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Internal Model Based Vector Control of Induction Motor

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ABSTRACT: *This paper deals with the design of PID and Internal Model Controllers (IMC) in adjusting the speed of induction machine under disturbances and set point changes. The performance of PID controller is compared with IMC. The internal model control is an alternative to the classic feedback structure. Internal model control is composed of an inverse model connected in series with the plant and a forward model connected in parallel with the plant, this structure allows the error feedback to reflect the effect of disturbances and plant mismodelling resulting in a robust control loop. The IMC provides good performance and robustness against the disturbances in system when compared with the PID controller. A simulation study of these methods is presented using MATLAB/SIMULINK.*
Keywords: *Indirect Vector control, Internal Model control, PID controller, Ziegler-Nichols rules, Induction motor.*

I. Introduction

The induction motor is widely used in industry because of its reliability and low cost. However, since the dynamical model of induction motor is strongly nonlinear, the control of induction motor is a challenging problem and has attracted much attention. Many control methods like Field-oriented control (FOC), Direct torque control (DTC) [1]-[3] have been proposed.

FOC or vector control of an induction machine achieves decoupled torque and flux dynamics leading to independent control of the torque and flux as for a separately excited DC motor. FOC methods are attractive but suffer from one major disadvantage: they are sensitive to motor parameter variations and sufferers from an incorrect flux measurement. The advent of vector control techniques has partially solved induction motor control problems. Consequently performance deteriorates and a controller is required to meet the desired specifications.

In this paper the design controllers such as PID [4], [5] and Internal Model Control (IMC) [6] are used along with indirect vector control to maintain satisfactory performance under set point changes and load disturbances.

The remainder of the paper is organized as follows: Section 2 introduces the model of induction motor. Section 3, 4 describes the design control schemes such as PID and IMC controllers. Section 5 presents simulation results. Section 6 concludes the paper

II. Model Of Induction Motor

The d-q axis dynamic equations for the squirrel cage induction motor with the reference frame fixed to the stator are given by following equations [7].

Voltage Equations

$$
\begin{aligned}
&v_{qs}^{s} = r_s i_{qs}^{s} + \frac{1}{\omega_b}\frac{d}{dt}\psi_{qs}^{s} \qquad v_{qr}^{'s} = r'_r i_{qr}^{'s} + \frac{1}{\omega_b}\frac{d}{dt}\psi_{qr}^{'s} - \frac{\omega_r}{\omega_b}\psi_{dr}^{'s} \\
&v_{ds}^{s} = r_s i_{ds}^{s} + \frac{1}{\omega_b}\frac{d}{dt}\psi_{ds}^{s} \qquad v_{dr}^{'s} = r'_r i_{dr}^{'s} + \frac{1}{\omega_b}\frac{d}{dt}\psi_{qr}^{'s} - \frac{\omega_r}{\omega_b}\psi_{dr}^{'s} \\
&v_{0s}^{s} = r_s i_{0s}^{s} + \frac{1}{\omega_b}\frac{d}{dt}\psi_{0s}^{s} \qquad v_{0r}^{'r} = r'_r i''^{r}_{0r} + \frac{1}{\omega_b}\frac{d}{dt}\psi_{0r}^{'r}
\end{aligned} \tag{1}
$$

Flux linkage Equations

$$\begin{bmatrix} \psi_{qs} \\ \psi_{ds} \\ \psi_{0s} \\ \psi'_{qr} \\ \psi'_{dr} \\ \psi'_{0r} \end{bmatrix} = \begin{bmatrix} x_{ls}+x_m & 0 & 0 & x_m & 0 & 0 \\ 0 & x_{ls}+x_m & 0 & 0 & x_m & 0 \\ 0 & 0 & x_{ls} & 0 & 0 & 0 \\ x_m & 0 & 0 & x'_{lr}+x_m & 0 & 0 \\ 0 & x_m & 0 & 0 & x'_{lr}+x_m & 0 \\ 0 & 0 & 0 & 0 & 0 & x'_{lr} \end{bmatrix} \begin{bmatrix} i^s{}_{qs} \\ i^s{}_{ds} \\ i^s{}_{0s} \\ i'_{qr} \\ i'_{dr} \\ i'_{0r} \end{bmatrix} \quad (2)$$

