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Power Electronic Converter Control for Multiphase Drive System

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Abstract: *Multiphase variable speed drives are nowadays serious contenders for various applications. The multilevel (predominantly three-level) voltage source inverters (VSIs) and converters have become industrially accepted technologies in three-phase systems. In recent times, attempts have commenced to integrate multilevel VSIs and converters with the multiphase drive technology. In our paper provides a review of recent advances in this area. A general configuration of converter is considered and the differences with regard to the control of standard three-phase to three-phase converters are underlined. Next, two different topologies of the multiphase multilevel supply are discussed and the emphasis is placed on appropriate pulse width modulation (PWM) techniques that can be used in conjunction with the given converter structure. The first topology utilizes multilevel (three-level) VSI and the machine's stator multiphase winding is star-connected. In the second topology the winding is open-ended and each side of the winding is connected to a two-level VSI. Carrier-based and space vector based PWM strategies are considered and the performance is illustrated using experimental results.*

Keywords: *Carrier-based PWM, converter, modulation strategy, multilevel inverter, multiphase drive, open-end winding, space vector PWM.*

1. Introduction

The use of power electronic converters has enabled the Number of phases to be considered as an additional Design parameter. Multiphase (more than three phases) Machines have some advantages over three-phase ones: Improved fault tolerance, reduced torque pulsations, lower per phase power handling requirements, enhanced modularity and improved noise characteristics. In spite their notable advantages, wide availability of three-phase machines restricts the application of multiphase ones to specialized applications, for which three-phase drives are either not readily available or do not satisfy the specification. The induction machine is used in wide variety of applications as a means of converting electric power to mechanical power. Pump steel mill, hoist drives, household applications are few applications of induction machines. Induction motors are most commonly used as they offer better performance than other ac motors. In this chapter, the development of the model of a three-phase induction motor is examined starting with how the induction motor operates. The derivation of the dynamic equations, describing the motor is explained. The transformation theory, which simplifies the analysis of the induction motor, is discussed. The steady state equations for the induction motor are obtained. The basic principles of the operation of a three phase inverter are explained, following which the operation of a three phase inverter feeding a induction machine is explained with some simulation results.

The voltage and torque equations that describe the dynamic behavior of an induction motor are time-varying. It is successfully used to solve such differential equations and it may involve some complexity. A change of variables can be used to reduce the complexity of these equations by eliminating all time-varying inductances, due to electric circuits in relative motion, from the voltage equations of the machine. By this approach, a poly phase winding can be reduced to a set of two phase windings (q-d) with their magnetic axes formed in quadrature. In other words, the stator and rotor variables (voltages, currents and flux linkages) of an induction machine are transferred to a reference frame, which may rotate at any angular velocity or remain stationary. Such a frame of reference is commonly known in the generalized machines analysis as arbitrary reference frame.

2. BASIC PRINCIPLE OF OPERATION OF THREE-PHASE INDUCTION MOTOR

The operating principle of the induction motor can be briefly explained as, when balanced three phase voltages displaced in time from each other by angular intervals of 120is applied to a stator having three phase windings displaced in space by 120electrical, a rotating magnetic field is produced. This rotating magnetic is 45 has a uniform strength and rotates at the supply frequency, the rotor that was assumed to be standstill until then, has electromagnetic forces induced in it. As the rotor windings are short circuited, currents start circulating in them, producing a reaction. As known from Lenz's law, the reaction is to counter the source of the rotor currents. These currents would become zero when the rotor starts rotating in the same direction as that of the rotating magnetic field, and with the same strength. Thus the rotor starts rotating trying to catch up with the rotating magnetic field. When the differential speed between these two become zero then the rotor currents will be zero, there will be no emf resulting in zero torque production. Depending on the shaft load the rotor will always settle at a speed rω, which is less than the supply frequency eω. This differential speed is called the slip speed soω. The relation between, ωe and ωso is given as:

$$\omega_{so} = \omega_e - \omega_r$$

If m_ω is the mechanical rotor speed then,

$$\omega_r = \frac{P}{2}\omega_m$$

3. THREE-PHASE INDUCTION MACHINE EQUATIONS

The winding arrangement of a two-pole, three-phase wye-connected induction machine is shown in Figure 3.1. The stator windings of which are identical, sinusoidally distributed in space with a phase displacement of 120, with equivalent turns and resistance. Two-pole three-phase symmetrical induction machine. The rotor is assumed to symmetrical with three phase windings displaced in space by an angle of 120, with effective turns and a resistance of The voltage equations for the stator and the rotor are as given in Equations:

