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Speed Control of Induction Motor using FOC Method

Hafeezul Haq*, Mehedi Hasan Imran**, H.Ibrahim Okumus***, Mohammad Habibullah****

*(Department of Electrical & Electronic Engineering, Karadeniz Technical University, Trabzon Turkey)
** (Department of Electrical & Electronic Engineering, Karadeniz Technical University, Trabzon Turkey)
*** (Department of Electrical & Electronic Engineering, Karadeniz Technical University, Trabzon Turkey)
**** (Department of Solar Energy, EGE University, Izmir Turkey)

ABSTRACT
An increasing number of applications in high performing electrical drive systems use nowadays, squirrel-cage induction motors. This paper describes a simplified method for the speed control of a three phase AC drive using Proportional-Integral controller. The simulation results show that the step response of the model is very fast, steady and able to work in four quadrants, and robustness and high performance is achieved.
Keywords – FOC, Induction motor, PI control, Vector control

I. Introduction

The induction motors are very common because they are inexpensive and robust, finding use in everything from industrial applications such as pumps, fans, and blowers to home appliances. Traditionally, induction motors have been run at a single speed, which was determined by the frequency of the main voltage and the number of poles in the motor. Controlling the speed of an induction motor is far more difficult than controlling the speed of a DC motor since there is no linear relationship between the motor current and the resulting torque as there is for a DC motor [1]. Moreover, in contrast to dc motors, induction motors can be used for a long time without maintenance because of their brushless structures.

The least expensive and most widely spread induction motor is the squirrel cage motor. There is no current supply needed from outside the rotor to create a magnetic field in the rotor. This is the reason why this motor is so robust and inexpensive [2].

The technique called Vector control or Field Oriented Control can be used to vary the speed of an induction motor over a wide range. It was initially developed by Blaschke (1971-1973) [3]. In the vector control scheme, a complex current is synthesised 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.

The field Oriented Control was originally developed for high-performance motor applications that are required to operate smoothly over the full speed range, generate full torque at zero speed, and have high dynamic performance including fast acceleration and deceleration. However, it is becoming increasingly attractive for lower performance applications as well due to FOC's motor size, cost and power consumption reduction superiority [4].

The vector control algorithm is based on two fundamental ideas. The first is the flux and torque producing currents [5]. An induction motor can be modelled 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 (id) and quadrature (iq) are responsible for producing flux and torque respectively in the motor. By definition, the Iq current is in phase with the stator flux, and Id 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. Once a sinusoidal quantity is transformed to a constant value by careful choice of reference frame, it becomes possible to control that quantity with traditional proportional integral (PI) controllers.

II. Vector control of Induction motor

Vector control in induction motor is about entirely orienting frequency. The proposed approach is simpler in the rotor flux in the direct-axes [6]. This is carried out by implementation and its trajectory tracking capability was using a unit vector to transform the command current in the investigated. The results show that it has a rotating d-q axis to the

stationary d-q axis. Mathematically, superior performance compared to a PI controller is made using the following equations,

$$i_{ds}* = i_{ds}\cos\theta - i_{qs}\sin\theta \tag{1}$$
$$i_{qs}* = i_{ds}\sin\theta + i_{qs}\cos\theta \tag{2}$$

where i_{ds} and i_{qs} are current commands referred to the rotating d-q axis. $i_{ds}*$ and $i_{qs}*$ are stator currents referred to the stationary d-q axis, and θ is the rotor flux angle. To achieve a dynamic performance equivalent to a separately excited dc motor, the flux command i_{ds} is usually kept constant and the torque current command i_{qs} is varied according to the speed signal command.

