$$L_{fdkd} = L_{kdfd} \quad (35)$$

$$L_{fdkd} = L_{kdfd} = L_{kdkq} = L_{kqkd} \quad (36)$$

Mutual Inductances between Stator and Rotor windings: The mutual inductance between a stator winding and any rotor winding are given in reference (Smith and Meng-Jen, 1993).

Reluctance Machines : Stator self inductances and stator mutual inductances are the same as synchronous machine.

Rotor Inductances: Since the stator surface has been considered smooth, the rotor inductances are all constants. It is also apparent that the mutual inductances between the direct axis windings and the quadrature axis windings are all zeros (the cross-field effect is not considered.) The rotor self inductances are

$$L_{kdkd} = L_{lkd} \quad (37)$$

$$L_{kqkq} = L_{lkq} + L_{mkq} \quad (38)$$

L_{lkd}, L_{lkq} are leakage inductances of the d-axis damping winding, and q-axis damping winding respectively. The mutual inductances between rotor windings are.

$$L_{fdkd} = L_{kdfd} = 0$$

Mutual Inductances between Stator and Rotor Windings: The mutual inductance between a stator winding and any rotor winding , varies sinusoidally with the rotor position . This sinusoidal variation can be predicted from the assumption that the stator windings are sinusoidally distributed.

The mutual inductances between stator windings and the d-axis are

$$L_{askd} = L_{kdas} = L_{mkd}\mathrm{Cos}\theta_a \quad (39)$$

$$L_{bskd} = L_{bdas} = L_{mkd}\mathrm{Cos}\theta_b \quad (40)$$

$$L_{cskd} = L_{kdcs} = L_{mkd}\mathrm{Cos}\theta_c \quad (41)$$

The mutual inductances between stator windings and the q-axis are

$$L_{askq} = L_{kqas} = L_{mkq}\mathrm{Sin}\theta_a \quad (42)$$

$$L_{bskq} = L_{kqbs} = L_{mkq}\mathrm{Sin}\theta_b \quad (43)$$

$$L_{cskq} = L_{kqcs} = L_{mkq}\mathrm{Sin}\theta_c \quad (44)$$

Modeling of Transmission Circuit and Disturbance: Fig. 2 shows a motor and transmission line model.

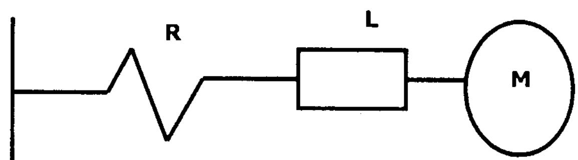


Fig. 2: Modeling of Single Phase Transmission Circuit

In this case the parameters of the transformed stator circuits are modified to take account of this and equation's coefficient matrices are modified and redefined as follows in three-phase coordinate.

$$[R] = \begin{array}{c} \\ as \\ bs \\ cs \end{array}\!\!\begin{array}{c} \begin{array}{ccc} as & bs & cs \end{array} \\ \begin{bmatrix} R_T & & \\ & R_T & \\ & & R_T \end{bmatrix} \end{array} + [R_{abc}] \quad (45)$$

$$[L] = \begin{array}{c} \\ as \\ bs \\ cs \end{array}\!\!\begin{array}{c} \begin{array}{ccc} as & bs & cs \end{array} \\ \begin{bmatrix} L_T & & \\ & L_T & \\ & & L_T \end{bmatrix} \end{array} + [L_{abc}] \quad (46)$$

in which $[R_{abc}]$ and $[L_{abc}]$ are the previous matrices in three-phase coordinate. The inclusion of the simple transmission circuit representation enables realistic simulations of those situations where a motor draws a high current from the supply over a relatively long transmission link. Alternatively, the facility of including reactance in the supply line may be seen to reflect in to the simulation level of system fault infeed which can have a profound effect on the recovery of a motor subsequent to the clearance of a fault (Subramaniam and Malik, 1971).

Adjustable Speed AC Drives: There are three aspects that are relevant to our study of adjustable speed AC motor drives:

1. The static converters employed to control such drives,
2. The motors employed,
3. The control strategies used, which depend on the motor type and the converter type.