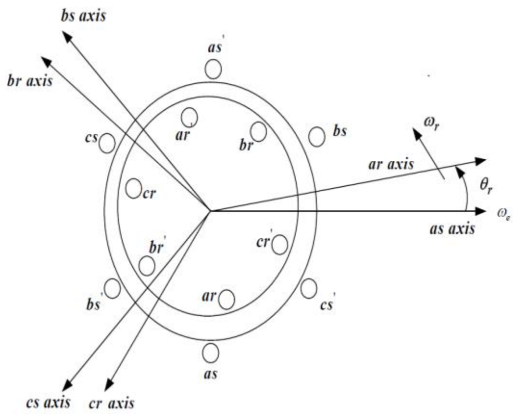


Fig.1. *Three phase Induction Machine*

4. VOLTAGE EQUATION OF INDUCTION MOTOR

$$V_{as} = r_s I_{as} + p\lambda_{as}$$

$$V_{bs} = r_s I_{as} + p\lambda_{bs}$$

$$V_{cs} = r_s I_{cs} + p\lambda_{cs}$$

Where V_{as}, V_{bs} , and V_{cs} are the three phase balanced voltages which rotate at the supply frequency. For the rotor the flux linkages rotate at the speed of the rotor, which is r_ω:

The above equations can be written in short as:

$$V_{abcs} = r_s I_{abcs} + p\lambda_{abcs}$$

$$V_{abcr} = r_s I_{abcr} + p\lambda_{abcr}$$

In the above two equations 's' subscript denoted variables and parameters associated with the stator circuits and the subscript 'r' denotes variables and parameters associated with the rotor circuits. Both and are diagonal matrices each with equal nonzero elements.

5. WINDING INDUCTANCES

$$L_s = \begin{bmatrix} L_{ls} + L_m & -\frac{1}{2}L_m & -\frac{1}{2}L_m \\ -\frac{1}{2}L_m & L_{ls} + L_m & -\frac{1}{2}L_m \\ -\frac{1}{2}L_m & -\frac{1}{2}L_m & L_{ls} + L_m \end{bmatrix}$$

$$L_r = \begin{bmatrix} L_{lr} + L_m & -\frac{1}{2}L_m & -\frac{1}{2}L_m \\ -\frac{1}{2}L_m & L_{lr} + L_m & -\frac{1}{2}L_m \\ -\frac{1}{2}L_m & -\frac{1}{2}L_m & L_{lr} + L_m \end{bmatrix}$$

$$L_{sr} = L_{sr} \begin{bmatrix} \cos\theta_r & \cos(\theta_r + \frac{2\pi}{3}) & \cos(\theta_r - \frac{2\pi}{3}) \\ \cos(\theta_r - \frac{2\pi}{3}) & \cos\theta_r & \cos(\theta_r + \frac{2\pi}{3}) \\ \cos(\theta_r + \frac{2\pi}{3}) & \cos(\theta_r - \frac{2\pi}{3}) & \cos\theta_r \end{bmatrix}.$$

In the above inductance equations, and are the leakage and magnetizing inductances of the stator windings; and are for the rotor windings. The inductance is the amplitude of the mutual inductances between stator and rotor windings.