The current command in the real three phase abc domain can then be calculated using equations,

$$i_{a} = i_{qs}* \tag{3}$$
$$i_{b} = i_{ds}\sin(-120) + i_{qs}\cos(-120) \tag{4}$$
$$i_{c} = \sin(120) + i_{qs}\cos(120) \tag{5}$$

The relationship between abc and d-q arbitrary coordinate reference frames and decoupling between rotor fux and torque is shown the figure below,
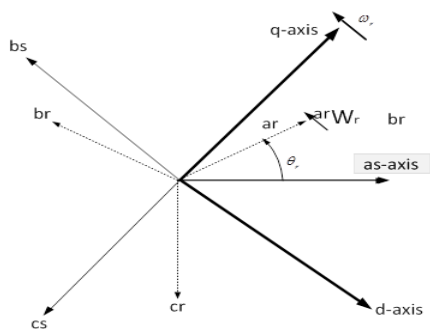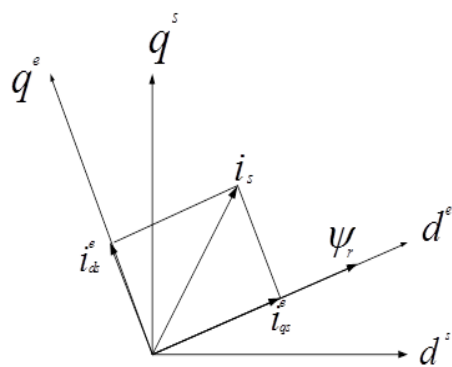

Fig 1: relationship between abc and d-q frames

Fig 2: decoupling between rotor flux and torque

III. The FOC algorithm
FOC (or vector-control) algorithm is summarized below:
1. Measure the stator phase currents ia, ib and ic. If only the values of ia and ib are measured ic can be calculated as for balanced current,

$$ia + ib + ic = 0 \tag{6}$$

2. Transform the set of these three-phase currents onto a two-axis system. This conversion provides the variables iα and iβ from the measured ia , ib and ic values where iα and iβ are time-varying quadrature current values. This conversion is popularly known as Clarke Transformation.
3. Calculate the rotor flux and its orientation.
4. Rotate the two-axis coordinate system such that it is in alignment with the rotor flux.
5. Using the transformation angle calculated at the last iteration of the control loop.
6. This conversion provides the id and iq variables from iα and iβ. This step is more commonly known as the Park Transformation.
7. Flux error signal is generate using reference flux and estimated flux value.
8. A PI controller is then used to calculate id* using this error signal.
9. Id* and iq* are converted to a set of three phase currents to produce ia*, ib*, ic*.
10. ia*, ib*, ic* and ia, ib, icare compared using hysteresis comparator to generate inverter gate signals.[8]

IV. Simulation of FOC or Vector control
4.1. System Overview
The motor to be controlled is in a close loop with the FOC block which generates switching commands for inverter to achieve the desired speed of the motor.
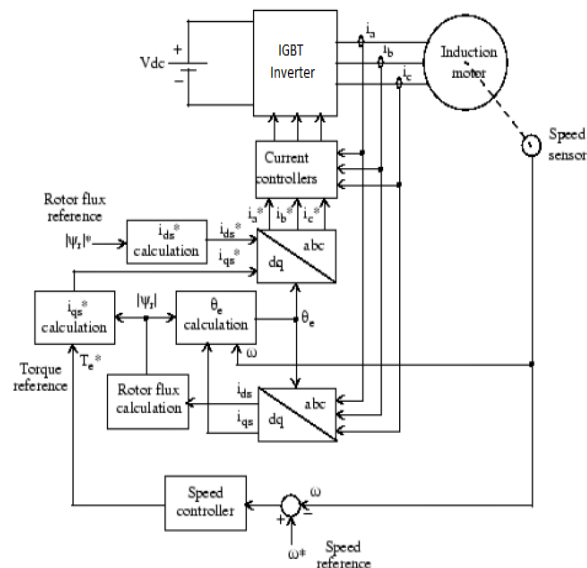

Fig 3: block diagram of vector control technique

4.2. Flux Estimator
This block is used to estimate the motor's rotor flux. This calculation is based on motor equation synthesis.[8]

$$\psi r = L_m . i_{ds}/(1 + T_r) \tag{7}$$

(Tr=Time constant)

4.3. ☐ fcalculation

This block is used to find the phase angle of the rotor flux rotating field using the following equations,

$$\theta f = \theta r + \theta m \qquad (8)$$

From which it can be established that,

$$\theta f = \int (\omega_r + \omega_m) dt \qquad (9)$$

4.4. Park Transformation

This translation of the a, b and c phase variables into dq components of the rotor flux rotating field reference frame.

