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Internal Model Control Approach to PI Tunning in Vector Control of Induction Motor

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***Abstract*— This paper deals with the design of PI controllers to meet the desired torque and speed response of Induction motor drive. Vector control oriented technique controls the speed and torque of induction motor separately. This algorithm is executed in two control loops, the current loop is fast innermost and outer speed loop is slow compared to inner loop. Fast control loop executes two independent current control loop, are direct and quadrature axis current PI controllers. Direct axis current is used to control rotor magnetizing flux and quadrature axis current is to control motor torque. If the acceleration or deceleration rate is high and the flux variation is fast, then the flux of the induction machine is controlled instantaneously. For this the flux regulator is incorporated in the control loop of the induction machine. For small flux and rapid variation of speed it is difficult to obtained maximum torque. And for the high flux regulation of current is difficult because of voltage deficiency. A proportional and integral (PI) regulator solves these problems. For the reasonable performance of the flux regulation the bandwidth of the current regulator is high compared to that of the flux regulator. PI regulator, the transfer function of the closed-loop system is set to the first-order low-pass filter. The current PI controller's outputs are the corresponding d and q axis components of the decoupled stator voltage. The fast control loop executes independent control of stator current components and slow control loop executes speed controller. The PI speed regulator output sets a reference for the torque producing quadrature axis component of the stator current (i_{sq}) and the PI flux regulator sets a reference for flux producing direct axis component of the stator current (i_{sd}).**

Keywords—Internal Model Control(IMC); Vector Control; Induction Motor; Speed regulator; Current regulator

I. NOMENCLATURE

ω_r	Rotor angular speed
ω_s	Synchronous speed
T_L	Load Torque
R_s, R_r	Resistance of stator and rotor windings
L_s, L_r	Self-inductance of stator and rotor windings
L_m	Mutual inductance
P_p	Number of pole pairs
V_{ds}	Direct-axis stator voltage component
V_{qs}	Quadrature axis voltage component
i_s	Space phasor of stator current
i_r	Space phasor of rotor current
i_{ds}	Direct axis stator current component
i_{qs}	Quadrature axis rotor current component
ψ_r	Space phasor of rotor flux linkages
ψ_{dr}	Direct axis rotor flux linkages
ψ_{qr}	Quadrature axis flux linkages
T_r	Rotor time constant
J	Motor Inertia

II. INTRODUCTION

HIGH-SPEED capability machines are needed in numerous applications for example, pumps, ac servo, traction and shaft drive. In Induction Motor this can be easily achieved by means of vector Control/field orientation control methodology [6]. And hence Field orientation control of an Induction Motor is widely used control strategy in the industry due to its high reliability [1]-[3]. In Field Orientation Control or Vector control, which is a variable frequency drive, a resultant vector of magnetic flux and torque realizes stator current and voltages. Using Vector control we can achieve the independent control over flux and torque [4] Different control methodologies have been studied and implemented along with field orientation control in last few decades for controlling the induction motor like open loop v/f control, v/f control with slip compensation. V/F control is least preferred control strategy because at low speed, resistive term dominates flux linkage which leads to sudden drop in magnetizing flux up to zero levels. To flourish the performance of Induction motor at low speed, method used is popularly known as voltage boost. It allows torque speed curve to become independent of electrical frequency [5]. According to current industry trend, PID controllers are most preferred controllers in industry. In this paper the Indirect Vector Control method is used for IM control over a wide range. The method consists of 3-PI controllers. Tuning a multiple PID's is a tedious job as algorithm presented in [6] for achieving the maximum torque is rather complex, requiring the tuning of several PI regulators (two PI regulators are used for the current regulation, another one for the speed regulation). While tuning multi-loop PID's, Inner loop must be faster as compared to outer loop. Most of the time for PID tuning trial and error method is used. But its very time consuming. This makes difficult to obtain an optimal controller gains to get excellent control over wide speed and torque range. In this paper the formula for PID gain calculation is derived. The PID's are tuned and model is simulated on Real Time simulator OPAL-RT (OP4500). The field-oriented control utilizes the stator current components as control variables. The d-component of the stator current acts on the rotor flux, whereas the q-component is proportional to the motor torque as the control of the motor flux is obtained indirectly by controlling the motor currents.