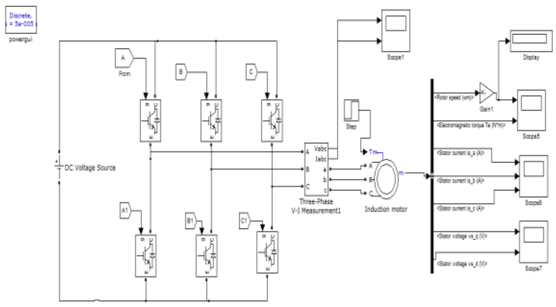


Fig.2. *Matlab model of 3 phase induction motor*

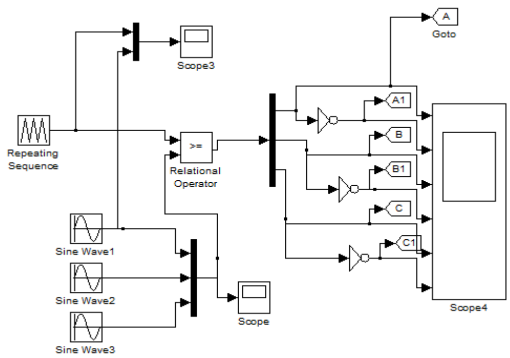
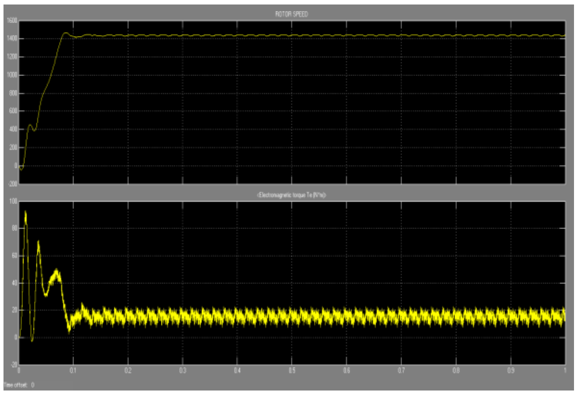
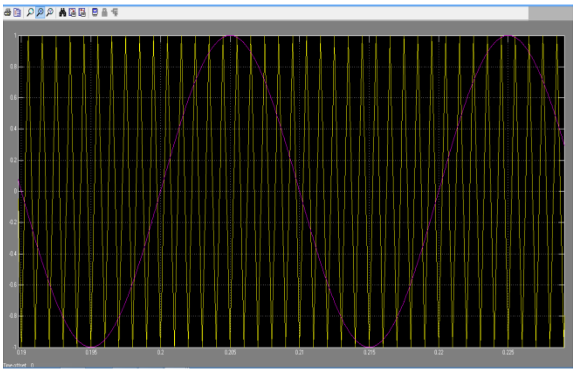


Fig.3. *Control Circuit of 3 phase induction motor*



Results: *Three phase induction motor*



Results: *Three phase Inverter*

6. MULTIPHASE

Multiphase induction motor (more than three phases) drives possess several advantages over conventional three-phase drives, such as lower torque pulsation, higher torque density, fault tolerance, stability, high efficiency and lower current ripple. To increase the motor's power per phase and to decrease its weight a multi-phase motors was used. Probably the first application of a multi-phase motor dates back to 1969, a five-phase motor, followed by a nine-phase motor (triple star), that was practically a cascade connection of some three-phase motors. The advantages of the multi-phase motor over the correspondent three-phase one, much improved in reliability, and reduction of the power per inverter leg.

Other advantages of the multi-phase motors are: the improvement of the noise, a possibility of reduction in the copper stator loss leading to an improvement in the efficiency and, also, the improvement of the torque-speed characteristics by increasing the low speed torque more than 5 times than the three-phase induction motors.

Multiphase motors have various advantages such as lower torque pulsation, reduced current per phase without increasing the voltage per phase, reduction in harmonic current, greater reliability, fault tolerance and minimal de-rating at occurrence of fault. Five-phase is the smallest phase number of multiphase motor which is commonly used. A five-phase machine can continue to operate if one or even two phases of the supply are lost. Various advantages of multiphase drives over conventional three phase drives, such as increase in frequency of pulsating torque, reduced torque pulsations. Reduction in harmonic currents, increase in current per phase without the need to increase the phase voltage; increase in torque/ampere relation for the same volume of the machine.

7. Mathematical Modeling Of Multiphase Induction Motor

$$v_a = \sqrt{2}V\cos(\omega t)$$

$$v_b = \sqrt{2}V\cos(\omega t - 2\pi/5)$$

$$v_c = \sqrt{2}V\cos(\omega t - 4\pi/5)$$

$$v_d = \sqrt{2}V\cos(\omega t + 4\pi/5)$$

$$v_e = \sqrt{2}V\cos(\omega t + 2\pi/5)$$

$$\underline{A}_s = \sqrt{\frac{2}{5}}\begin{bmatrix} \cos\theta_s & \cos(\theta_s-\alpha) & \cos(\theta_s-2\alpha) & \cos(\theta_s+2\alpha) & \cos(\theta_s+\alpha) \\ -\sin\theta_s & -\sin(\theta_s-\alpha) & -\sin(\theta_s-2\alpha) & -\sin(\theta_s+2\alpha) & -\sin(\theta_s+\alpha) \\ 1 & \cos(2\alpha) & \cos(4\alpha) & \cos(4\alpha) & \cos(2\alpha) \\ 0 & \sin(2\alpha) & \sin(4\alpha) & -\sin(4\alpha) & -\sin(2\alpha) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix}$$

Transformation Equation

Transformation of the rotor variables is performed using the same transformation expression,

Except that **θs** is replaced with β, where β = θ s−θ.

