SUST Journal of Engineering and Computer Science (JECS), Vol. 15, No. 2, 2014

Speed Control of Vector Controlled Induction Motors Using Integral-Proportional Controller

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Received: 10.02.2014
Accepted: 13.04.2014

ABSTRACT - Control of Induction Motor (IM) is well known to be difficult owing to the fact the mathematical models of IM are highly nonlinear and time variant. The advent of vector control techniques has solved induction motor control problems. The most commonly used controller for the speed control of induction motor is traditional Proportional plus Integral (PI) controller. However, the conventional PI controller has some demerits such as: the high starting overshoot in speed, sensitivity to controller gains and sluggish response due to sudden change in load torque. To overcome these problems, replacement of PI controller by Integral plus Proportional (IP) controller is proposed in this paper. The goal is to determine which control strategy delivers better performance with respect to induction motor's speed. Performance of these controllers has been verified through simulation using MATLAB/SIMULINK software package for different operating conditions. According to the simulation results, IP controller creates better performance in terms of overshoot, settling time, and steady state error compared to conventional PI controller. This shows the superiority of IP controller over conventional PI controller.

Keywords: *Induction Motor, Vector Control, Speed Control, Integral-Proportional Controller, Proportional-Integral Controller.*

المستخلص– من المعلوم صعوبة التحكم فى المحرك الحثى (IM) نظرًا لحقيقة أن النماذج الرياضية للمحرك الحثى غير خطية و متغيرة مع الزمن. ظهور تقنيات التحكم المتجهى أدى لحل مشاكل التحكم فى المحرك الحثى. المتحكم الأكثر إستخداماً للتحكم فى سرعة المحرك الحثى هو الحاكمة التناسبية–التكاملية (PI) التقليدية. و رغم ذلك، الحاكمة التناسبية–التكاملية التقليدية لها بعض العيوب مثل: التجاوز العالى فى بداية السرعة، والحساسية لثوابت الحاكمة، و الأداء الردئ بسبب التغيير المفاجئ فى عزم الحمل. للتغلب على هذه المشاكل، استبدلت الحاكمة التناسبية–التكاملية التقليدية بالحاكمة التكاملية–التناسبية (IP) فى هذه الورقة. و الهدف من ذلك تحديد إستراتيجية التحكم التى تعطى أداء أفضل فيما يتعلق بالتحكم فى سرعة المحرك الحثى. تم التحقق من أداء هذه المتحكمات من خلال نتائج المحاكاة المتحصلة عليها بواسطة برنامج MATLAB/SIMULINK تحت ظروف التشغيل المختلفة. وفقاً لنتائج المحاكاة، نجد أن الحاكمة التكاملية–التناسبية أعطت أداء أفضل فما يتعلق بتجاوز الهدف، زمن الترسيخ، و الخطأ عند حالة الإستقرارية مقارنة مع الحاكمة التناسبية–التكاملية التقليدية. وهذا يدل على تفوق الحاكمة التكاملية–التناسبية على الحاكمة التناسبية–التكاملية التقليدية.

INTRODUCTION

There is a demand for high performance electric drives capable of accurately executing torque, speed or position demands. In the past, Direct Current (DC) motor was largely used in the field of the variable speed applications, where torque and flux are naturally decoupled and can be controlled independently by the torque producing current and the flux producing current. It was considered as a main work horse in the industry [1]. However, DC motor had its disadvantage like maintenance, sparking, difficulty in commutation at high current and voltage so it is limited to low power and low speeds. Nowadays, like a consequence of the important progress in the power electronics and of micro- computing, the control of the AC electric machines known a considerable development and a possibility of the real time implantation applications. It is widely recognized that the induction motor is going to be the main actuator for industrial purposes. Indeed, as compared to the DC machine, it provides a better power/mass ratio, a simpler maintenance and relatively lower cost.

However, it is traditionally for a long time, used in industrial applications that do not require high performances, this because its control is a more complex problem, its high nonlinearity and its high coupled structure. Furthermore, the motor parameters are time-varying during the normal operation and most of the state variables are not measurable [2-3]. Since Blashke and Hasse have developed the new technique known as Vector Control (VC) or Field-Oriented Control (FOC), the use of the induction machine becomes more and more frequent.