4.5. Inverse Park Transformation

This conversion of the dq component of the rotor flux rotating field reference frame into a, b and c phase variables.

4.6. Current Regulator

The current regulator is a current controller with adjustable hysteresis band width. Modulation Technique used in current regulator. The hysteresis modulation is a feedback current control method. Where the motor current tracks the reference current within a hysteresis band. The operation principle of the hysteresis modulation to controller and generates sinusoidal reference current of desired magnitude frequency which then is compared to the actual motor line current. If current cross the upper limit of the hysteresis band, the upper switch of the inverter arm is turned off and the lower switch is turned on. As a result, the current starts to decrease. If the current cross the lower limit of the hysteresis band, the lower switch of the inverter arm is turned off and the upper switch is turned on. As a result, the current gets back into the hysteresis band. Hence, the actual current is forced to track the reference current within the hysteresis band.[8]

4.7. PI-Controller

Control law used for this strategy is given by,

$$T = Kp\ e + Ki \int e\ dt \qquad (10)$$

Its output is the updating in PI controller gains (Kp and Ki) based on a set of rules to maintain excellent control performance even in the presence of parameter variation and drive nonlinearity. At starting mode the high value of the error is amplified across the PI controller provoking high variations in the command torque. If the gains of the controller exceed a certain value, the variations in the command torque become too high and will destabilize the system. To overcome this problem, a limiter ahead of the PI controller is used. This limiter causes the speed error to be maintained within the saturation limits provoking, when appropriately chosen, smooth variations in the command torque even when the PI controller gains are very high. The motor reaches the reference speed rapidly and without overshoot, step commands are tracked with almost zero steady state error and no overshoot, load disturbances are rapidly rejected and variations of some of the motor parameters are fairly well dealt.[7]The motor to be controlled is in a close loop with the FOC block which generates switching commands for inverter to achieve the desired speed of the motor.

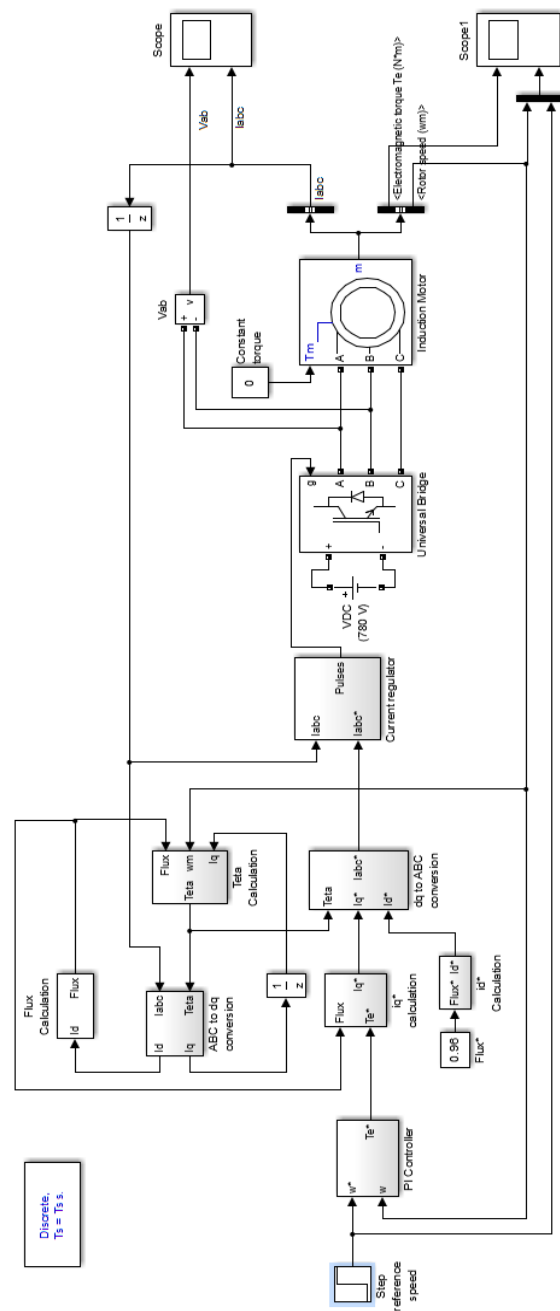## V. Simulink Model of Vector Control Induction motor