III. INDUCTION MOTOR MODELLING

Induction motor is modelled in a d-q Stationary reference frame given by the equations of the fluxes and voltages as

$$V_{ds} = R_s i_{ds} + \frac{d}{dt}\psi_{ds} - \omega_s \psi_{qs} \quad (1)$$

$$V_{qs} = R_s i_{qs} + \frac{d}{dt}\psi_{qs} - \omega_s \psi_{ds} \quad (2)$$

$$0 = R_r i_{dr} + \frac{d}{dt}\psi_{dr} - (\omega_s - \omega_r)\psi_{qr} \quad (3)$$

$$0 = R_r i_{qs} + \frac{d}{dt}\psi_{qr} - (\omega_s - \omega_r)\psi_{dr} \quad (4)$$

The rotor flux linkages in the reference frame fixed to the rotor ($\psi_{\alpha r}$ $\psi_{\beta r}$) are related to the rotor flux-linkages components expressed in the stationary reference frame (ψ_{dr} ψ_{qr}) by the transformation $e^{j\theta_r}$. Thus the following equation holds,

$$\overrightarrow{\psi_r} = \psi_{dr} + j\psi_{qr} \quad (5)$$

$$\overrightarrow{\psi_r} e^{j\theta_r} = (\psi_{\alpha r} + j\psi_{\beta r})e^{j\theta_r} \quad (6)$$

In matrix form:-

$$\begin{bmatrix}\psi_{dr}\\ \psi_{qr}\end{bmatrix} = \begin{bmatrix}cos\theta_r & -sin\theta_r\\ sin\theta_r & cos\theta_r\end{bmatrix}\begin{bmatrix}\psi_{\alpha r}\\ \psi_{\beta r}\end{bmatrix} \quad (7)$$

$$\psi_{ds} = L_s i_{ds} + L_m i_{dr}$$
$$\psi_{qs} = L_s i_{qs} + L_m i_{qr}$$
$$\psi_{dr} = L_r i_{dr} + L_m i_{ds}$$
$$\psi_{qr} = L_r i_{qr} + L_m i_{qs}$$

Based on rotor flux linkages and stator current, the torque is expressed as:

$$T_e = P_p \frac{Lm}{L_r}(i_{qs}\psi_{dr} - i_{ds}\psi_{qr}) \quad (8)$$

From the field orientation condition i. e. $\psi_{qr} = 0$ torque equation is written as:

$$T_e = P_p \frac{Lm}{L_r}(i_{qs}\psi_{dr}) \quad (9)$$

The slip angular frequency is represented in terms of rotor flux linkage and q-axis current as:

$$\omega_s - \omega_r = \omega_{sl} = -\frac{R_r i_{qr}}{\psi_{dr}} = \frac{R_r}{\psi_{dr}}\frac{Lm}{L_r} i_{qs} \quad (10)$$

Under the condition of the constant rotor flux linkages, instantaneous torque of the induction machine is directly proportional to the q-axis stator current. Hence, it is called as torque component current and d-axis stator current regulates rotor flux linkages. After calculating slip frequency with the required torque and flux component current, the instantaneous angle of the rotor flux is expressed as:

$$\theta_r = \int_0^t \omega_s d\tau = \int_0^t \omega_r + \omega_{sl} d\tau \quad (11)$$

Adjusting the slip angular frequency indirectly controls the position of the rotor flux. Using this process, the stator current is decomposed to the torque and flux component.