Torque Equation

$$T_e = \frac{P_m}{\omega_m} = \frac{3}{2}\left(\frac{p}{2\omega_b}\right)(\psi^s{}_{ds} i^s{}_{qs} - \psi^s{}_{qs} i^s{}_{ds}) \quad (3)$$

$[i^s{}_{qs} \quad i^s{}_{ds}]$ d- and q-axis stator currents

$[i^s{}_{qr} \quad i^s{}_{dr}]$ d- and q-axis rotor currents

$[v^s{}_{qs} \quad v^s{}_{ds}]$ d- and q-axis stator voltages

$[v^s{}_{qr} \quad v^s{}_{dr}]$ d- and q-axis rotor voltages

The field orientation principle is based on the following conditions which are expressed in the synchronous reference frame .The resultant rotor flux linkage, λ_r , is assumed to be on the direct axis to reduce the number of variables in the equations by one. Hence, rotor flux phasor is aligned along with d-axis yields

$$\lambda_r = \lambda^e_{dr} \qquad \lambda^e_{qr} = 0 \quad (4)$$

Under these conditions, the induction machine is transformed into a linear current/torque converter:

$$T_e = K_{te}\lambda_r i_T \quad (5)$$

where $K_{te} = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r}$

The equations ensuring the indirect field orientation are expressed as

$$i_f = i_{ds} = \frac{1}{L_m}[1+T_r\frac{d}{dt}]\psi_{dr} \quad (6)$$

$$\omega = \omega_r + \omega_{s1} = \omega_r + \frac{i_T}{i_f}\left(\frac{R_r}{L_r}\right) \quad (7)$$

$$\theta_s = \int(\omega_r + \omega_{sl})dt \quad (8)$$

$$\theta_f = \theta_s = \theta_r + \theta_{sl} \quad (9)$$

where $i_f = i^e_{ds}$

$i_T = i^e_{qs}$

The field-oriented control block receives the computed torque/current from the speed controller and the flux from the field weakening block. In the look-up table used for field-weakening, the flux is assumed to be constant when the motor operates below the rated speed, and beyond the rated speed the flux speed product is held constant. The overall block diagram of a current controlled induction motor with indirect field orientation is given in Figure.1.

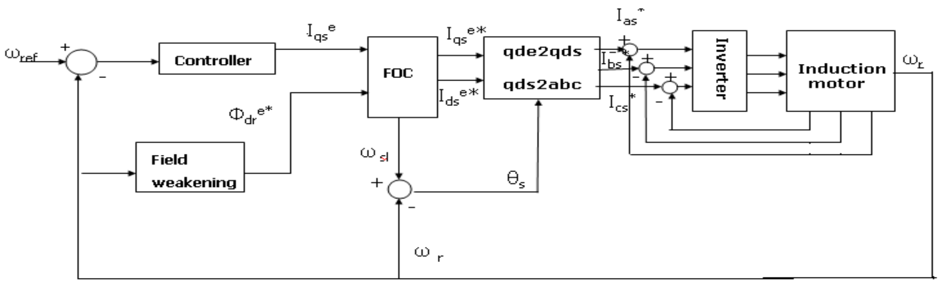


Figure.1 Speed control of current regulated indirect field oriented induction motor

The FOC block performs the slip calculation and generates $i_{ds}^{e\,*}$ and $i_{qs}^{e\,*}$. Inside the qde to the abc transformation block, the following transformations are performed:

qde to qds
$$\begin{aligned} i_{qs}^{s\,*} &= i_{qs}^{e\,*}\cos\theta_s + i_{ds}^{e\,*}\sin\theta_s \\ i_{ds}^{s\,*} &= -i_{qs}^{e\,*}\sin\theta_s + i_{ds}^{e\,*}\cos\theta_s \end{aligned} \tag{10}$$

qds to abc
$$\begin{aligned} i_{as}{}^{*} &= i_{qs}^{s\,*} \\ i_{bs}{}^{*} &= -\frac{1}{2}i_{qs}^{s\,*} - \frac{\sqrt{3}}{2}i_{ds}^{s\,*} \\ i_{cs}{}^{*} &= -\frac{1}{2}i_{qs}^{s\,*} + \frac{\sqrt{3}}{2}i_{ds}^{s\,*} \end{aligned} \tag{11}$$

Here θ_s represents the sum of slip and rotor angles.

