

Induction motor control by vector control method.

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ABSTRACT:- The 3-phase alternating current (AC) induction motors are mechanically simple, rugged, highly reliable, lower in cost per horsepower than DC motors and capable of more torque and efficiency than single-phase AC motors. A 3-phase AC induction motor can be controlled by varying its inputs according to a mathematical model of the rotor flux field in a complex vector space (vector control). Vector control provides efficient and accurate control of the motor's speed and torque. The vector control analysis of an induction motor allows the decoupled analysis where the torque and the flux components can be independently controlled (just as in dc motor). This makes the analysis easier than the per phase equivalent circuit.

Keywords: Constant Volts Per Hertz, dq Transform, Torque Speed Curve,.

I. INTRODUCTION

The induction motor, which is the most widely used motor type in the industry, has been favored because of its good self-starting capability, simple and rugged structure, low cost and reliability, etc. Along with variable frequency AC inverters, induction motors are used in many adjustable speed applications which do not require fast dynamic response. The concept of vector control has opened up a new possibility that induction motors can be controlled to achieve dynamic performance as good as that of DC or brushless DC motors.

The v/f control principle adjust constant volt-per-Hertz ratio of the stator voltage by feed forward control. It serves to maintain magnetic flux in the machine at desired level. It satisfies only moderate dynamic requirement. High dynamic performance is achieved by field orientation, also called Vector control. The technique called vector control can be used to vary the speed of an induction motor over a wide range. It was initially developed by Blaschke (1971-1973). In the vector control scheme, a complex current is synthesized from two quadrature components, one of which is responsible for the flux level in the motor, and another which controls the torque production in the motor. Essentially, the control problem is reformulated to resemble the control of a DC motor. Vector control offers a number of benefits including speed control over a wide range, precise speed regulation, fast dynamic response, and operation above base speed. The vector control algorithm is based on two fundamental ideas. The first is the flux and torque producing currents. An induction motor can be modeled most simply (and controlled most simply) using two quadrature currents rather than the familiar three phase currents actually applied to the motor. These two currents called direct (I_d) and quadrature (I_q) are responsible for producing flux and torque respectively in the motor. By definition, the I_q current is in phase with the stator flux, and I_d is at right angles. Of course, the actual voltages applied to the motor and the resulting currents are in the familiar three-phase system. The move between a stationary reference frame and a reference frame, which is rotating synchronous with the stator flux, becomes then the problem. This leads to the second fundamental idea behind vector control. The second fundamental idea is that of reference frames. The idea of a reference frame is to transform a quantity that is sinusoidal in one reference frame, to a constant value in a reference frame, which is rotating at the same frequency.

II. Methods of Speed control of Induction Motor:

The various methods of speed control of 3- ϕ Induction motor are as under:

1. Pole Changing
2. Variable Supply Frequency
3. Variable rotor resistance control
4. Variable supply voltage control
5. Constant V/f control
6. Slip recovery
7. Vector Control

Some methods are explained below:

III. Variable Rotor Resistance

This method is applicable only to the wound rotor motor as external resistance can be added to it through the slip rings.

A MATLAB code was developed to observe the variation in Torque-Speed characteristics of a 3 ϕ induction motor with variable rotor resistance. Torque-Speed characteristics are shown in Figure [1]

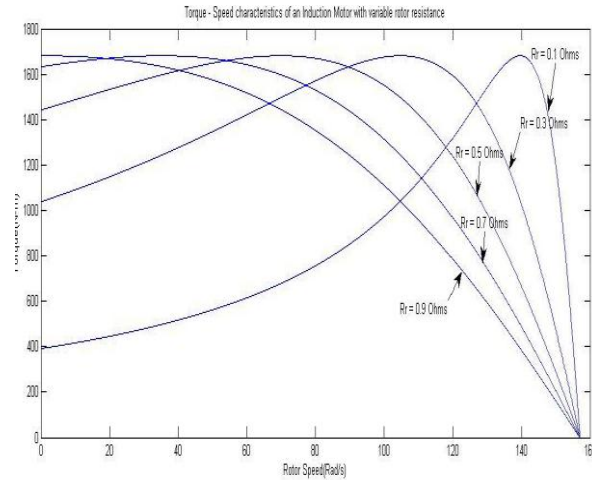


Figure [1]: Torque-Speed characteristics of a 3- ϕ IM with Variable rotor resistance.

IV. Variable Stator Voltages

The torque developed by an induction motor varies as square of the voltage applied to its stator terminals. Thus by varying the applied voltage, the electromagnetic torque developed by the motor can be varied. This method is generally used for small squirrel-cage motors where cost is an important criterion and efficiency is not.

A MATLAB code was developed to observe the variation in torque-speed characteristics of a 3- ϕ induction motor with variable stator voltage. Torque-Speed characteristics are shown in Figure [2] below.