Here **θs** is the instantaneous angular

Position of the d-axis of the common reference frame with respect to the phase 'a' magnetic axis of the stator, while β is the instantaneous angular position of the d-axis of the common reference frame with respect to the phase 'a' magnetic axis of the rotor.

$$\underline{A}_r = \sqrt{\frac{2}{5}}\begin{bmatrix} \cos\beta & \cos(\beta-\alpha) & \cos(\beta-2\alpha) & \cos(\beta+2\alpha) & \cos(\beta+\alpha) \\ -\sin\beta & -\sin(\beta-\alpha) & -\sin(\beta-2\alpha) & -\sin(\beta+2\alpha) & -\sin(\beta+\alpha) \\ 1 & \cos(2\alpha) & \cos(4\alpha) & \cos(4\alpha) & \cos(2\alpha) \\ 0 & \sin(2\alpha) & \sin(4\alpha) & -\sin(4\alpha) & -\sin(2\alpha) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix}$$

Multi-phase induction motor parameters

No. of Phases(n)	5	6	7	9	12
Power	2Kw	1hp	5hp	1hp	3Kw
V in volts	100	220	260	230	127
I in Amps	7.5	2.5	7.5	3	6
N_r in RPM	1440	1440	1440	1440	1440
T in N-m	13.26	10	45	15	20
F in Hz	50	50	50	50	50
Poles	4	4	4	4	4
R_s in Ω	1.26	10	2.238	1.98	7
R_r in Ω	1.03	6.3	0.855	1.85	2.4
L_{ls} in H	0.00476	0.04	0.012	0.0091	0.01
L_{lr} in H	0.0017	0.04	0.012	0.0091	0.01
M in H	0.1515	0.42	0.297	0.1986	0.3914
J in Kgm^2	0.015	0.003	0.03	0.003	0.025
B in Nms	0.0015	0.0015	0.0015	0.0015	0.004

