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# Fuzzy-Logic-Based Self-Tuning PI Controller for Speed Control of Indirect Field-Oriented Induction Motor Drive

Mohammad Abdul MANNAN*, Toshiaki MURATA*,
Junji TAMURA* and Takeshi TSUCHIYA**

In this paper, a new self-tuning proportional and integral (PI) controller based on fuzzy logic is proposed to improve the performance of conventional PI speed control of induction motor (IM) taking core loss into account. A new parameterization technique to tune the proportional and integral gains of PI controller is adopted by using a single parameter ($h$) from the knowledge of pole placement technique. To tune the parameter $h$ depending on the operating points, a simple fuzzy logic system is designed where only one input, one output variables, three membership functions for each input-output variable, and three fuzzy rules are used. Since the poles of PI speed controller are placed in negative real values by using the proposed parameterization technique, the speed controller always works in stable region. Moreover, the overshoot and steady state error problems are also overcome by changing of $h$ based on the proposed fuzzy system under the variations of load torque and parameters. The performance of proposed fuzzy-logic-based self-tuning PI controller has been demonstrated through the simulations. The simulation results confirm that the excellent desired speed is achieved against the variations of load torque and parameters without any overshoot and steady state error by using the proposed system.

**Key Words:** fuzzy-logic, induction motor, speed control, self-tuning PI controller

## 1. Introduction

The field-oriented control (FOC) method of IM with conventional PI speed controller has been widely used in the industry applications [1),2)]. Due to the inherent disadvantages of conventional PI controller, numerous methods have been proposed to replace PI controller schemes, which include the model reference adaptive control [3)], sliding mode control [4)], optimal regulator control [5)], internal model control [6)], input-output linearizing control [7)], genetic algorithm [8)], fuzzy logic control (FLC) [9),10)], fuzzy tuning PI controller [11)] and neural network [12)]. The design of the proposed controllers [1)~8)] depends on mathematical model. The design of FLC and neural network is independent on mathematical model. To train the weighting factors of neural network and calculation of output variable of fuzzy system, where rule table is large, are time consuming. However, FLC is robust under the variations of load torque and parameters [9)], FLC is not better than PI controller for all operating points [10)]. The above discussed controller [1)~4),6)~12)] for IM have been designed by neglecting core loss.

The performance of torque and flux control of IM drive is deteriorated due to the effects of core loss [5),13)]. So, it is desirable to consider core loss to achieve precise performance of IM. The discrete time PI controller, where PI controller gains have been chosen by trial and error method [14)] and applying pole placement technique [15)], has been applied to obtain high performance of IM drive in taking core loss into account. But the overshoot problem for step change of speed and under the variation of parameters of IM cannot be overcome by using the proposed PI controller [14),15)].

Since, the PI controller is widely used for IM drive [1),2)], it is desirable to have an intelligent PI controller which is able to self-tune its control gains to overcome the steady-state error and overshoot problems for step change of desired speed, and variations of load torque and parameters with consideration of core loss.

The classical PI controller gains tuning formulae have been proposed as Ziegler-Nichols [16)] and Refined Ziegler-Nichols [17)]. A natural step forward along the line is to consider self-tuning PID controller, which tunes the PID gains [17)]. The demerits of above- mentioned PI gains tuning formulae have been clarified and a fuzzy adaptive mechanism has been proposed to overcome those disadvantages in [18]. Therefore, it has been clear that the tuning of PI controller gains based on fuzzy logic is better than the classical tuning formulae. But, the PI controller

* Department of EEE, Kitami Institute of Technology, 165 Koen-cho, Kitami, Hokkaido
** Department of EEE, Hokkaido Institute of Technology, 4-1, 7-15 Maeda, Teine-ku, Sapporo, Hokkaido
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gains are parameterized from the knowledge of Ziegler-Nicholos formula in [18] which is capable to provide the stable and good performance of IM under the variations of load torque and parameters. Different types of PID controller gains tuning method based on fuzzy logic controller have been compared in [19].

Conventionally, two input variables each having five membership functions have been considered in [11, 18, 19] so that the rule table has become large and the calculation of output variable has been a time consuming task. A recursive method has been used in [18] to update gains and two individual rule tables have been used for proportional and integral gains in [11], so that the proposed methods in [11, 18] are time consuming. The stability of the proposed controller in [11, 18, 19] and the overshoot problem for the variations of parameters have not been verified.