A sinusoidal current source of variable magnitude and frequency is used to represent the fundamental component of the actual inverter waveform. This avoids lengthy simulation times caused by the inverter switching.

III. PID Control

In feedback control system, the control device is made of the controller only as shown in Figure. 1

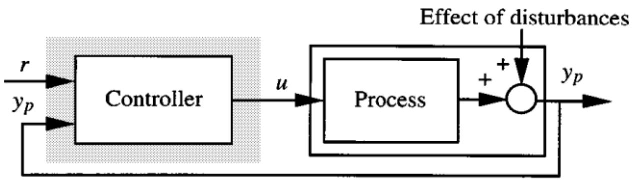


Figure.2 Feedback control system

The family of PID controllers is constructed from various combinations of the proportional, integral and derivative terms as required to meet specific performance requirements.

The formula for the basic parallel PID controller is

$$G_C(s) = \left[K_P + K_I\frac{1}{s} + K_D s\right]E(s) \tag{12}$$

Time constant form of eq.(12) is of the form

$$G_C(s) = K_P\left[1 + \frac{1}{s\tau_i} + \tau_d s\right]E(s) \tag{13}$$

where $\tau_i = \frac{K_I}{K_P}$ and $\tau_d = \frac{K_D}{K_P}$

Ziegler-Nichols Rules for Tuning of PID Controller

Ziegler-Nichols proposed rules for determining values of the proportional gain K_p, integral time T_i, and derivative time T_d based on the transient response characteristics of a given plant. The dynamics of a process can be determined from the response of a process to the step input [4]. From the transient response method a simple model of process is obtained. The model obtained is used for PID controller tuning.

The response of a plot for a unit step input is like an S-shaped curve as shown in Figure.3

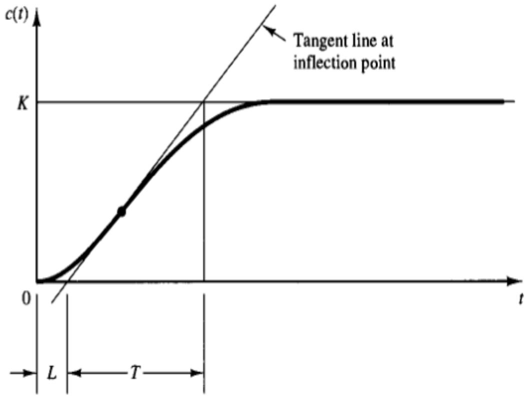


Figure.3 Step response of the process

The S-shaped curve is characterized by two constants delay time L and time constant T. L and T are determined by drawing a tangent line at the inflection point of S-shaped curve and determining the intersections of tangent line with time axis as shown in Fig 3.4. Ziegler-Nichols suggested setting the values of K_p, T_i and T_d according to the formula shown in table.1

Table.1.Tuning Parameters of PID Controller

	K_p	T_i	T_d
P	T/L	∞	0
PI	0.9T/L	L/0.3	0
PID	1.2T/L	2L	0.5L

Design of PID controller for Induction motor

In order to illustrate the performance of PID controller under disturbances let us consider the induction motor. The design of PID controller through Z-N method is based on the step response of the original system required [6]. Hence, let us consider the induction motor which is considered in section 2.11 for the design of PID controller.

The step response of the Induction motor is as shown in Figure.3.4. From the response the parameters delay time (L) and time constant (T) are determined by drawing a tangent line at the inflection point of S-shaped curve and determining the intersections of tangent line with time axis.

From Figure.4 the parameters L and T are as follows.