This control strategy can provide the same performance as achieved from a separately excited DC machine, and is proven to be well adapted to all type of electrical drives associated with induction machines. In order to understand and analyze vector control, the dynamic model of the induction motor is necessary. It has been found that the dynamic model equations developed on a rotating reference frame is easier to describe the characteristics of induction motors. It is the objective of the article to derive and explain induction motor model in relatively simple terms by using the concept of space vectors and d-q variables. It will be shown that when we choose a synchronous reference frame in which rotor flux lies on the d-axis, dynamic equations of the induction motor is simplified and analogous to a DC motor [4-7].

There are essentially two general methods of vector control. One called the direct or feedback method, and the other, the indirect or feed forward method. Indirect Vector Controlled (IVC) induction motor drives used in high performance systems is very popular in industrial applications due to their relative simple configuration, as compared to the Direct Vector Controlled (DVC) technique which requires flux and torque estimator. The primary advantages of indirect vector control are the decoupling of torque and flux characteristics and easy implementation. In an Indirect Vector Control Induction Motor (IVCIM) drive, the flux and torque commands are calculated from the IM variables based on machine parameters. It is desirable that those parameters match the actual parameters of the machine at all operating conditions to achieve decoupling control of the machine. The block diagram of an indirect field-oriented induction motor drive is shown in Figure 1 [8-12].

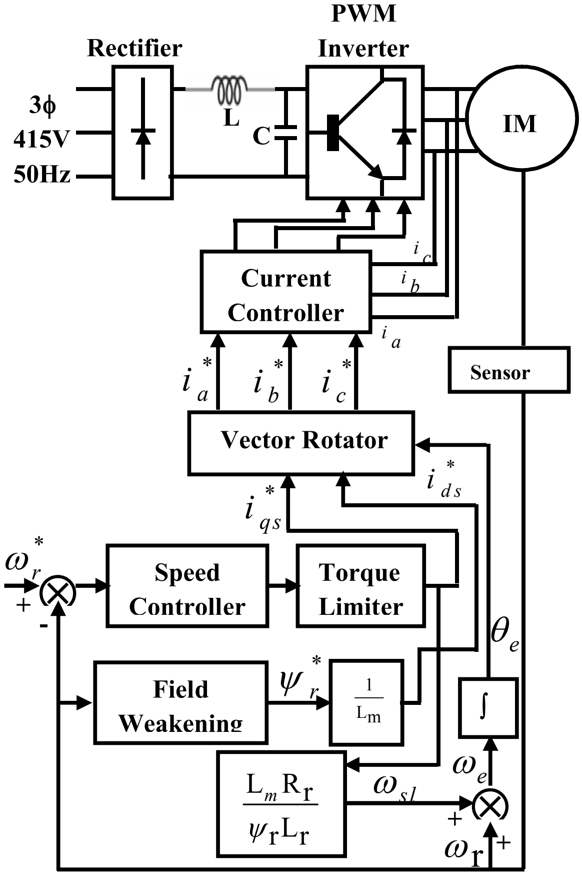

Figure 1: Indirect vector controlled induction motor drive

Traditionally, two feedback loops are configured to implement a vector controlled IM drive system. The inner loop is a current regulation loop whereas the outer one is a speed or position regulation loop. The most commonly used controller for the speed control of induction motors is conventional PI controller. Conventional PI controllers have several important features. The reason is that the conventional PI controller is easy to implement either by hardware or by software.

No deep mathematical theory is necessary to understand how the conventional PI controller works, so everybody is able to imagine what is happening inside the controller during the control process. Furthermore, it has the ability to eliminate steady state offset trough integral action and it can anticipate the changes through derivative action. In addition to this, traditional PI controllers have very simple control structure and inexpensive cost.

In spite of the major features of the fixed PI controller, it has some disadvantages such as the high starting overshoot in speed, the sensitivity to controller gains and the sluggish response due to sudden change in load torque disturbance. This makes the use of traditional PI controller a poor choice for industrial variable speed drive applications where higher dynamic control performance with little overshoot and high efficiency is required [13-17]. To overcome the above problems and achieve accurate control performance of speed control of induction motor, the relatively integral plus proportional controller is presented [18-20].