In this paper, a new self-tuning PI controller for speed control of IM based on fuzzy-logic has been proposed to take advantages of simplicity and feasibility of conventional PI controller. A new idea, that the gains of PI controller based on pole placement technique are parameterized by a single parameter $h$, is adopted. According to the proposed parameterization technique, the PI controller is stable under the variations of load torque and parameters because the real parts of poles of PI speed controller dynamic are always negative. And no steady-state error occurs due to the proper selection of PI controller gains. Moreover, a simple FLC system is also designed to tune the parameter $h$. In the proposed FLC system one input, one output variables, three membership functions for each input-output variable and three fuzzy rules are used. So the proposed FLC is simpler, less time consuming one to calculate output variable than those proposed in [11,18]. And overshoot is not arisen for step change of desired speed and under the variations of load torque and parameters due to the online tuning of PI controller gains.

The performance of proposed fuzzy-logic-based self-tuning PI controller has been verified through simulations. The simulation results confirm that the desired speed is achieved under the variations of load torque and parameters without any overshoot and steady error problems. The proposed controller can provide better performance than a conventional PI controller.

## 2. Model of Induction Motor Taking Core Loss into Account

**Fig. 1** shows the equivalent circuit of an IM taking core loss into account in the $d$-$q$ axis synchronously rotating reference frame. It is seen that the core loss resistance is connected in parallel with the magnetizing inductance [13]. According to Fig. 1, the voltage equations are given by

$$\begin{aligned} v_{1d} &= R_1 i_{1d} + d\Phi_{1d}/dt - \omega_e \Phi_{1q} \\ v_{1q} &= R_1 i_{1q} + d\Phi_{1q}/dt + \omega_e \Phi_{1d} \end{aligned} \quad (1)$$

$$\begin{aligned} 0 &= R_2 i_{2d} + d\Phi_{2d}/dt - \omega_s \Phi_{2q} \\ 0 &= R_2 i_{2q} + d\Phi_{2q}/dt + \omega_s \Phi_{2d} \end{aligned} \quad (2)$$

$$\begin{aligned} R_c i_{cd} &= d\Phi_{md}/dt - \omega_e \Phi_{mq} \\ R_c i_{cq} &= d\Phi_{mq}/dt + \omega_e \Phi_{md} \end{aligned} \quad (3)$$

where, $p$ is differential operator; $v_{1d}$ and $v_{1q}$ are the stator $d$- and $q$-axis input voltages; $i_{1d}$ and $i_{1q}$ are the stator $d$- and $q$-axis currents; $i_{2d}$ and $i_{2q}$ are the rotor $d$- and $q$-axis currents; $i_{cd}$ and $i_{cq}$ are the core loss $d$- and $q$-axis currents; $\Phi_{1d}$ and $\Phi_{1q}$ are the stator $d$- and $q$-axis fluxes; $\Phi_{2d}$ and $\Phi_{2q}$ are the rotor $d$- and $q$-axis fluxes; $\Phi_{md}$ and $\Phi_{mq}$ are the magnetizing $d$- and $q$-axis fluxes; $R_1$, $R_2$ and $R_c$ are stator, rotor and core loss resistances; $\omega_e$ and $\omega_s$ are primary and slip angular frequencies.

The current equations can be written as

$$i_{1d} + i_{2d} = i_{cd} + i_{md}; \quad i_{1q} + i_{2q} = i_{cq} + i_{mq} \quad (4)$$

where, $i_{md}$ and $i_{mq}$ are the magnetizing $d$- and $q$-axis currents.

The stator, rotor and magnetizing fluxes equations are given as

$$\Phi_{1d} = L_1 i_{1d} + \Phi_{md}; \quad \Phi_{1q} = L_1 i_{1q} + \Phi_{mq} \quad (5)$$

$$\Phi_{2d} = L_2 i_{2d} + \Phi_{md}; \quad \Phi_{2q} = L_2 i_{2q} + \Phi_{mq} \quad (6)$$