Fig 4: simulink diagram of vector control technique

VI. Simulation Results

A complete mathematical model of Vector control of induction motor with a 10 HP is simulated in MATALAB-SIMULINK. The performance of Vector control drive with proportional plus integral (PI) controller are presented and analyzed. One common linear control strategy is proportional integral (PI) control. The Induction motor used here is10 HP, 460 V, Two-pole, 60 Hz motor. The proportional gain is 166.2 and the integral gain is 27700.
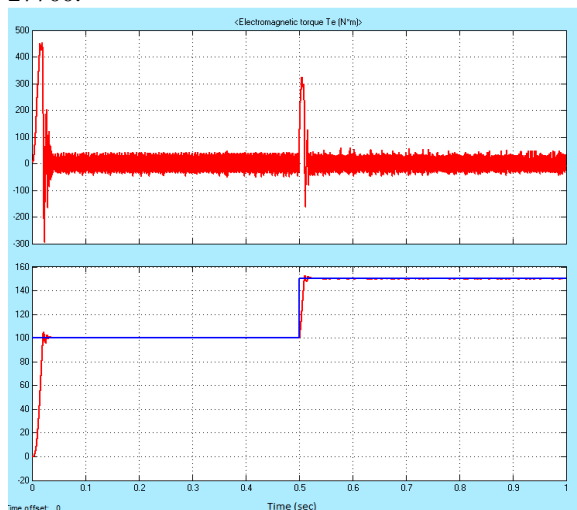

Fig 5: speed and torque simulation for the reference speed goes up from 100 (rad/s) to 150 (rad/s) at 0.5sec
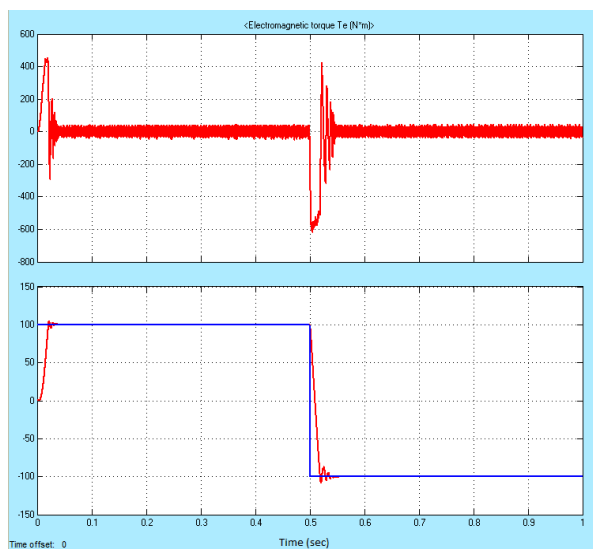

Fig 6: speed and torque simulation for the reference speed goes up from 100 (rad/s) to -100 (rad/s) at 0.5 sec.

VII. Appendix

The specifications of the Induction motor and PI controller are listed in the table below.

Table: specifications of Induction motor & controller

Motor type	10HP, 460v,60Hz
Stator resistance, R_s	0.6837 ohm
Stator inductance, L_s	0.004152 H
Rotor resistance, R_r	0.451ohm
Rotor inductance, L_r	0.004152 H
Mutual inductance, L_m	0.1486
Inertia, J	0.05 kg.m^2
No of poles	2
Proportional gain, P	166.2
Integral gain, I	27700

VIII. Conclusion

Fast response of vector control make it better than other method of speed control of induction motor, by using this method we attain maximum response in minimum time. The response is fast, accurate and give a good result for variable speed of induction motor. Here the induction motor speed control is discussed using PI controller in the field oriented coordinates. The method uses a Proportional Integral controller to adjust the motor speed based on speed errors, and draws the motor speed quickly to reference speed. The simulation results shows good performance of the designed controller that has very low overshoot.

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