L=0.016

T=0.124

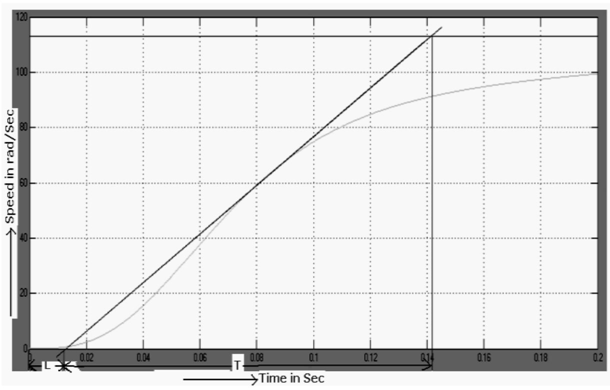


Figure.4 Step response of Induction Motor

From the Table.1 and Eq.3.6, the tuning parameters of PID controller for the Induction motor based on the Ziegler-Nicholes step response method is given as follows.

K_p= 9.3

K_i = 0.283

K_d =0.072

IV. Internal Model Control

The internal model control is an alternative to the classic feedback structure. Internal model control is composed of an inverse model connected in series with the plant and a forward model in parallel with the plant, this structure allows the error feedback to reflect the effect of disturbance and plant mismodelling resulting in a robust control loop [5].

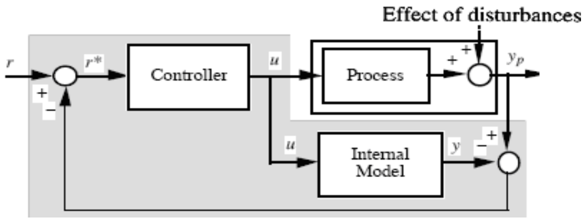


Figure.5 Internal model control system

It includes two blocks labeled controller and internal model. The control system has inputs as the set points and process output y_p and output as manipulated process input 'u' as shown in Figure.4.1. The internal model is connected in parallel to the process. It is also called process model. The effect of parallel path with the model is to subtract the effect of manipulated variables from the process output. If model is perfect representation of the process, then the feed back signal equal to the influence of disturbances and is not affected by the action of the manipulated variables. Thus the system is efficient open loop and the usual stability problems associated with feedback have disappeared the over all system is simply stable if and only if both the process and the IMC controller are stable.
The IMC design is followed by two step design procedure [5]. In step 1 controller is designed for optimal set point tracking i.e. disturbance rejection without regards for model uncertainty. In step 2 the controller is detuned for robust performance.

Procedure for design of IMC controller
Let us consider the following notations in internal model control: Input v ,Process model $\tilde{p}$, Inverse model $\tilde{q}$.
The IMC design procedure consists of the two steps

***Step 1*: Nominal Performance**
Model inverse 'q' is selected to yield good system response for the inputs without regard for constraint and model uncertainty. The selection of 'q' is such that it is H_2 Optimal for a particular input v .Thus $\tilde{q}$ has to solve

$$\min_{\tilde{q}} \| e \|_2 = \min_{\tilde{q}} \| (1 - \tilde{p}\tilde{q}) v \|_2 \qquad (14)$$

Subjected to constraint that $\tilde{q}$ is stable and causal. The Eq. (14) reaches to the absolute minimum for

$$\tilde{q} = \frac{1}{\tilde{p}} \qquad (15).$$

The model inverse is an acceptable solution for Minimum Phase systems.
Step 2: Robust stability and performance
$\tilde{q}$ is augmented with a low pass filter f to achieve robust stability and performance. That is

$$q = \tilde{q} f \qquad (16)$$

Internal model control algorithm
The internal model is summarized by following algorithm.

i. *Model design*: the process model is connected in parallel with the plant. Obtain the internal model or forward model of the plant based on the reduced model of the plant. The process model is considered as the Minimum Phase system i.e. there are no zeroes in the right half of the plane.
ii. *Inverse model design*: The inverse model must be connected in series with the plant. The model inverse is an acceptable solution for Minimum Phase systems. The inverse model is selected to yield good system response for the given input and the controller must be H_2 optimal.
iii. *IMC Filter design*: In general the inverse model exhibit undesirable behavior in response. For robustness inverse model has to be augmented by a low pass filter.