$$\Phi_{md} = L_m i_{md}; \quad \Phi_{mq} = L_m i_{mq} \quad (7)$$

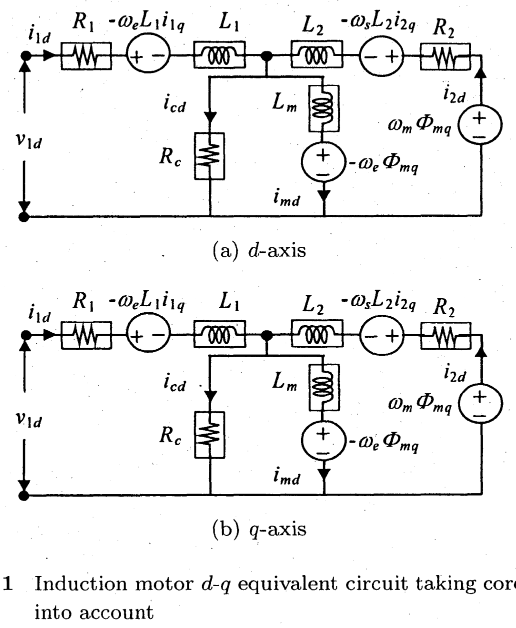



**Fig. 1** Induction motor $d$-$q$ equivalent circuit taking core loss into account

where, $L_1$ is stator leakage inductance; $L_2$ is rotor leakage inductance; and $L_m$ is magnetizing inductance.

The mechanical dynamic and developed torque are given as

$$p\omega_m = -(D/J)\omega_m + (P_n/J)(T_e - T_L) \quad (8)$$

$$T_e = P_n(L_m/L_2)(i_{mq}\Phi_{2d} - i_{md}\Phi_{2q}) \quad (9)$$

where, $\omega_m$ is rotor angular frequency; $T_e$ and $T_L$ are electromagnetic and load torques respectively; $P_n$ is number of pole pair; $J$ is moment of inertia; and $D$ is damping factor. The ratings and parameters of used IM are given in **Table 1** [5].

## 3. Indirect Field-Oriented Control

The torque and rotor flux decoupling control can be designed in terms of magnetizing current components [13), 14)]. The constraints of indirect FOC of IM are given by

$$\Phi_{2q} = 0.0; \quad \Phi_{2d} = \text{Constant} \quad (10)$$

Using the constraint, the $d$-axis rotor current becomes zero and the following equations are obtained at steady state condition.

$$\Phi_{2d} = L_m i_{md} \quad (11)$$

$$T_e = P_n(L_m/L_2)i_{mq}\Phi_{2d} \quad (12)$$

$$\omega_s = (R_2L_m/L_2)(i_{mq}/\Phi_{2d}) \quad (13)$$

From (11) – (12), it is seen that the decoupling control of torque and rotor flux of IM taking core loss into account can be designed easily in terms of magnetizing current components instead of stator current components. **Fig. 2** shows the proposed indirect FOC strategy for current source inverter [12]. But, the control structure Fig. 2 is valid only for steady state condition.

To regulate speed in both steady state and transient conditions, the PI controller, which is shown in **Fig. 3**, has been proposed applied in [14, 15]. But the PI controller, where the controller gains are chosen by trial and error method [14], does not show the robustness under the variation of load torque and parameters. Again, using the PI controller, where the gains are chosen based on pole placement technique [15], the overshoot problem cannot be eliminated. Therefore, we proposed a fuzzy-logic based self-tuning PI speed controller to improve the performance and to increase the robustness.

**Table 1** Ratings and parameters of induction motor

| 1.1 Kw, $200\sqrt{3}$ V/phase, 6 Poles, 50 Hz | | |
|---|---|---|
| $R_1 = 0.2842\,\Omega$, | $R_2 = 0.2878\,\Omega$, | $R_c = 404.397\,\Omega$, |
| $L_s = 28.3\,$mH, | slip = 0.03, | $L_r = 28.8\,$mH, |
| $L_m = 26.8\,$mH, | $J = 0.0179\,$Kg-m$^2$, | $D = 0$ |

## 4. Fuzzy-Logic-Based Self-Tuning PI Controller of IM Drives

### A. PI Controller Design

According to the mechanical dynamics (8), and electromagnetic torque (12), the desired magnetizing $q$-axis current can be obtained by using PI speed controller. By keeping constant rotor $d$-axis flux, the high performance of an IM taking core loss into account can be achieved by using two inner loop PI stator current dynamics controllers and one outer PI speed dynamics controller as shown in Fig. 3. In Fig. 3, superscript * denotes the desired quantities.