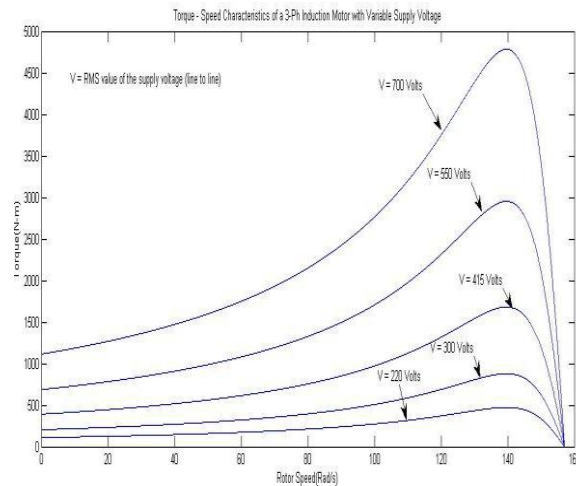
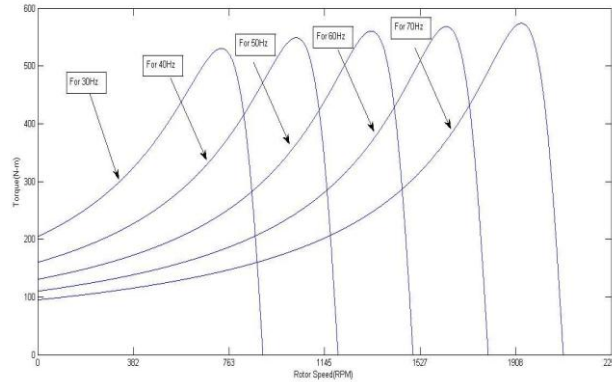


Figure [2]: Torque-Speed characteristics of a 3 ϕ IM with Variable stator voltage

V. Constant V/f Control

We vary the stator voltage in such a way that the flux remains constant by simultaneously varying the supply frequency such that the ratio V/f remains constant.

A MATLAB code was developed to observe the variation in torque-speed characteristics of a 3- ϕ induction motor with constant V/f. Figure [3]: Torque-Speed characteristics of a 3- ϕ IM with constant V/f ratio.



VI. Closed Loop V/f speed control method

The basis of constant V/f speed control of induction motor is to apply a variable magnitude and variable frequency voltage to the motor. Both the voltage source inverter and current source inverters are used in adjustable speed ac drives. The following block diagram shows the closed loop V/f control using a VSI is as shown below. A speed sensor or a shaft position encoder is used to obtain the actual speed of the motor. It is then compared to a reference speed. The difference between the two generates an error and the error so obtained is processed in a Proportional controller and its output sets the inverter frequency. The synchronous speed, obtained by adding actual speed ω_f and the slip speed ω_{sl} , determines the inverter frequency. The reference signal for the closed-loop control of the machine terminal voltage V_s is generated from frequency.

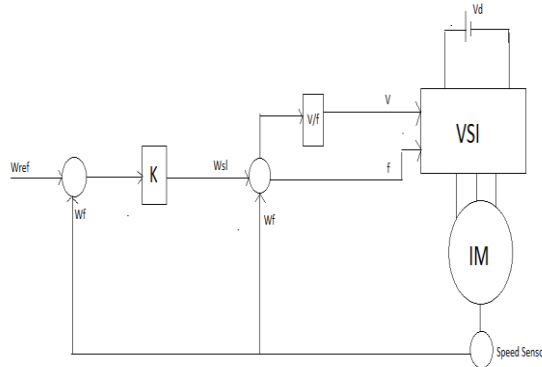


Figure [4]: Block diagram for closed loop V/f control on a 3- ϕ IM

VII. Vector Control Method

The induction motor is the most widely used electrical motor due to its rugged structure, low cost and reliability. However, the nonlinearity in the Torque-Voltage relationship of an IM makes its analysis difficult. Also it is a fifth order system making its dynamic response poor. Development of Vector Control analysis has enabled us to get as good dynamic performance from an IM as a dc motor. The torque and the flux components can be controlled independently using vector control just like in a dc motor. In order to analyses vector control, we need to develop a dynamic model of the IM. This is done by converting the 3- ϕ quantities into 2-axes system called the d-axis and the q-axis. Such a conversion is called axes transformation. The d-q axes can be chosen to be stationary or rotating. Further, the rotating frame can either be the rotor oriented or magnetizing flux oriented. However, synchronous reference frame in which the d-axis is aligned with the rotor flux is found to be the most convenient from analysis point of view. A major disadvantage of the per phase equivalent circuit analysis is that it is valid only if the three phase system is balanced. Any imbalance in the system leads to erroneous analysis. Even this problem is eradicated if we use the d-q model.