IMC design for Induction Motor

(a)Process model

Process model of the indirect vector controller induction motor drive **is** given by

$$\tilde{p} = \frac{\omega_r(s)}{I_T(s)} = \frac{K_m}{1+sT_m} \tag{17}$$

Where $K_m = \frac{P}{2}\frac{K_t}{B_t}$; $B_t = B + B_l$; $T_m = \frac{J}{B_t}$;

ω_r is the rotor speed

$I_T = I_{qs}$ is torque producing component of current

The process considered is a minimum phase system

(b)Inverse model

For the minimum phase system, the model inverse is given by Eq.15

$$\tilde{q} = \frac{I_T(s)}{\omega_r(s)} = \frac{1+sT_m}{K_m} \tag{18}$$

(c)IMC filter

The simplest form of filter is of the form

$$f(s) = \frac{1}{(\lambda s+1)^n} \tag{19}$$

Filter parameter n is selected as 1 for Minimum phase system. Adjusting λ is equivalent to adjusting the speed of closed loop response.

In order to get robust stability IMC filter is augmented with inverse model as in Eq. (16). The controller q along with the model inverse and filter of induction motor is as shown.

$$q = (\frac{1+sT_m}{K_m})(\frac{1}{1+\lambda s}) \tag{20}$$

The block diagram of internal model control for induction motor is as shown in Figure.6.

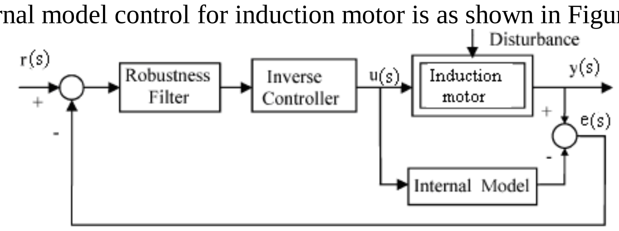


Figure.6 Block diagram of IMC for Induction motor

V. Simulation Results

In order to evaluate the performance of induction motor, the Simulink model for the given induction motor has been developed. Induction Motor with the following parameters has been considered:

3 phase, 20 hp, 220 V, 4-pole

Frequency:	60 Hz
Stator resistance (rs):	0.1062 ohm
Rotor resistance (rr′):	0.0764 ohm
Stator inductance (Ls):	0.01604H
Rotor inductance (Lr′):	0.01604H
Magnetizing inductance (Lm):	0.01547H

In simulation, Load variations are applied 0 to -80 N-m and 0 to 40 N-m at 0.5sec and 0.8 sec, respectively. Consider the set point changes at 0.2 sec and 0.4 sec. Due to the load variations and set point changes the IVC based induction motor undergoes large fluctuations in speed response as shown in Figure.7.it is not going to attain the reference speed.

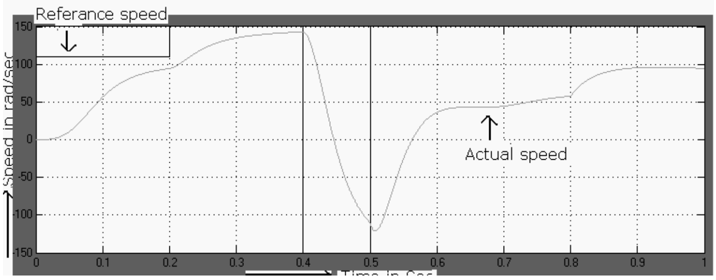
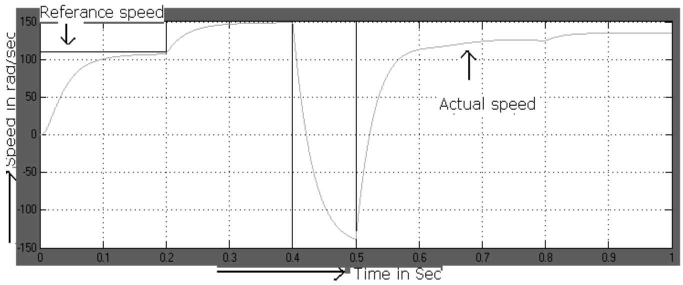
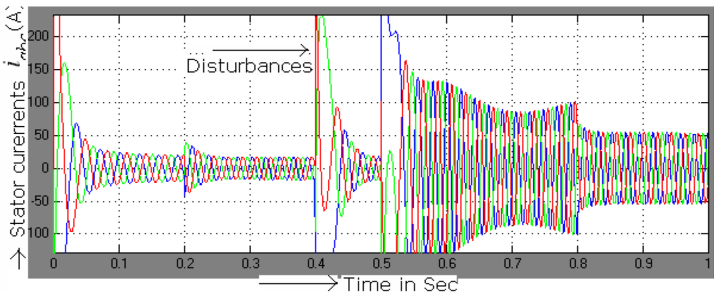


Figure.7 Speed response of IVC based Induction motor without any controller.