The conventional PI controller can be expressed by

$$u(t) = K_p e(t) + K_i \int e(t)dt \quad (14)$$

where, $e$ is the error between the desired value and actual value, $K_p$ is proportional gain and $K_i$ is integral gain. In Fig. 3, the error $e$, output of controller $u$ and the gains of PI controllers can be given as:

For PI speed controller: $e = e_\omega = \omega_r^*\text{-}\omega_r, u = i_{mq}^*,$
$K_p = K_{p\omega};\ K_i = K_{i\omega}.$

For PI d-axis current controller: $e{=}e_{id}{=}i_{1d}^*\text{-}i_{1d}, u{=}v_{1d}^*,$
$K_p = K_{pi};\ K_i = K_{ii}.$

For PI q-axis current controller: $e = e_{iq} = i_q^*\text{-}i_q, u = v_q^*,$
$K_p = K_{pi};\ K_i = K_{ii}.$

The discrete-time form of PI controller (14) can be expressed by

$$\Delta u(k) = K_p\Delta e(k) + K_iT_s e(k) \quad (15)$$

where, $\Delta e(k) = e(k) - e(k-1)$, $\Delta u(k) = u(k) - u(k-1)$, $T_s$ is sampling time, $k$ is sampling instant and $\Delta$ indicates increment.

Then, the present value of $u(k)$ can be obtained by

$$u(k) = u(k-1) + \Delta u(k) \quad (16)$$

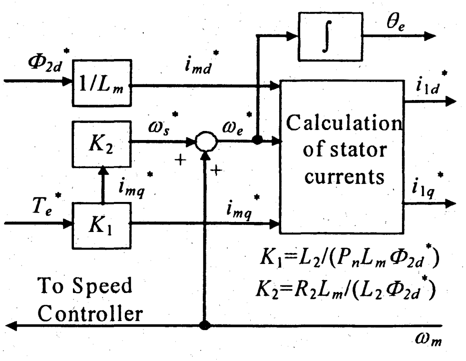



**Fig. 2** Indirect field-oriented control structure in steady state operation

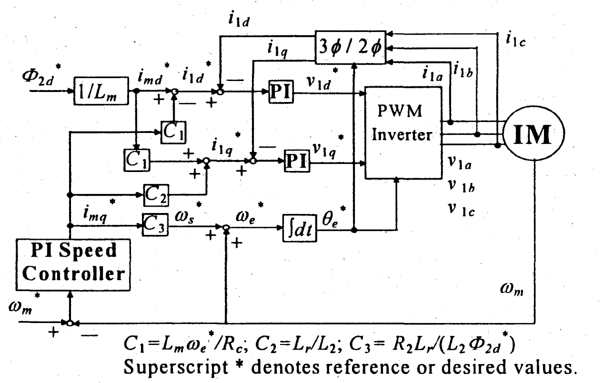



**Fig. 3** Indirect FOC of IM taking core loss into account based on PI controller

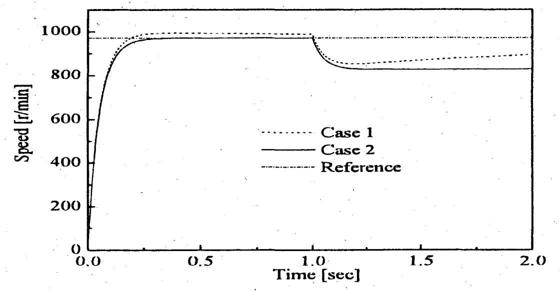



**Fig. 4** Desired speed response using PI controller for different PI controller gains

**Table 2** PI speed controller gains table for different cases

| | $K_{p\omega}$ | $K_{i\omega}$ |
|---|---|---|
| Case 1 | 0.009 | $5.0 \times 10^{-5}$ |
| Case 2 | 0.009 | $5.0 \times 10^{-3}$ |