II d-q Equivalent Circuit

In many cases, analysis of induction motors with space vector model is complicated due to the fact that we have to deal with variables of complex numbers. For any space vector Y , let us define two real quantities S_q and S_d as,

$$S = S_q - j S_d \quad \dots\dots (1)$$

In other words,

$$S_q = \text{Re}(S) \text{ and } S_d = -\text{Im}(S)$$

Axes Transformation

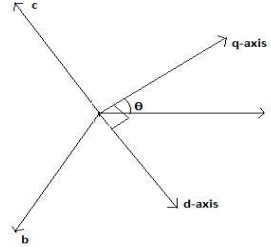


Figure [5]: Angular relationships between reference axes

$$\begin{bmatrix} V_{qs}^a \\ V_{qs}^b \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R_s + L_{sp} & \omega_a L_s & L_{mp} & \omega_s L_m \\ -\omega_a L_s & R_s + L_{sp} & -\omega_a L_m & L_{mp} \\ L_{mp} & -(\omega_a - \omega_0)L_m & R_r + L_{rp} & -(\omega - \omega_0)L_r \\ -(\omega_a - \omega_0)L_m & L_{mp} & -(\omega - \omega_0)L_r & R_r + L_{rp} \end{bmatrix} \begin{bmatrix} I_{qs}^a \\ I_{ds}^a \\ I_{qr}^a \\ I_{dr}^a \end{bmatrix} \quad (2)$$

Substituting $\omega_a = 0$, the above equation can be written as below: (This is called stationary reference frame)

$$\begin{bmatrix} V_{qs}^a \\ V_{qs}^b \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R_s + L_{sp} & 0 & L_{mp} & 0 \\ 0 & R_s + L_{sp} & 0 & L_{mp} \\ L_{mp} & -\omega_0 L_m & R_r + L_{rp} & -\omega_0 L_r \\ \omega_0 L_m & L_{mp} & \omega_0 L_r & R_r + L_{rp} \end{bmatrix} \begin{bmatrix} I_{qs}^s \\ I_{ds}^s \\ I_{qr}^s \\ I_{dr}^s \end{bmatrix} \quad (3)$$

Sometimes vector control includes calculation in rotor reference frame (frame is attached to the rotor rotating at ω_0). In this case, $\omega_a = \omega_0$ in equation 2. Hence the matrix will be changed as

$$\begin{bmatrix} V_{qs}^a \\ V_{qs}^b \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R_s + L_{sp} & \omega_0 L_s & L_{mp} & \omega_0 L_m \\ -\omega_0 L_s & R_s + L_{sp} & -\omega_0 L_m & L_{mp} \\ L_{mp} & \omega_r L_m & R_r + L_{rp} & \omega_r L_r \\ -\omega_0 L_m & L_{mp} & -\omega_0 L_r & R_r + L_{rp} \end{bmatrix} \begin{bmatrix} I_{qs}^r \\ I_{ds}^r \\ I_{qr}^r \\ I_{dr}^r \end{bmatrix} \quad (4)$$

For dynamic simulation of induction motors, equation 3 or equation 4 may be used.

Also we have

$$V_{qs} = R_s I_{qs} + p \lambda_{qs} + \omega_s \lambda_{ds} \quad (5)$$

$$V_{ds} = R_s I_{ds} + p \lambda_{ds} - \omega_s \lambda_{qs} \quad (6)$$

$$0 = R_r I_{qr} + p \lambda_{qr} + \omega_r \lambda_{dr} \quad (7)$$

$$0 = R_r I_{dr} + p \lambda_{dr} - \omega_r \lambda_{qr} \quad (8)$$

where flux linkage variables are defined by

$$\lambda_{qs} = L_s I_{qs} + L_m I_{qr} \quad (9)$$

$$\lambda_{ds} = L_s I_{ds} + L_m I_{dr} \quad (10)$$

$$\lambda_{qr} = L_m I_{qs} + L_r I_{qr} \quad (11)$$

$$\frac{d\mathbf{r}}{dt} = \mathbf{L}_m \mathbf{I}_{ds} + \mathbf{L}_r \mathbf{I}_{dr} \quad (12)$$