There are different types of inverters that are used in this paper. These are:

a. The three-phase six-step type
b. The pulse width modulated type
c. Current-controlled dead-beat type

The types of motors to be considered are the induction motor and the synchronous motor, which may have one of the two types of rotors, namely the permanent magnet type and the reluctance type (Vithaythill and Joseph, 1971).

Industrial Applications of Adjustable-Speed AC Drives (Variable Torque Applications): Variable torque applications are by far the easiest to work with centrifugal pumps, centrifugal compressors, and fans are typical examples. The torque varies with the square of speed. Since the starting torque requirements are very low, very little, if any, offset voltage is required to start the drive. This is valid for all pumping applications as long as the fluid being pumped has a minimal solids content.

Constant Torque Applications: Drives requiring constant torque operation are much more difficult to apply. Not only is the torque requirement constant but also occasionally the starting torque requirement might exceed 150 percent. Practically , the determination of the starting torque is difficult. Historical data or existing drives may aid in determining it. However, the constant torque load accounts for over 2/3 of the motor applications. These loads generally involve friction that the torque is required to overcome. Typical loads are conveyors, extruders, and positive displacement pumps.

Constant Volts/Hertz Operation: In order to produce constant torque, the controller must maintain a constant flux and consequently a V/H output in same manner. As the frequency is varied, the motor has a particular speed, torque, and current characteristic for each frequency. As the frequency decreases, the maximum torque available and the breakdown torque decrease. This is caused by the stator resistance voltage drop, which becomes significant at lower frequencies where low voltage would be applied. This reduction in maximum torque at low frequency can be overcome by introducing an offset or voltage boost at low frequency. This voltage would be adjusted to offset the resistance voltage drop of the stator winding.

Voltage Fed Inverters: In an inverter circuit, DC power is converted to AC power. The output frequency of the static inverter is determined by the rate at which the semiconductor devices are switched on and off by the inverter control circuitry; consequently, an adjustable frequency AC output is readily provided. The inverter may receive its DC power from a battery, but in most industrial applications it is fed by a rectifier. This configuration is classified as a DC link converter because it is a two-stage static frequency converter in which AC power at network frequency is rectified and then filtered in the DC link before being inverted to AC at an adjustable frequency. Inverters can be broadly classified either as voltage-source or current-source inverters. The voltage-fed inverter (VSI) is powered from a stiff, or low impedance, DC voltage source such as a battery or rectifier, the output voltage of which is smoothed by an LC filter. The large filter capacitor across the inverter input terminals maintain a constant DC link voltage. The inverter is therefore an adjustable-frequency voltage source, the output voltage of which is essentially independent of load current.

The Three-Phase Six-Step Voltage Source Inverter: The three-phase six-step inverter is a voltage-source inverter that has been widely used in commercial adjustable-speed ac motor drives. As shown in Fig. 3 (a), a third leg, or half-bridge, is added to the single-phase bridge circuit of Fig. 3 (b), and the output terminals A, B, and C are connected to a three-phase ac motor. A reversal of the direction of motor rotation is readily accomplished by changing the inverter output phase sequence by means of the firing signals. Conventional thyristors have been used in many three-phase six-step inverters, and the general circuit diagram of Fig. 3 (b) shows each thyristor device within a dashed rectangle.

A three-phase output is obtained by preserving a mutual phase displacement of 120^0 between the switching sequences in the three legs of the inverter. This phase displacement results in the firing sequence indicated by the numbering of the thyristors in Fig. 3(b). Thus, the thyristors are gated at regular intervals of 60^0 in the sequence TH1, TH2, TH3, TH4, TH5, TH6, to complete one cycle of the output voltage waveform. The feedback diode conducts on reactive loads so that the output terminal is clamped to the positive or negative supply rail when the thyristor is not conducting. Again, this means that the terminal voltage is uniquely defined at all times and the six-step inverter may be represented in terms of the ideal mechanical switches shown in Fig. 3(c) (Murphy and Turnbull, 1986).

By taking the midpoint of the dc supply as reference point O and assuming instantaneous switching, the pole voltages V_{AO}, V_{BO}, and V_{CO} have the square waveforms shown in Fig. 4.