The gains of conventional PI controller are chosen by trial and error method, where the mathematical model of plant is unknown, and these gains are kept constant for all operating conditions [13),14)]. **Fig. 4** shows the simulation results for different values of PI controller gains where PI controller gains are chosen by trial and error. In this simulation study, the reference speed is changed from 0 r/min to 970 r/min of its rated value at 0.0 sec, and the load torque is changed from 50% to 100% of its rated value at 1.0 sec. The gains of PI controller are given in **Table 2**. The gains for PI stator current controllers are chosen as: $K_{pi} = 3.0$ and $K_{ii} = 1500.0$. The sampling period is used 75 $\mu$sec. For case 1, the actual speed follows the reference speed with steady state error and overshoot for step change of reference speed, and the convergence of actual speed to desire speed is very slow for step change of load torque. For case 2, the actual speed follows reference speed without steady state error and overshoot for step change of reference speed, and the desired speed is not achieved for step change of load torque. It is comprehended from Fig. 4 that the performance of fixed gain PI controller is not good for all operating conditions. Moreover, it is very difficult to design a fixed gain PI controller to eliminate overshoot and steady state error problems.

The steady state error can be overcome by applying pole placement technique. To place the pole in negative real value of characteristic equation of PI speed dynamics, transfer function is used. The closed loop transfer function of PI speed controller can be given by:

$$\frac{\omega_m(s)}{\omega_m^*(s)} = \frac{(K_t/J)(K_{p\omega}s + K_{i\omega})}{s^2 + \{(D + K_tK_{p\omega})/J\}s + K_tK_{i\omega}/J} \quad (17)$$

where, $K_t = P_n^2(L_m/L_2)\Phi_{2d}^r$ and $\Phi_{2d}^r$ is rated rotor flux.

Therefore the characteristic equation can be written as

$$s^2 + \{(D + K_tK_{p\omega})/J\}s + K_tK_{i\omega}/J = 0 \quad (18)$$

Assuming the critical damping $\beta = 0$ and the two poles equal to $\alpha$, the PI controller gains are obtained as

$$K_{p\omega} = (2J\alpha - D)/K_t; \quad K_{i\omega} = J\alpha^2/K_t \quad (19)$$

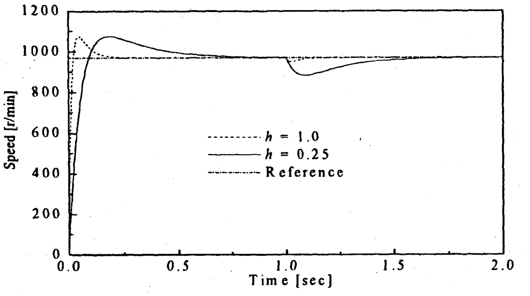
It is comprehended from (18)–(19) that the proportional gain is proportional to pole and the integral gain is proportional to the square of pole. Using this pole placement technique the overshoot problem cannot be overcome as shown in **Fig. 5**. Moreover, the robust performance cannot be achieved because the calculation of gains depends on the IM parameters $D$ and $J$. As a result, it is necessary to design a robust controller which can be achieved the desired speed without steady state error and overshoot problems for all operating conditions and also against the variations of load torque and parameters.

The robust performance from a conventional PI controller can be achieved by online tuning gains $K_{p\omega}$ and $K_{i\omega}$. The gains of PI controller are tuned by a single parameter $h$. From the knowledge of pole placement technique (19), the gains of PI controller can be parameterized by using $h$. Hence, the gains of PI controller can be expressed by

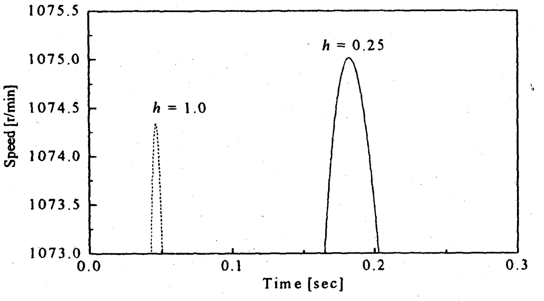
$$K_{p\omega} = K_{pm}h; \quad K_{i\omega} = K_{im}h^2 \quad (20)$$

where, $K_{pm}$ and $K_{im}$ are the maximum value of $K_{p\omega}$ and $K_{i\omega}$, respectively.