IV. INDIRECT VECTOR CONTROL

Induction machines have been utilized for over a hundred years. Because of their simplicity, ruggedness, reliability, efficiency, low cost, compactness, economical and volume manufacturing advantages. Induction machines with a squirrel cage rotor are the most widely used machines at fixed speed. The dynamic model of an induction machine can be expressed by sixth-order state space matrix. Which consists of stator voltage and frequency as inputs and the outputs can be rotor speed, rotor position, electromagnetic torque, stator-rotor flux linkages, magnetic flux linkages, stator-rotor currents and magnetizing current or a combination of these. Induction machine can have different rotor windings viz. a wound rotor (slip ring machine) or a squirrel cage windings. The vector control of an induction machine is possible in both types of windings. The fundamental part in vector control is to get a correct space angle, which is the imperative work. The space angle between field winding and stator direct axis as well as magnetic flux and stator direct axis can be directly measured in case of an electrically exited synchronous machine and permanent magnet synchronous machine but not in case of an Induction machine. Furthermore in case of the converter-fed induction machine as there is no external excitation both reactive (excitation) and active (torque producing) currents must simultaneously exist in the stator winding. It has been proved that in special reference frame fixed to magnetizing and stator or rotor flux linkages space phasor, the expression for the electromagnetic torque of the smooth air gap machine is similar to that of separately excited D.C. machine. This recommends that torque and speed control of an induction machine can achieve by decoupled control of flux and torque producing component of stator currents, which is similar to the field and armature currents in separately excited D.C. machine. The stator currents can be separated into flux and torque producing component by utilizing transformations In case of an induction machine rotor flux oriented control is usually employed, the modulus and space angle of the rotor flux linkages space phasor are obtained by utilizing the measured stator currents and the rotor speed [8]. As shown in Fig 1 number of PI's are involved in precise control of an induction motor. In such case trial and error method of PI tuning is not useful in addition to this tuning by Ziegler Nichols method is also not useful as the to get the transfer function of such interconnected PI system is not that simple. In next section the more useful and easier method of PI tuning is discussed.

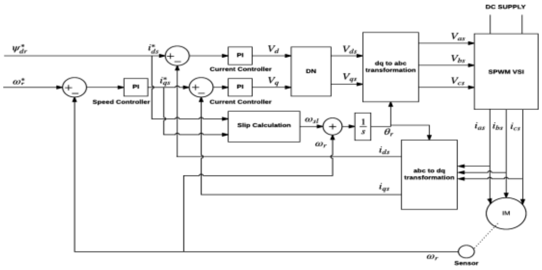


Fig 1: Indirect Vector Control of Induction Motor

V. INTERNAL MODEL CONTROL

The Internal Model Control (IMC) philosophy relies on the Internal Model Principle, which states that control can be achieved only if the control system encapsulates, either implicitly or explicitly, some representation of the process to be controlled. In particular, if the control scheme has been developed based on an exact model of the process, and then perfect control is theoretically possible [9]. In practice, however, process-model mismatch is common; the process model may not be invertible and the system is often affected by unknown disturbances. The effects of process model mismatch should be minimized. Since discrepancies between process and model behavior usually occur at the high frequency end of the system's frequency response, for process-model mismatch attenuation a low-pass filter is usually added. The Behavior of an AC machine is like a separately exited DC machine in steady state. An inverter fed Induction motor drive's steady state performance; it is comparable to a separately excited DC machine. Vector Control of an AC machine has been evolved to such extend that it makes possible to control of AC machine in similar manner that of separately excited DC motor. In this paper our main focus is on the controller tuning. Control of Induction motor mainly consists of a Speed and Torque control.