Three thyristors are turned on at any instant to define the three pole voltages, and these voltage waveforms are unaffected by changes in load or operating

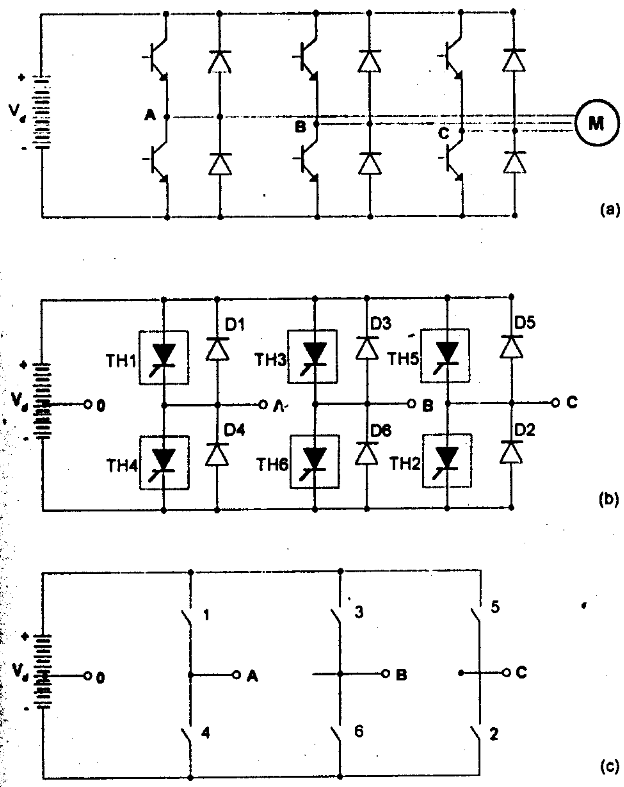


Fig. 3: The Three Phase Bridge Inverter:
Fig. 3a: Transistor Bridge Circuit Feeding an AC Motor
Fig. 3b: General Three Phase Bridge Circuit
Fig. 3c: Equivalent Circuit Using Ideal Mechanical Switches

frequency. As in the single-phase bridge, the pole voltage is +Vd/2 for the half-period while the upper thyristor in the half-bridge is turned on, and is -Vd/2, while the lower thyristor is turned on. Each line-to-line voltage is obtained as the difference of two pole voltages. Thus

$$
\begin{aligned}
V_{AB} &= V_{AO} - V_{BO} \\
V_{BC} &= V_{BO} - V_{CO} \\
V_{CA} &= V_{CO} - V_{AO}
\end{aligned}
\tag{47}
$$

The resulting output line voltage waveforms of Fig. 4 have 60^0 intervals of zero voltage in each half-cycle and are termed quasi-square waves. Since the pole voltage waveform is a square wave of amplitude Vd/2 , it has the familiar Fourier series expression involving all odd harmonics. Thus

$$V_{AO} = \frac{4}{\pi}\frac{V_d}{2}\left[\sin wt + \frac{1}{3}\sin 3wt + \frac{1}{5}\sin 5wt + \frac{1}{7}\sin 7wt + \frac{1}{9}\sin 9wt + ...\right] \tag{48}$$

Similarly, V_{BO} is a square wave displaced by 120 degrees. Its Fourier series expression is

$$V_{BO} = \frac{4}{\pi}\frac{V_d}{2}\left[\sin(wt - \frac{2\pi}{3}) + \frac{1}{3}\sin 3wt + \frac{1}{5}\sin 5(wt - \frac{2\pi}{3}) + \frac{1}{7}\sin 7(wt - \frac{2\pi}{3}) + \frac{1}{9}\sin 9wt + ...\right] \tag{49}$$