Fig. 5 shows the speed response using equation (20) for different values of $h$. The operating points for this simulation study are same those are used for Fig. 4. In this simulation study, the maximum values of PI speed controller are chosen as: $K_{pm} = 0.045$ and $K_{im} = 0.8$. By using the values of $K_{pm}$ and $K_{im}$, the poles of speed error and change of speed error dynamics are obtained as $-77.6$ and $-23.06$, respectively. According to (20) the




(a) Speed response




(b) Zoomed speed response between 0.0 to 0.3 sec

**Fig. 5** Desired speed response using PI controller for different values of parameter $h$

poles of speed error and change of speed error dynamics are always negative which can provide the stable operation of control system. It is evident from Fig. 5 that the response is become faster and the overshoot is decreased by increasing $h$, and the deviation of speed for changing of load torque is decreased. Similarly, the response is become slower and the overshot is increased by decreasing $h$, and the deviation of speed for changing of load torque is increased. As a result, the desired speed can be achieved by changing online parameter $h$ without overshoot and steady state error.

**B. Proposed Fuzzy Logic for tuning PI speed controller gains**

According to the realization of desired speed responses Fig. 4 and 5, only one input $\Delta e_\omega(k)$ is chosen for fuzzy logic system, from which the parameter $h$ is obtained as output of fuzzy logic system.

The input variables are normalized with $K_{de}$ as shown in **Fig. 6**. The membership functions with overlap of triangular shape are used for input and output variables. The membership functions of input and output linguistic variables are shown in **Fig. 7**. The input linguistic variable is represented by N (Negative), Z (Zero), P (Positive) and the output linguistic variable is represented by S (Small), B (Big). The grade of input membership functions can be obtained as follows:

$$\mu(x) = [w - 2|x - m|]/w \tag{21}$$

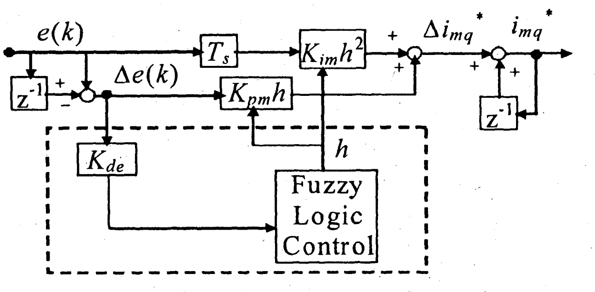



**Fig. 6** Structure of fuzzy adaptation mechanism for tuning PI controller gains

where, $\mu$ $(x)$ is the value of grade of membership, $w$ is the width and $m$ is the coordinate of the point at which the grade of membership is 1, $x$ is the value of the input variable.

It is comprehended from Fig. 4 and 5 that the gains of PI controller should be kept small to overcome the overshoot problem, when the change of speed error is large. Since the change of speed error becomes small near to the reference value of speed, the gains of PI controller should be kept large which can provides fast convergence of actual speed to desired speed under the variation of load torque and parameters of IM. Therefore, the mapping of the scaled input variables to the output variable $h$ is represented by fuzzy IF-THEN rules according to **Table 3**. There would be total three rules to achieve the desired speed trajectory as three membership functions for input are chosen.

According to the rule base in Table 3, the inference engine provides fuzzy value of $h$. The Mamdani's max-min composition with center of gravity (COG) method is considered as the most popular method on inference and defuzzification [16]. Therefore, the COG method is used for defuzzification to obtain $h$. The output from fuzzy adaptation mechanism is given as

$$h = \sum_{i=1}^{N} \mu_i C_i / \sum_{i=1}^{N} \mu_i \tag{22}$$

where, $N$ is total number rules; $\mu_i$ is the membership grade for $i$th rule; $C_i$ is the coordinate corresponding to the maximum value of the respective consequent membership function for $i$th rule where the possible values of $C_i$ are 0.0 and 1.0. After finding out the parameter $h$, the gains of PI controller can be calculated by using (20), which is also illustrated in Fig. 6.

In order to verify the performance of the proposed online gains tuning of PI speed controller, computer simulations have been performed. The ratings and parameters of the IM model are listed in Table 1. The scaling factors of fuzzy logic system are chosen as: $K_{de} = 2.1$. The gains