INDCTION MOTOR MODEL

Under the assumptions of linearity of the magnetic circuit, equal mutual inductances, and neglecting iron losses, a three-phase squirrel-cage induction machine model in the fixed stator d-q reference frame can be described as a fifth order nonlinear differential equations with four electrical variables (stator currents (i_{ds}, i_{qs}) and rotor fluxes (ψ_{dr}, ψ_{qr})), and one mechanical variable (rotor speed ω_r) [8-12].

$$\dot{x} = f(x) + g_1 v_{ds} + g_2 v_{qs} \tag{1}$$

where:

$$f(x) = \begin{bmatrix} -\alpha\, i_{ds} + \beta\, \psi_{dr} + \omega_r\, \gamma\, \psi_{qr} \\ -\alpha\, i_{qs} + \beta\, \psi_{qr} - \omega_r\, \gamma\, \psi_{dr} \\ \delta\, i_{ds} - T_{ri}\, \psi_{dr} - \omega_r\, \psi_{qr} \\ \delta\, i_{qs} - T_{ri}\, \psi_{qr} + \omega_r\, \psi_{dr} \\ \frac{P}{2}\left(\frac{3PL_m\left(\psi_{dr} i_{qs} - \psi_{qr} i_{ds}\right)}{4L_r J} - \frac{T_L}{J} \right) \end{bmatrix}$$

$$g_1 = [\frac{1}{L_a}\ 0\ 0\ 0\ 0]^T$$

$$g_2 = [0\ \frac{1}{L_a}\ 0\ 0\ 0]^T$$

$$x = [i_{ds}\ i_{qs}\ \psi_{dr}\ \psi_{qr}\ \omega_r\ ]^T$$

$$\alpha = \frac{R_s}{L_a} + \frac{R_r L_m^2}{L_r^2 L_a}$$

$$\beta = \frac{R_r L_m}{L_r^2 L_a}$$

$$\gamma = \frac{L_m}{L_r L_a}$$

$$L_a = L_s - \frac{L_m^2}{L_r}$$

$$\delta = \frac{L_m}{T_r}$$

$$T_{ri} = \frac{1}{T_r}$$

$$d = \frac{3P^2 L_m}{8L_r J} \tag{2}$$

where L_s is the stator inductance, L_r is the rotor inductance, L_m is the mutual inductance, L_a is the redefined leakage inductance. R_s and R_r are stator and rotor inductance resistances, respectively. J is the moment of inertia of the motor, T_L is the torque of external load disturbance, P is the number of pole, and T_r is the time constant of the rotor dynamics. From

Equation (1) the rotor speed is a nonlinear output with respect to the state variables of the dynamical model. Therefore, it is difficult to control the rotor speed directly from control inputs v_{ds} and v_{qs}.

PI CONTROLLER BACKGROUND

The conventional proportional-integral controller remains the most popular design approach used in industrial applications due to its simplicity and reliability for the control of first and second order plants, and even high order plants with well-defined conditions. A well- tuned PI controller is capable in achieving an excellent performance [13-17]. However, it suffers a crucial disadvantage of getting a poor performance whenever the plant is subjected to some kind of disturbance or, the plant has high order nonlinear structure. Figure 2 shows the Simplified block diagram of the speed control of induction motor using a PI controller [21].

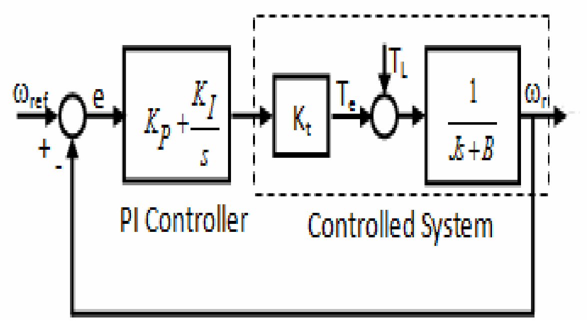

Figure 2: Simplified model of the IVCIM drive with conventional PI controller

Where ω_{ref} is the reference rotor angular speed, ω_r is the rotor angular speed, $e=\omega_{ref}-\omega_r$ is the tracking speed error, K_P is the proportional gain, K_I is the integral gain, B is the total damping coefficient, and Te denotes the electromagnetic torque. The T_e can be defined as [8-12]:

$$T_e = K_t i^*_{qse} = \frac{3PL_m^2}{2L_r} i^*_{dse} i^*_{qse} \qquad (3)$$

where i^*_{qse} and i^*_{dse} denote the torque and flux current commands, respectively. If TL=0, the closed loop transfer function is as follows:

$$\frac{\omega_r}{\omega_{ref}} = \frac{K_t\,(K_P s + K_I)}{Js^2 + (B + K_P K_t)s + K_I K_t} \qquad (4)$$

IP CONTROLLER BACKGROUND

To improve the dynamic performance for transient state and avoid overshoot, the speed control is confided to an integral plus proportional controller [22]. The IP controller is considered the major contribution in this paper. Figure 3 shows the Simplified block diagram of the speed control of induction motor using the integral plus proportional controller.