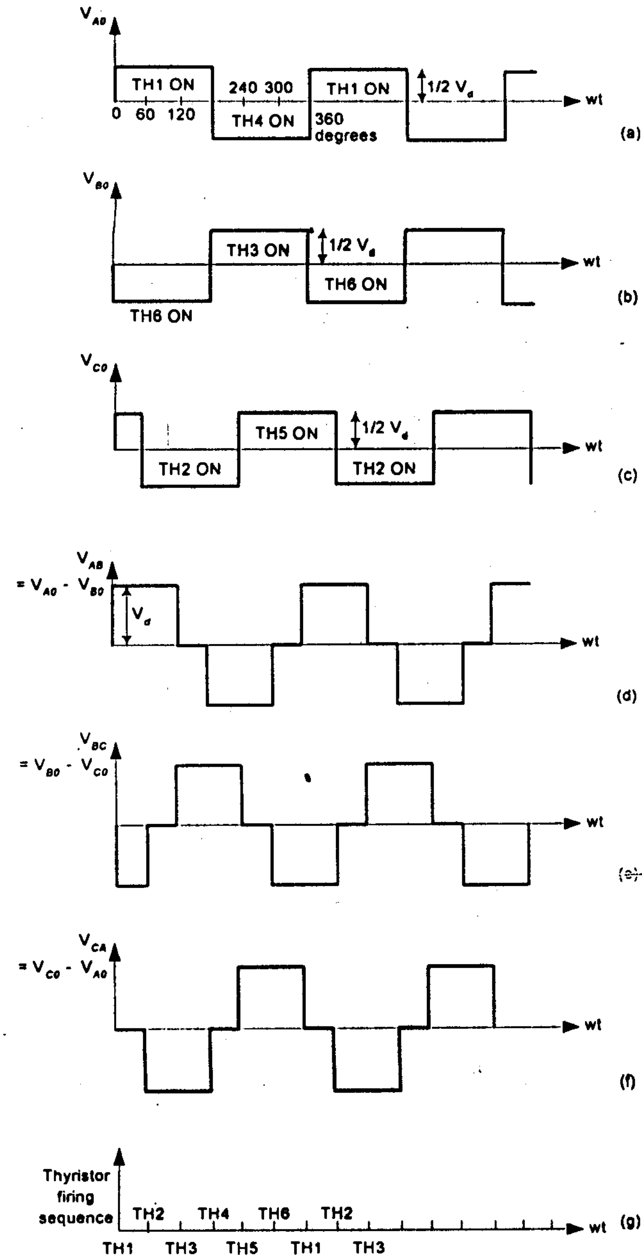


Fig. 4: Voltage Waveforms for Six-Step Operation of the Three-Phase Bridge Inverter:
Fig. 4a, b, c: Pole Voltages
Fig. d, e, f: Line-to-line Voltages
Fig. 4g: Thyristor Gating Sequence

The line voltage V_{AB}, which is obtained as the difference between V_{AO} and V_{BO}, contains no third harmonic or multiples thereof, because these so-called "triplen" harmonics are in time phase in each of the square-wave pole voltages, as shown by Equations 48 and 49. The remaining harmonics in the line voltage waveform are of order $k = 6n \pm 1$, where n is any positive integer. The complete Fourier series expression for V_{AB} is

$$V_{AB} = \frac{2\sqrt{3}}{\pi} V_d \left[\sin wt - \frac{1}{5}\sin 5wt - \frac{1}{7}\sin 7wt + \frac{1}{11}\sin 11wt + \frac{1}{13}\sin 13wt + ... \right]$$

Sinusoidal PWM Inverter: Most ac motors are designed to operate on a sine wave supply, and the inverter output voltage should be as nearly sinusoidal as possible. Each inverter phase or half-bridge has a comparator which is fed with the reference voltage for that phase and a symmetrical triangular carrier wave which is common to all three phases, as shown in Fig. 5(a). Again, the ratio of carrier to reference frequency or carrier ratio, p, must be a multiple of three to ensure identical phase voltage waveforms in a three-phase system. The triangular carrier has a fixed amplitude, and A the ratio of sine wave amplitude to carrier amplitude is termed the modulation index, M. Output voltage control is achieved by variation of the sine wave amplitude. This variation alters the pulse widths in the output voltage waveform but preserves the sinusoidal modulation pattern. In Fig. 5, the carrier ratio is nine and the modulation index is almost unity. The corresponding pole voltages V_{AO}, V_{BO}, V_{CO}, and the resultant line-to-line voltage, V_{AB}, are shown in Fig. 5 (b), (c), (d), and (e), respectively.