3- ϕ quantities converted into d-q quantities can be expressed as:

$$\mathbf{S}_{qs} = (2/3) \operatorname{Re}\{\exp(-j\phi) (\mathbf{S}_a + \alpha \mathbf{S}_b + \alpha^2 \mathbf{S}_c)\} \quad (13)$$

$$\mathbf{S}_{ds} = - (2/3) \operatorname{Im}\{\exp(-j\phi) (\mathbf{S}_a + \alpha \mathbf{S}_b + \alpha^2 \mathbf{S}_c)\} \quad (14)$$

$$\begin{bmatrix} Y_q \\ Y_q \\ 0 \end{bmatrix} = \begin{bmatrix} \cos\theta & \cos(\theta-2\pi/3) & \cos(\theta+2\pi/3) \\ \sin\theta & \sin(\theta-2\pi/3) & \sin(\theta+2\pi/3) \\ 0.5 & 0.5 & 0.5 \end{bmatrix} \begin{bmatrix} Y_a \\ Y_b \\ Y_c \end{bmatrix}$$

and its inverse transform is given by

$$\begin{bmatrix} Y_a \\ Y_b \\ Y_c \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 1 \\ \cos(\theta-2\pi/3) & \sin(\theta-2\pi/3) & 1 \\ \cos(\theta+2\pi/3) & \sin(\theta+2\pi/3) & 1 \end{bmatrix} \begin{bmatrix} Y_q \\ Y_d \\ 0 \end{bmatrix}$$

For any frame of reference, in terms of space vector instantaneous input power can be written as,
 $P_i = (3/2) \operatorname{Re}(\mathbf{V}_s \mathbf{I}_s')$

Or

$$P_i = (3/2) [V_{ds} I_{ds} + V_{qs} I_{qs}]$$

The reactive power Q_i can also be defined as

$$Q_i = (3/2) \operatorname{Im}(\mathbf{V}_s \mathbf{I}_s')$$

Or

$$Q_i = (3/2) [V_{qs} I_{ds} - V_{ds} I_{qs}]$$

Torque in terms of d-q parameters is given by

$$T_e = \frac{3}{2} P \frac{L_m}{L_r} (\lambda_{dr} i_{dr} - \lambda_{qr} i_{ds})$$

A MATLAB code was developed to observe the variations in q-axis and d-axis stator currents with change in stator voltage for a three phase induction motor.

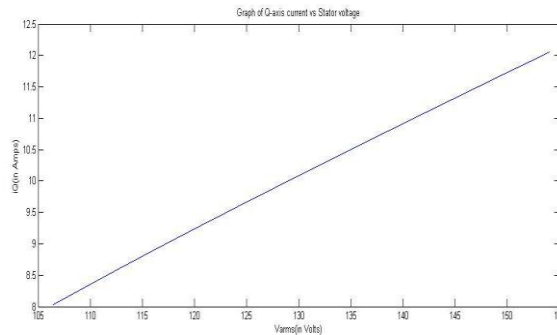


Figure [6]: Variation of q-axis stator current with change in stator voltage

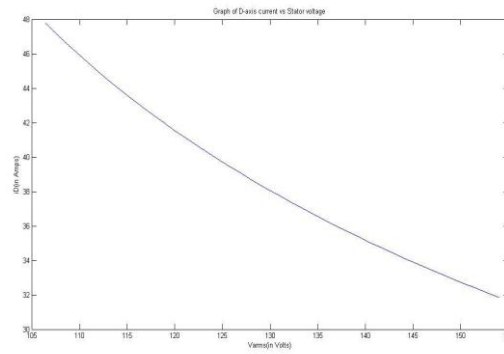


Figure [7]: Variation of d-axis stator current with change in stator voltage

Table 1: Motor rating and parameters used in MATLAB code execution for Vector control method

Rated Power	12 KW
Rated Stator Voltage (line to line)	230 V RMS
Operational frequency	50Hz
Number of Poles	4
Stator Resistance	0.095 ohms
Rotor Resistance	0.2 ohms
Stator Reactance	0.68 ohms
Rotor Reactance	0.672 ohms
Magnetizing Reactance	18.7 ohms

VIII. CONCLUSIONS

Torque-Speed characteristics for different methods of speed control of an IM were obtained and analysed for different methods.

In rotor resistance control method the starting torque can be varied with the variation of rotor resistance. The maximum torque however, remains unaffected. Thus for operations requiring high starting torque, the rotor resistance can be varied to even obtain the maximum torque during starting. But simultaneously the copper losses will increase due to increase of resistance. So this method is highly inefficient and cannot be used throughout the operation. In variable supply voltage control method of speed control, the maximum torque decreases with the decrease of supply voltage and thus the motor remains underutilized. So even this method cannot be used for good performance.

In constant v/f control, by use of rectifier and PWM inverter, we can vary the supply voltage as well as the supply frequency such that the ratio v/f remains constant so that the flux remains constant too. So we can get different operating zone for various speeds and torques and also we can get different synchronous speed with almost same maximum torque. Thus the motor is completely utilized and also we have a good range of speed control.

The vector control method or the d-q axes model leads to a simpler analysis of an induction motor. A d-q axes model with the d-axis aligned along the synchronously rotating rotor frame, leads to the decoupled analysis where the torque and the flux components can be independently controlled just like in case of a dc motor.

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