A. Speed Regulator :

Fig 2 shows the typical block diagram of speed regulator. In speed control, the aim is to control mechanical speed of an induction motor as per the reference has been set. The reference is compared with the mechanical rotor speed measured using speed sensor. Here, the error (the slip speed) should be zero. In industry, most widely used controller for regulation purpose is PID controller. Transfer function of PI controller is given as: -

$$G(s) = K_p + \frac{K_i}{s} \tag{12}$$

We have a relation between slip speed and q-axis stator current

$$\omega_{sl} = \frac{1}{T_r i_{ds^e}} (1 + sT_r) i_{qs}^e \tag{13}$$

$$i_{qs}^e = \frac{\omega_{sl} T_r i_{ds}^e}{(1+sT_r)} \tag{14}$$

Transfer function: -

$$T.F. = \frac{O/P}{I/P} = \frac{i_{qs^e}}{\omega_{sl}} = \frac{T_r i_{ds}^e}{(1+sT_r)} (K_p + \frac{K_i}{s}) \tag{15}$$

Equate with first order low pass filter

$$\frac{\omega_c}{(s+\omega_c)} \tag{16}$$

$$\frac{\omega_c}{s+\omega_c} = \frac{(T_r i_{ds}^e)(sK_p+K_i)}{s(1+sT_r)} \tag{17}$$

$$T_r \omega_c s^2 + \omega_c s = T_r i_{ds}^e (sK_p + K_i)(s + \omega_c) \tag{18}$$

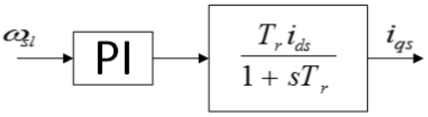


Fig 2: Speed Regulator

$$\frac{T_r \omega_c}{T_r i_{ds}^e} s^2 + \frac{\omega_c}{T_r i_{ds}^e} = s^2 K_p + sK_i + s\omega_c K_p + \omega_c K_i \tag{19}$$

$$= s^2 K_p + s(K_i + \omega_c K_p) + \omega_c K_i \tag{20}$$

By equating R.H.S. and L.H.S., we get.

$$K_p = \frac{\omega_c}{i_{ds}^e} \tag{21}$$

$$K_i = (\frac{1}{T_r} - \omega_c) K_p \tag{22}$$

B. Current Regulator

Fig 3 shows the typical block diagram of current regulator. The driving force or torque of an induction motor is a function of current flowing through a converter. So for proper control of torque, controlling a current is important. Current regulator is design like a first order low pass filter. Gains for PI controller of current regulator are given as:-

$$\frac{\left(K_p+\frac{K_i}{s}\right).(\frac{1}{sL_S+R_S})}{1+\left(K_p+\frac{K_i}{s}\right).(\frac{1}{sL_S+R_S})} = \frac{\omega_{cc}}{s+\omega_{sc}} \tag{23}$$

$$K_p = L_s \omega_{cc} \tag{24}$$

$$K_i = R_s \omega_{cc} \tag{25}$$

VI. REAL TIME SIMULATOR

Opal-RT provides extremely high accuracy that allows great fidelity of testing. Opal-RT OP4500 is completely incorporated with Simulink, SimPower, SimScape, HYPERSIM and OPAL-RT eHS FPGA power electronic circuit solver, which brings fast, accurate, reliable power system simulation with complex high voltage alternating current networks. The model considered has the capability of simulating 75 nodes at a time and is packed with an Intel Xeon Quad-Core Processor with a clock of 3.4 GHz. The Opal-RT system bundle consists of the Opal-RT hardware and Accessories, RT-LAB Real Time Suite and the License. Real time simulator needs discrete time step solvers. While using discrete time-step solver, sampling time or step size must be appropriately chosen so as to avoid overruns during simulation. The performance of induction motor as per the set gains is validated using above real time simulator.