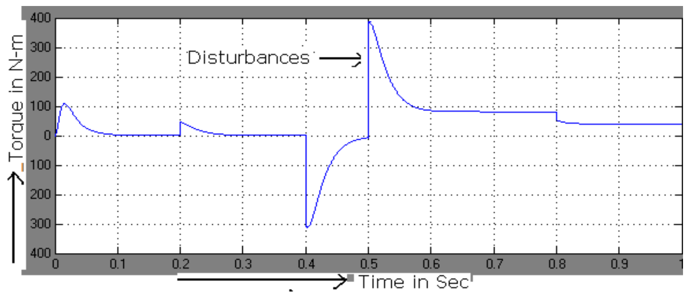
The simulation results of PID control of IVC based induction motor are shown in Figure.8.



(a)Speed response



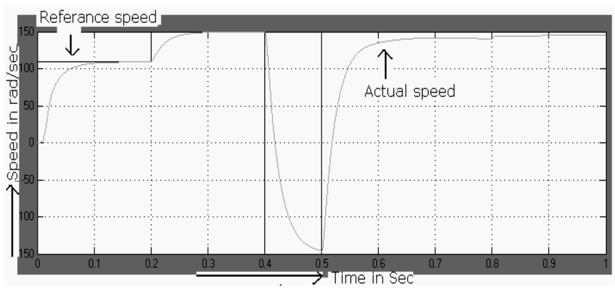
(b) Current response



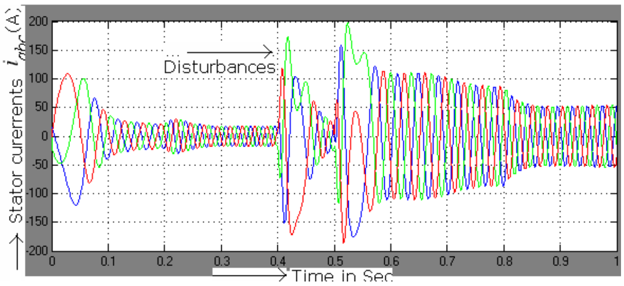
(c) Torque response

Figure.8 PID control of IVC based induction motor

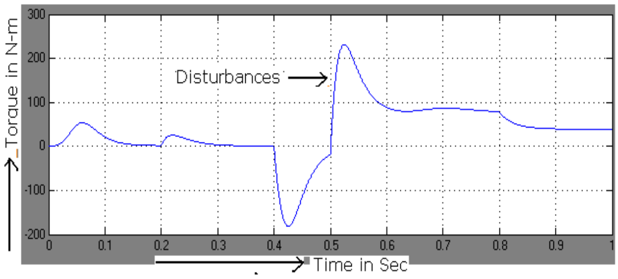
The simulation results of internal model control of IVC based induction motor are shown in Figure.9.



(a)Speed response



(b) Current response



(c) Torque response

Figure.9 Internal model control of IVC based Induction Motor

In internal model control the disturbances are less when compared with PID controller. This is as shown in Figure.'s 8 and 9.

VI. Conclusions

The speed control of the induction motor through Z-N based PID controller and Internal Model Control (IMC) controller has been implemented. It has been observed that due to the load disturbances and set point changes the vector controlled induction motor undergoes large fluctuations in speed response. In order to overcome those fluctuations, the design of PID controller and internal model controller has been developed and applied to the induction motor. The results demonstrate the ability of controllers to produce the required response compensating the component of load variations in order to maintain a stable response. It has been observed that the speed control obtained with the internal model controller is smoother and better than that obtained through the PID controller. Hence it can be say that the internal model controller is better than the PID controller for the speed control of induction motor.

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