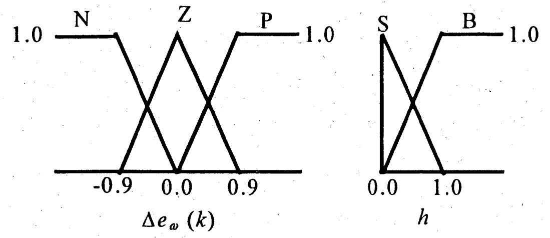



**Fig. 7** Fuzzy sets and their corresponding memberships functions

**Table 3** Rules table used to update the gains of PI controller

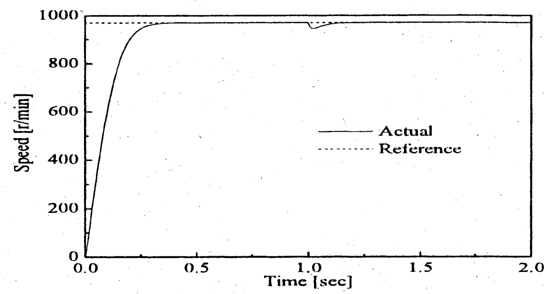
| | $\Delta e_\omega$ | | |
|---|---|---|---|
| | N | Z | P |
| $h$ | S | B | S |

of PI stator current controller, which are used for Fig. 4, and the maximum value of PI speed controller, which are used for Fig. 5, are used in order to obtain good response of the proposed control system.

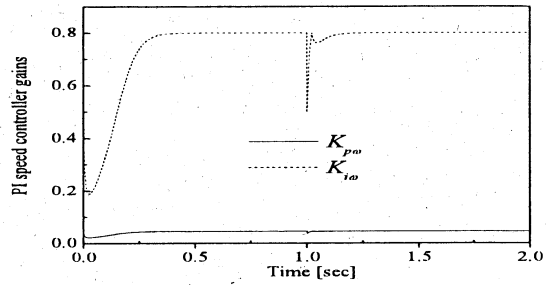
**Fig. 8** shows the transient response for step change of speed and load torque of IM taking core loss into account. At $t = 0.0$ sec, the desired speed is changed from 0.0 r/min to rated 970.0 r/min with 50% load torque. At $t = 1.0$ sec, load torque is changed from 50% to 100% by its rated value. It is seen in Fig. 8 (a) that the actual speed follows the desired speed without any overshoot and steady state error for step change of desired speed and the actual speed reach to the desired speed after step changing of load torque. The corresponding change of parameter $h$ is shown in Fig. 8 (b). The changing value of $h$ helps to overcome the overshoot problem.

**Fig. 9** shows also the desired speed response for step change of reference speed. It is comprehended from Fig. 9 that the desired speed is achieved without overshoot and steady error for large and small step change of reference speed.

In order to show the robustness of the proposed control system against the parameters variation ($R_2$, $J$, $L_m$ and $R_c$), simulation results are presented as shown in **Fig. 10**. It can be seen that the desired speed is achieved without any overshoot and steady state error against the variations of rotor resistance, inertia, magnetizing inductance and core loss resistance by using the proposed control system. Therefore, it can be stated that the desired speed can be achieved without overshoot and steady state error against the variations of parameters by using the proposed control system.




(a) Speed




(b) PI speed controller gains

**Fig. 8** Transient response for step change of desired speed and step change of load torque

## 5. Conclusion

A novel design of a self-tuning PI speed controller based on fuzzy logic is fully explained to achieve the desired speed of indirect FOC of IM taking core loss into account. The achievement of the proposed controller for various operating conditions and parameter variations was investigated by the simulation study. The overshoot and steady state error problems of conventional PI speed controller for IM drive taking core loss into account can be overcome by using the proposed self-tuning PI controller. The proposed controller is very simple for implementation and robust under the variations of load torque and parameters of IM. The robust performance of existing conventional PI speed controller of IM drive, which has been used in industry, can be achieved by using the proposed self-tuning PI speed controller based on fuzzy logic. By placing the proposed fuzzy logic system in parallel to the conventional PI controller, the proposed controller can be implemented in industrial application.

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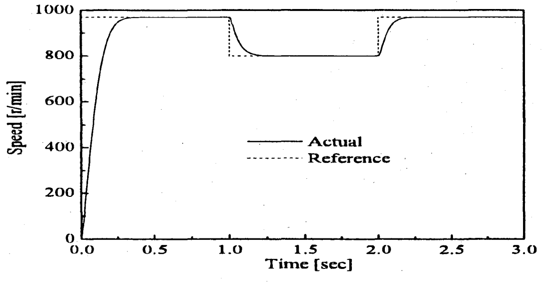