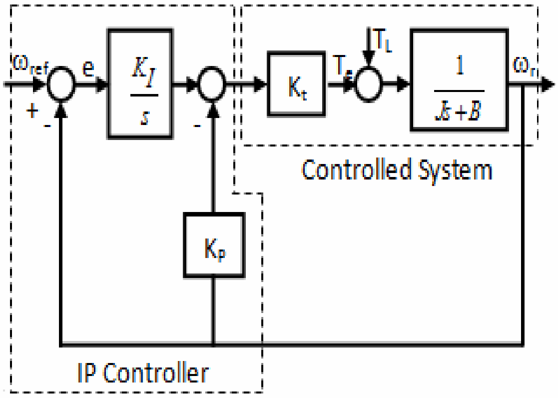

Figure 3: Simplified model of the IVCIM drive with IP controller

It has some clear differences with PI controller. If $TL=0$, the closed loop transfer function is as follows:

$$\frac{\omega_r}{\omega_{ref}} = \frac{K_t K_I}{Js^2 + (B + K_P K_t)s + K_I K_t} \qquad (5)$$

From Equations (4) and (5), conventional PI and IP controllers have the same characteristic equations, and it can be seen that the zero introduced by the PI controller is absent in the case of the IP controller. Therefore the overshoot in the speed, for a step change in the input reference ω_{ref}, is expected to be smaller for the IP controller [18-20].

RESULTS AND DISCUSSION

Several simulation tests for indirect vector control of IM were carried out using both IP controller and conventional PI controller. The speed responses under different operating conditions such as nominal condition, step change in command speed, moment of inertia mismatch, and sudden change in external load torque. Simulations are based on the facts that whether the IP controller is better and more robust than the conventional PI controller or not. The physical and functional parameters of induction motor used for simulation testing are given in Table1 [23].

The MATLAB/SIMULINK model of system under study with conventional PI controller and IP controller is shown in Figure 4 and Figure 5, respectively. For all simulations performed in this paper, the best gain, found of conventional PI controller are Kp=10 and Ki=20, and of IP controller are Kp=24 and Ki=500. The two controller technique schemes are compared using the same rotor speed reference command.