Stator Side Voltage,

$$v_{ds} = R_s i_{ds} - \omega_a \psi_{qs} + p\psi_{ds}$$

$$v_{qs} = R_s i_{qs} + \omega_a \psi_{ds} + p\psi_{qs}$$

$$v_{xs} = R_s i_{xs} + p\psi_{xs}$$

$$v_{ys} = R_s + p\psi_{ys}$$

$$v_{os} = R_s i_{os} + p\psi_{os}$$

Rotar Side Voltage

$$v_{dr} = R_r i_{dr} - (\omega_a - \omega)\psi_{qr} + p\psi_{dr}$$

$$v_{qr} = R_r i_{qr} + (\omega_a - \omega)\psi_{dr} + p\psi_{qr}$$

$$v_{xr} = R_r i_{xr} + p\psi_{xr}$$

$$v_{yr} = R_r i_{yr} + p\psi_{yr}$$

$$v_{or} = R_r i_{or} + p\psi_{or}$$

Electromagnetic torque

$$T_e = \frac{5P}{2} M[i_{dr} i_{qs} - i_{ds} i_{qr}]$$

Rotar Speed

$$\text{Wr} = \int \left(\frac{P}{2J}\right)(T_e - T_L)$$

Where J = Moment of Inertia

T_L = Load Torque

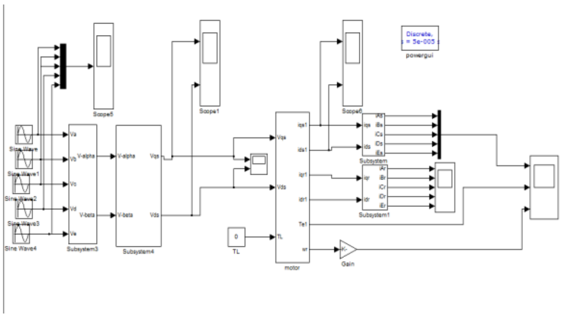
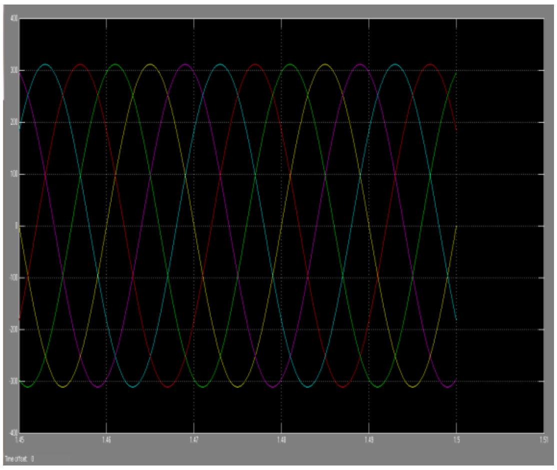
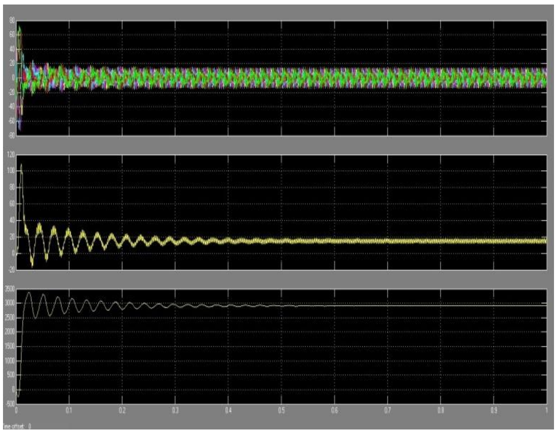


Fig. 4. *Matlab Model of Five phase Induction Motor*



Result: *Five phase Supply Voltage*



8. Step Operation of a Five-Phase Voltage Source Inverter

Power circuit topology of a five-phase VSI which was used probably for the first time by Ward and Härer (1969). Each switch in the circuit consists of two power semiconductor devices, connected in anti-parallel. One of these is a fully controllable semiconductor, such as a bipolar transistor or IGBT, while the second one is a diode.

The input of the inverter is a dc voltage, which is regarded further on as being constant. Each switch is assumed to conduct for 180°, leading to the operation in the ten-stepmode. Phase delay between firing of two switches in any subsequent two phases is equal to 360°/5 = 72°.

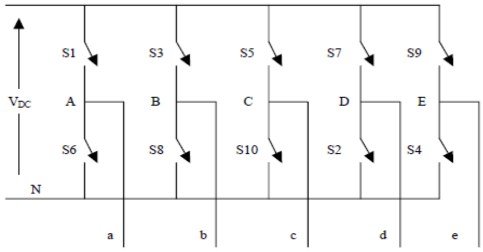
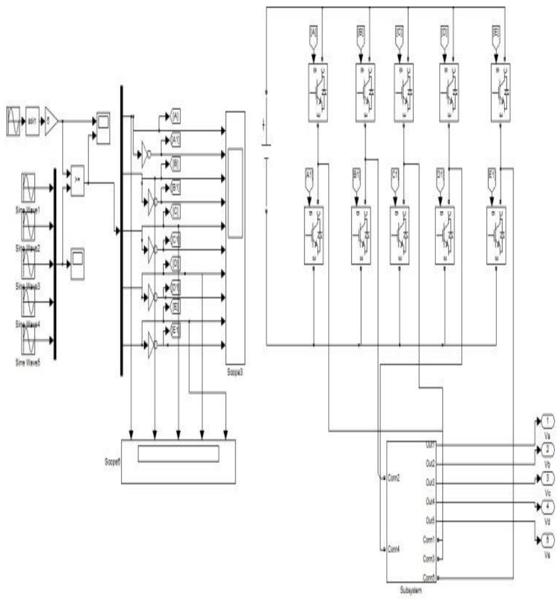
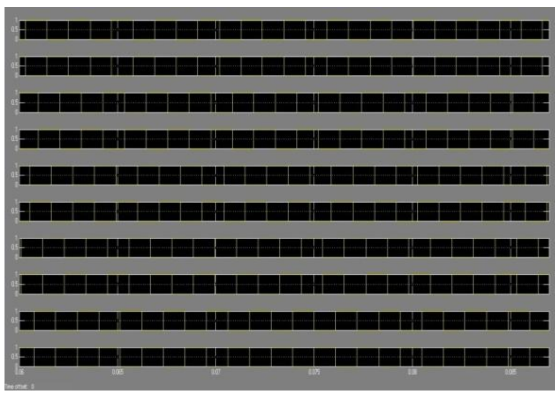


Fig.5. *five-phase voltage source inverter*

Matlab Model of Inverter





Results: *Five phase inverter*

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