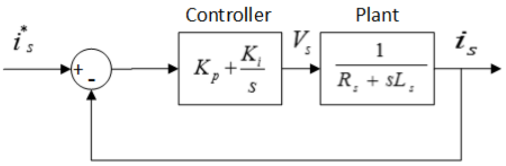


Fig 3: Current Regulator

VII. SIMULATION RESULTS

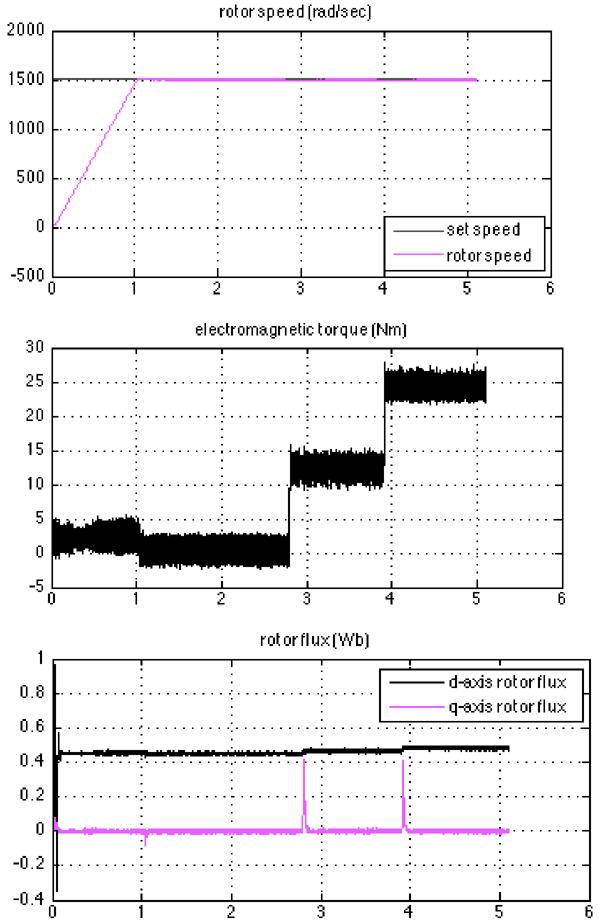
A. Motor Parameters:

Nominal Power	5.4 HP (4 KW)
Voltage (L-L)	400 V
Frequency	50 Hz
R_s, R_r	1.405 Ω, 1.395 Ω
L_s, L_r	0.1780 H, 0.1780 H
L_m	0.1722 H
P_p	2
J	0.0131 (Kg.m^2)

B. Simulation Results:

The techniques presented here were tested using an induction motor drive. The motor parameters are shown in Table I. An Internal Model Control based indirect vector control was implemented with proper bandwidth of speed and current control loops. Fig. 4 shows response of a system at 1500 rpm with step change (100%) in torque and observes that speed will be constant throughout. As torque is increases there is dip in motor speed and i_{qs} is increases proportionally with respect to torque. Maintaining q-axis rotor flux at zero satisfies criterion of rotor flux field orientation.

Fig. 5 shows response of system at rated torque (12 Nm) with step change in speed and observes that motor speed is tracking the speed set point. As maintain constant torque i_{qs} is constant and rotor flux is also constant.