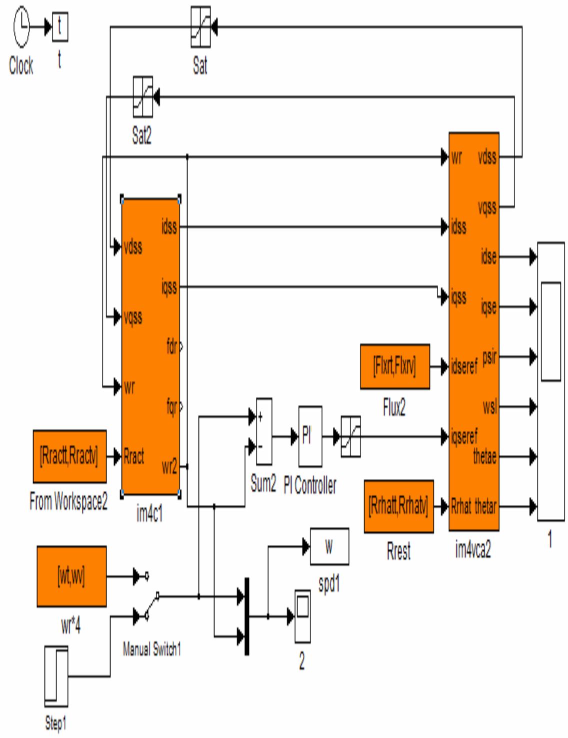

Figure 4: MATLAB/SIMULINK block diagram of IVCIM using PI controller

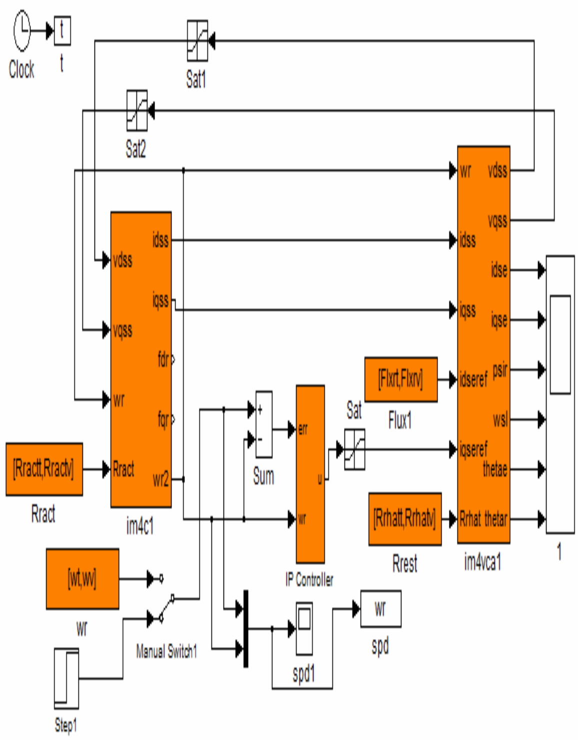

Figure 5: MATLAB/SIMULINK block diagram of IVCIM using IP controller

Table I: Electrical and mechanical parameters of the inductiom motor

Parameters	Values
Number of phases	3
Connection	star
Rated power	2.24 KW
Line voltage	230V rms
Line current	9 A rms
Rated speed	1430 rpm
Rated torque	14.96 Nm
Rotor resistance, R_r	0.72 Ω
Stator resistance, R_s	0.55 Ω
Rotor inductance, L_r	0.068 H
Stator inductance, L_s	0.068 H
Magnetizing inductance, L_m	0.063 H
Moment of inertia, J	0.05 $kg.m^2$
Viscous friction coefficient, B	0.002 Nms^{-1}

Nominal Condition

In this section the tracking performances of the IP controller and conventional PI controller schemes are compared under nominal condition. Simulation results for the nominal system is presented in Figure 6, which shows the rotor speed responses for IP controller and conventional PI controller when the induction motor is operating at a reference speed of 10rad/s. In terms of the rotor speed control trajectories shown in Figure 6, two different controllers have a similar performance in term of fast tracking of the desired speed. However, the IP controller shows no overshoot and then tracks the reference speed closely.

Furthermore, the settling time for IP controller is shorter than for conventional PI controller. However, the rise time for conventional PI controller is shorter than for IP controller. From the above comparison the IP controller can replace the conventional PI controller for the speed control of the induction motor drives.

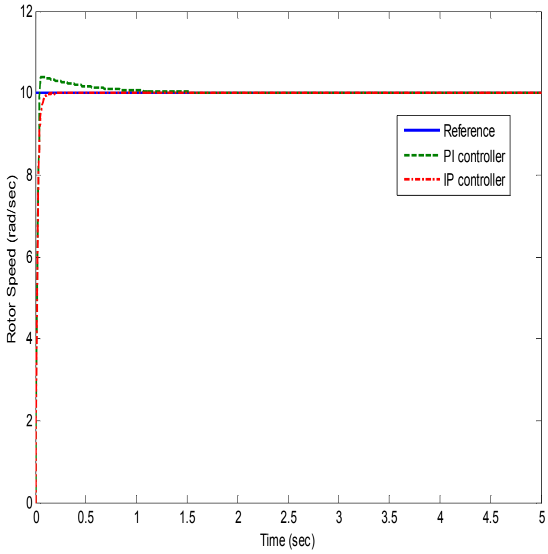

Figure 6: Step response of the IM system using IP controller and conventional PI controller

The performance of both the controllers is also tested by applying a large step change in the reference speed from 10rad/s to 30rad/s at t=3sec. The system response for the above case is shown in Figure 7. As can be seen, under the condition of given speed changing, IP controller system, compared with traditional PI controller system, able to quickly reach a steady state and has better tracking performance for the speed control of indirect vector controlled induction motor drive.

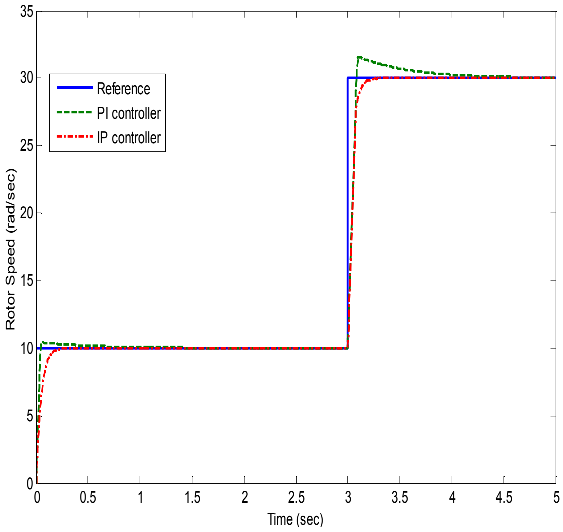

Figure 7: Speed responses of the IM using two controllers under step change in command speed

Increase the Moment of Inertia J

For high performance applications the proposed IP controller scheme should be robust to parameter variations. A change in the moment of inertia is investigated through simulation tests. The motor is commanded to accelerate from rest to reference speed of 10rad/s under no torque load. Figure 8 shows the motor responses of IP controller and conventional PI controller when the moment of inertia is increased by 100% of its original value.