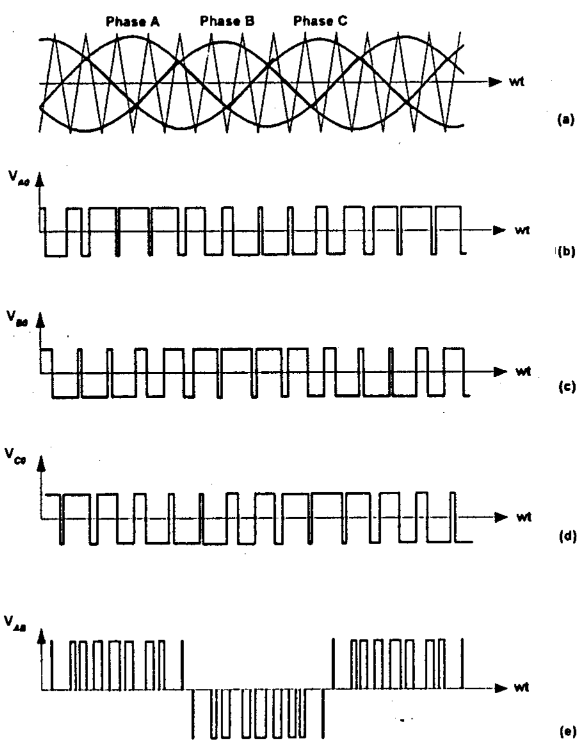
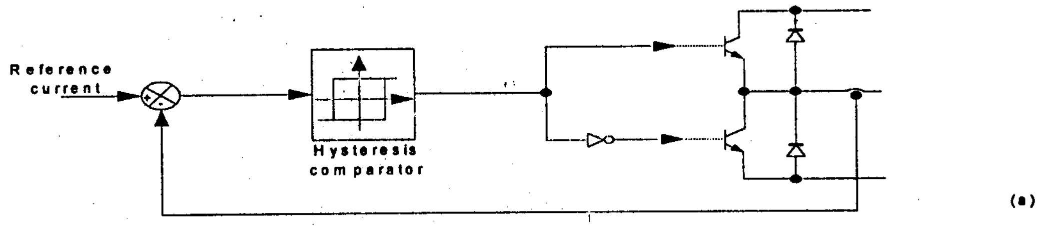
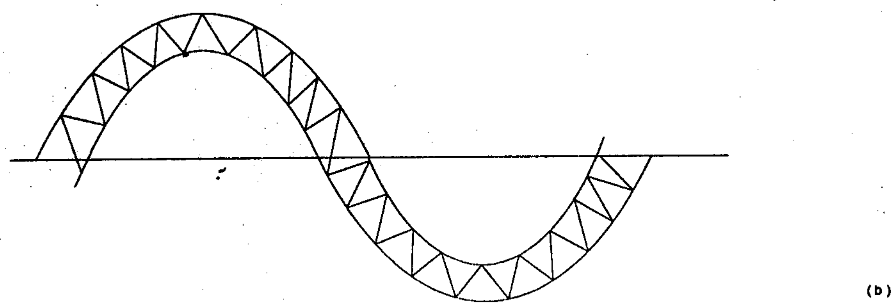


Fig. 5: Voltage Waveforms for a Three-Phase Sinusoidal PWM Inverter
Fig. 5a: Comparator Voltages
Fig. 5b, c, d: Pole Voltages
Fig. 5e: AC Line Voltage

Current-Controlled Dead-Beat Inverter: The current-controlled dead-beat inverter consists of a conventional PWM voltage-source inverter fitted with current-regulating loops to provide a controlled current output. If the inverter has a high switching frequency, the stator currents of the synchronous or induction motor can be rapidly adjusted in magnitude and phase. As in a dc drive, high-quality dynamic control of motor current is particularly important for the implementation of a high-performance, single-phase ac drives. The current controller can take a number of different forms (Andrieux and Lajoie, 1985). Usually, a sinusoidal reference current waveform is generated and fed to a comparator, together with the actual measured current of the motor. The simplest approach uses the comparator error to switch the devices in the inverter half-bridge so as to limit the instantaneous current error. Fig. 6a shows the control for one inverter leg. If the motor phase current is more greater than the reference current value, the upper device is turned off and the lower device is turned on, causing the motor current to decrease, and vice versa. The comparator has a dead band, or hysteresis, that determines the permitted deviation of the actual phase current from the reference value before an inverter switching is initiated . Fig. 6b illustrates the type of output current waveform obtained with the simple hysteresis or on/off current controller. A small deadband gives a near-sinusoidal motor current with a small current ripple, but requires a high switching frequency in the inverter. However, the switching frequency is not constant for a given deadband but is modulated by the variations in motor inductance and back emf. When the back emf of the motor is low, the switching frequency may rise excessively. It has been shown that in a three-phase system without a neutral connection, the instantaneous current error can reach double the hysteresis band .