**Fig. 9** Transient response for step change of desired speed


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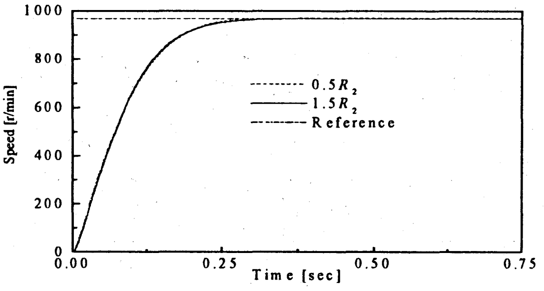
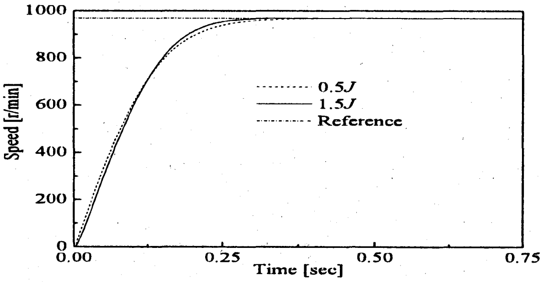
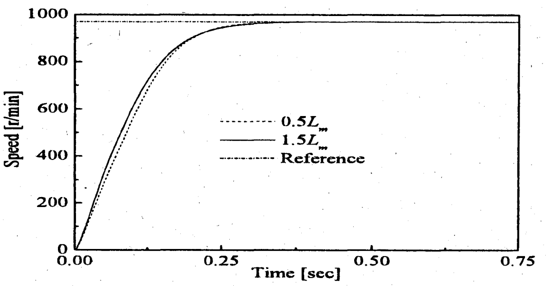


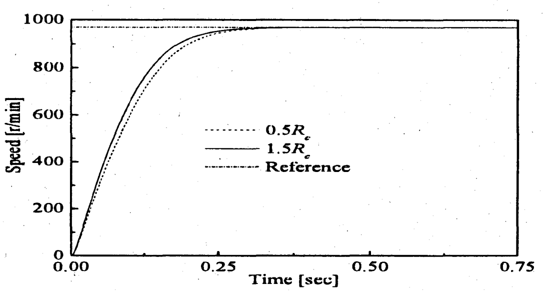

(a) Speed response under the variation of $R_2$




(b) Speed response under the variation of $J$



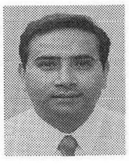

(c) Speed response under the variation of $L_m$




(d) Speed response under the variation of $R_c$

**Fig. 10** Desired speed responses against the variations of parameters of IM

### Mohammad Abdul MANNAN

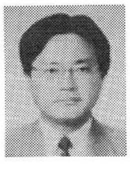


He was born in Laxmipur, Bangladesh on January 01, 1975. He received his B.Sc. Eng. Degree from Bangladesh Institute of Technology (BIT)-Rajshahi, Bangladesh and M.Sc. Eng. Degree from Kitami Institute of Technology, Japan, in 1998 and 2003 respectively, all in Electrical and Electronic Engineering. Presently he is working towards his Ph.D. degree at the Kitami Institute of Technology, Japan. His research interests are in the areas of electrical machines, power electronics, power systems, and applications of different controller and observer systems to electrical machines, power electronics, and power systems.

### Toshiaki MURATA (Member)

He completed his Electrical Engineering Curriculum of the Teacher Training School from Hokkaido University, Japan. Since 1969, he had been a Research Assistant at the Kitami Institute of Technology, Japan. He received Dr. Eng. degree from Hokkaido University in 1991. Presently he is an associate professor at the Kitami Institute of Technology.

### Junji TAMURA



He received his B. Sc. Eng. Degree from Muroran Institute of Technology, Japan, in 1979 and M.Sc. Eng. and Dr. Eng. degrees from Hokkaido University, Japan, in 1981 and 1984 respectively, all in electrical engineering. In 1984, he became a lecturer and in 1986, an associate professor at the Kitami Institute of Technology, Japan. Currently he is a professor at the Kitami Institute of Technology.

### Takeshi TSUCHIYA (Member)

He received the B. E. and M. E. degrees in electrical engineering from Hokkaido University, Sapporo, Japan, in 1963 and 1965, respectively. He obtained the degree of Doctor of Engineering from Hokkaido University in 1974. Presently he is a professor at the Hokkaido Institute of Technology.