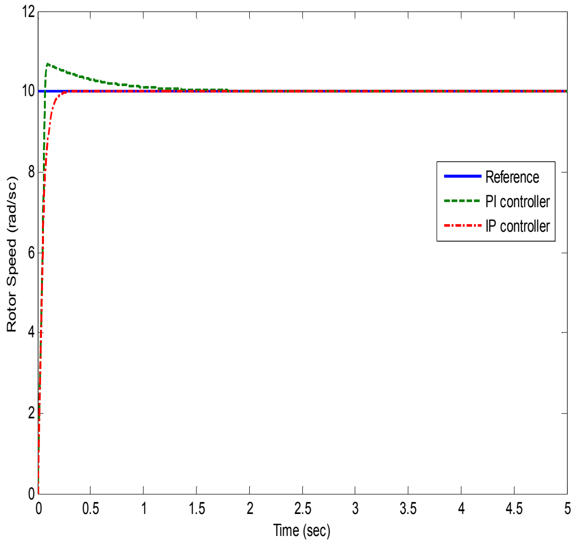

Figure 8: Responses of the IM using two controllers with variation in the moment of inertia

From figure 8, it can be seen that the increment of the moment of inertia does not impose any significant effect on the performance of the IP controller technique but only affects the rise time. Furthermore, when carefully study Figure 8 according to the settling time and overshoot, the best performance belongs to IP controller. This means that the IP controller is insensitive to parametric variations and a robust tracking performance is achieved in presence of the uncertain parameters.

Load Torque

In order to testify the robustness of the controlled system, a 10Nm load torque is suddenly added at time 3s and then removed at time 4s while the command speed is set as 10rad/s. Figure 9 gives the speed responses when induction motor is commanded to follow the reference speed with sudden change in torque load. The conventional PI controller has the worse rotor speed response at these two instants. However, the system controlled by the IP controller demonstrates an excellent rotor speed response whether the load is added or removed. Again the IP controller performs a better tracking ability than the conventional PI controller does. Therefore, it is true to say that the conventional PI controller is not robust to load torque variations.

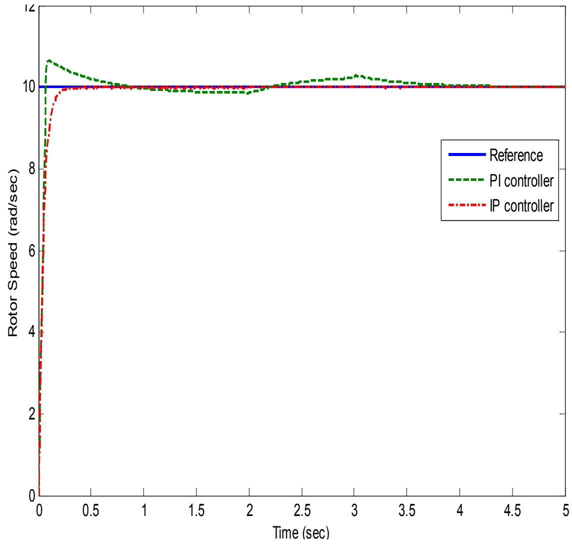

Figure 9: Speed responses of IP controller and PI controller against sudden change in torque load

CONCLUSIONS

The simulation results obtained on an induction motor speed control system using the IP controller are presented in this paper. IP controller’s performance was compared with that of conventional PI controlled system. A comparison method has been studied to show the relative advantages and limitations of each controller. From the comparative simulation results, one can conclude that the two controllers demonstrate nearly the same performances under nominal condition. However, it is observed that IP controller provide important advantages over the traditional PI controller like limiting the overshoot in speed, thus the starting current overshoot can be reduced. Robustness of the two controllers against system parameters variation and external load torque is also verified. Simulation results show that the proposed IP controller strategy scheme shows better performance than the PI controller strategy in the face of system parameters variation and external load torque.

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