Also, low current levels cannot be achieved because the modulation vanishes when the reference current lies within the hysteresis band. In addition, the variable switching frequency produces objectionable acoustic In commercial applications, a fixed switching frequency is preferred because acoustic noise is less annoying and inverter switching losses are more predictable. Fig. 6c pared with a fixed-frequency triangular carrier wave. Thus, the current error is essentially the reference or modulating signal in a conventional, asynchronous, pulse-width modulator. The resulting PWM signal, whose duty cycle is proportional to the current error, controls the inverter switching as before. If the reference current is more positive than the actual current, the resulting error is positive , and the on-period of the upper device exceeds that of the lower device. Consequently, the inverter leg is switched predominantly in the positive direction to increase the ac line current.





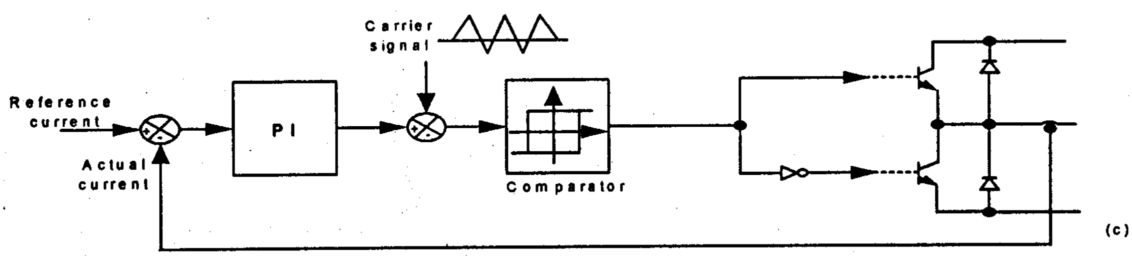


Fig. 6: The Current-Controlled Dead-Beat İnverter
Fig. 6a: Hysteresis Control for One İnverter Leg
Fig. 6b: Sinusoidal Current Waveform Generated by Hysteresis Control
Fig. 6c: Fixed-Frequency PWM Control for One İnverter Leg

Conclusion

In this part of the paper, three phase coordinate mathematical model of the AC machines and drives have been implemented. The three-phase models offer advantages in easy simulation of the unbalanced faults and more potential for connecting the adjustable-speed AC drives with generating system in practically industrial application where the harmonic components in adjustable-speed AC drive may cause significant disturbance to the system. The paper also explains the theory of Adjustable speed AC drives.

References

Adkins B., 1964. "The General Theory of Electrical Machines" Chapman &Hall

Andrieux, C. and M. Lajoie, 1985. "Analysis of Different Current Control System for Inverter-Fed Synchronous Machine" Proc.Eoropean Power Electronic Conf. 159-165.

D.Hoadley, S. Moorthy, M. Al-Dabbagh, 2001. "Steady-State Phase Coordinate Model For Induction Machines" EPSR, 89-194.

Hancock, N, 1974. "Matrix Analysis of Electrical Machines" Pergamon Press, USA.

John R.Smith and Meng-Jen Chen, 1993. "Three-Pahse Electrical Machine Systems" Research Studies Press Ltd.

Krause,P.C. and . Thomas, 1965. "Simulation of Symmetrical Induction Machinery" IEEE PAS 1038-1053.

Murphy, J.M. and E. G. Turnbull, 1986. " Powewr Electronic Control of AC Motors" Pergamon Press,England.

Peter Vas, 1990. "Vector Control of AC Machines" Oxford Uni. Press, USA.

Subramaniam,P and Malik,O., 1971. "Digital Simulation of a Synchronous Generator In Direct Phase Quantities" Proc. IEE , 153-160.

Vithaythill, Joseph, 1971. "Power Electronics" Mcgraw Hill, Usa.

Yildir, Y. B., 1995. "Simulation of Polyphase Induction Machines" Int.Aegean Conference on Electrical Machines, Turkey.