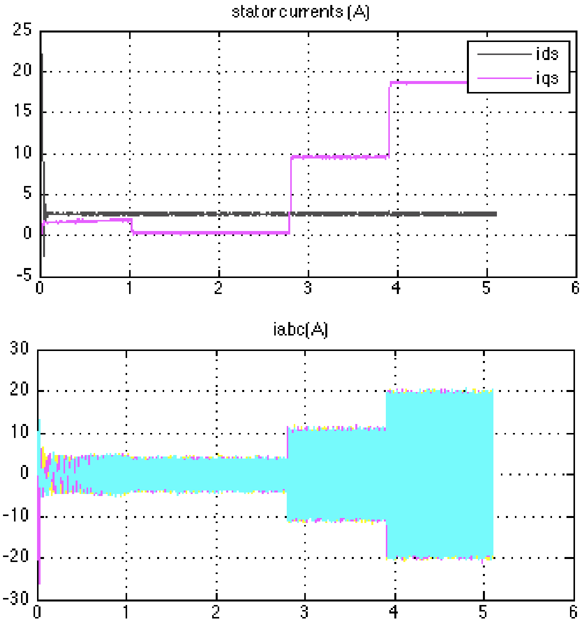
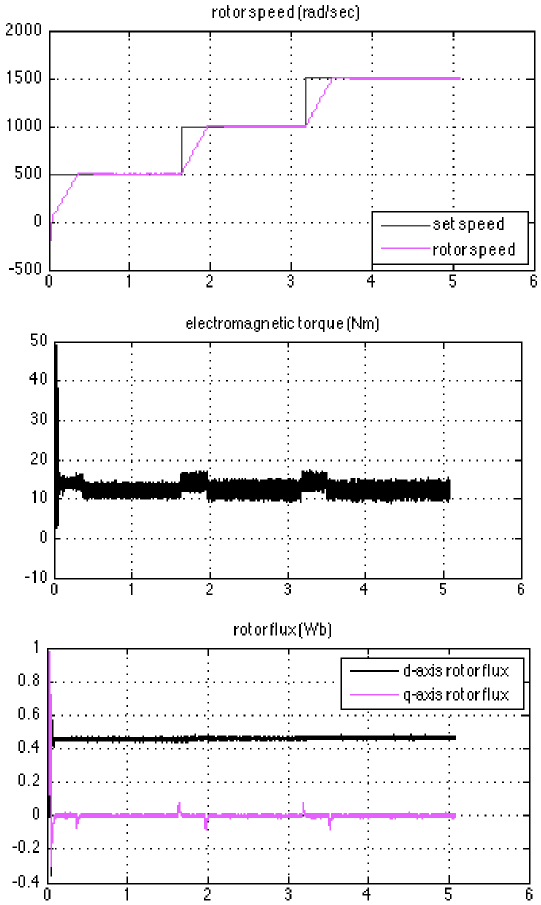


Fig 4: Response of proposed system at 1500 rpm with step change in load torque



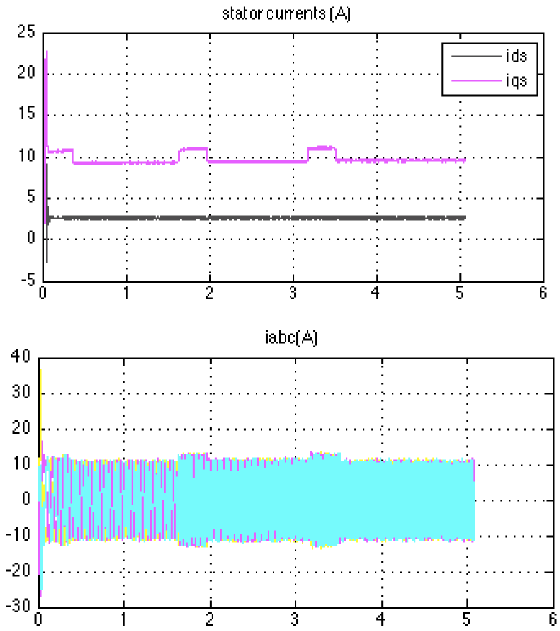


Fig 5: Response of proposed system at rated torque (12Nm) with step change in speed

VIII. CONCLUSION

The indirect field orientation of IM drive is implemented in this paper. The IMC method that is simple to use has been presented to design PI controller gains giving satisfied performance at low as well as high speed. This paper shows a relation for proportional and integral gains in terms of motor parameters. Therefore, results obtained can be applied to many applications. Synthesis of controller has been presented. Digital simulations over Opal-RT (Real Time Simulator) have been carried out in order to validate the effectiveness of the proposed scheme. The simulation results shows that the proposed drive response has many advantages; very fast response, robustness against parameter uncertainties and load changes, well tracking of trajectory at low speeds.

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