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Induction Motor Drive Performance Improvement of Indirect Vector Control using Fuzzy PID controller

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Abstract— This paper presents the speed control scheme of indirect vector controlled of induction motor (IM) drive. Voltage source inverter type space vector pulse width modulation (SVPWM) is used for PWM controlling scheme. Regarding the capabilities and potentials of intelligent based on Fuzzy logic in the control of non-linear and complex systems, the Fuzzy PID controllers is developed for controlling the speed, torque, and flux of an IM. The performances of the proposed FLC-based IM drives are investigated and compared to those obtained from the conventional proportional-integral (PI) controller-based drives both simulated at different dynamic operating conditions such as step change in command speed, load change, and increase in the rotor resistance. The comparative results show that the FLC is more robust, found to be a suitable replacement of the conventional PI controller for the high-performance industrial drive applications.

Index Terms— Fuzzy Logic, Induction motors, Inverter, Machine vector control, Space vector pulse width modulation

I. INTRODUCTION

In recent years, the application of field oriented vector control of induction motors drives has been increased especially in the high performance drives because of advantages of that method [1-6]. With regard to the advances in the construction of power semiconductor elements and also the low cost of drive, the industry attempts follow the higher efficiency.

Although the torque and flux control of DC motor is more simpler compared with the induction motor, the induction motor is quite applicable in the industry because of its advantages. By using vector or field-oriented control method, the performance of induction motor drives can be made to somewhat identical to that of a separately excited DC motor [7-9]. The source of magnetizing current is determined by the field weakening block. This field-weakening capability permits the drive to operate in an extended speed range, beyond the base speed. Also, this source determines the maximum torque (dependent on speed). The position of rotor flux linkages is obtained indirectly via the amount of reference flux and electromagnetic torque. This method called indirect field oriented control which was introduced by Hasse [8]. Space Vector Modulation (SVM) method benefits the more

percentages of DC link compared with Pulse Width Modulation (PWM) technique. Moreover, SVM produces less THD outputs in various frequencies compared with PWM [10].

The PI controllers are used widely in industrial control systems. Their structures are so simple. They can be applied efficiently in a broad range. As a result of the permanent transformation in the machine parameters and the nonlinear regime, it is so difficult and somewhat impossible to determine the gain of PI controller [11]. Also, it needs the accurate mathematical model which is regarded as one of its challenges [12]. In the complex systems, the approximate model is used for linearization. It weakens the performance of the control system [13]. The Fuzzy controllers do not need the accurate model of the system and can improve both efficiency and performance of the control system in nonlinear and complex systems [8], [10].

In the direct vector control, it is necessary to have Hall Effect sensors and a powerful digital signal processor (DSP) in order to calculate the angle of rotor flux linkage [11]. In the indirect vector control, the flux is obtained by the induction machine equations. In that system, the problems of designing and manufacturing the drive would be decreased and the effect of stator resistant and rotor slot would not appear. That method has many applications in manufacturing vector drives [2], [14].

In this paper, the configuration and design of Fuzzy logic PID controller of indirect vector control of an induction motor is investigated. Three fuzzy controllers are used to control the speed, torque, and flux. Results of speed and torque variations are compared with conventional PI controllers. The effect of the rotor resistance changes, which is the most important parameter for the rotor time constant change, has been studied and shows that the fuzzy controller is very efficient because it is independent of motors parameters. The ratio of torque to the current is an important characteristic that is discussed.

II. INDIRECT FIELD ORIENTED CONTROL

In d-q coordinate system, the induction motor model equations can be written as follows [4], [15], [22]. The description of the notations is tabulated in Table 1.

$$\begin{aligned}
 U_{sq} &= R_s I_{sq} + \frac{d\psi_{sq}}{dt} + \Omega_{sr} \psi_{sd} & (1) \\
 U_{sd} &= R_s I_{sd} + \frac{d\psi_{sd}}{dt} - \Omega_{sr} \psi_{sq} & (2) \\
 0 &= R_r I_{rd} + \frac{d\psi_r}{dt} & (3) \\
 0 &= R_r I_{rq} + \psi_r (\Omega_{sr} - p_b \Omega_m) & (4) \\
 \psi_{sd} &= L_s I_{sd} + L_M I_{rd} & (5) \\
 \psi_{sq} &= L_s I_{sq} + L_M I_{rq} & (6) \\
 \psi_r &= L_r I_{rd} + L_M I_{sd} & (7) \\
 0 &= L_r I_{rq} + L_M I_{sq} & (8) \\
 \frac{d\Omega_m}{dt} &= \frac{1}{J} [p_b \frac{m_s}{2} \frac{L_M}{L_r} \psi_r I_{sq} - M_L] & (9)
 \end{aligned}$$

TABLE I
NOMENCLATURE

Stator voltage vector components in rotating d-q coordinate system	U_{sd}, U_{sq}
Stator current vector compon...	I_{sd}, I_{sq}
Rotor current vector compon...	I_{rd}, I_{rq}
Stator flux vector compon...	ψ_{sd}, ψ_{sq}
Rotor flux amplitude	ψ_r
Angular speed of the rotor flux vector	Ω_{sr}
Slip speed	Ω_{sl}
Angular speed of the rotor	Ω_m
Electromagnetic torque	M_e
Reference electromagnetic torque	M_{ec}
Load torque	M_L
Stator winding resistance	R_s
Rotor winding resistance	R_r
Stator inductance	L_s
Rotor inductance	L_r
Mutual inductance	L_M
Moment of inertia	J
Number of phase windings	m_s
Rotor flux vector angle	γ_{sr}

Equations 3 and 7 could be easily transformed to:

$$\frac{d\psi_r}{dt} = \frac{L_M R_r}{L_r} I_{sd} - \frac{R_r}{L_r} \psi_r \tag{10}$$

The motor torque can be expressed by rotor flux magnitude ψ_r and stator current component I_{sq} as follows:

$$M_e = p_b \frac{m_s}{2} \frac{L_M}{L_r} \psi_r I_{sq} \tag{11}$$

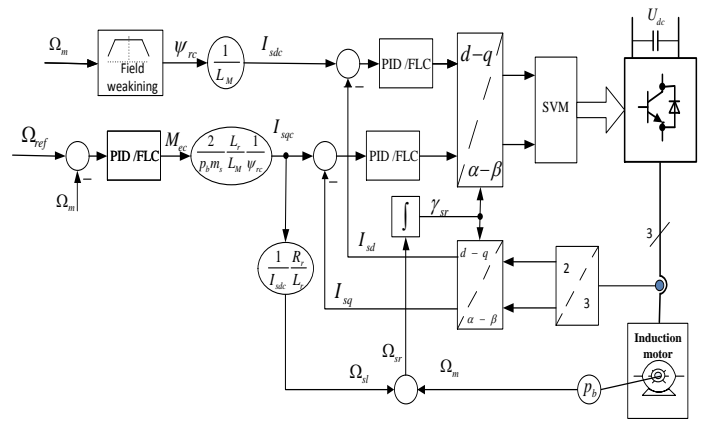


Figure 1. The block diagram of indirect vector control method with voltage source inverter

In the indirect vector control, the rotor flux angle is obtained by reference currents. The speed of rotor angle (Ω_{sr}), is calculated [9]:

$$\Omega_{sr} = \Omega_{sl} + p_b \Omega_m \tag{12}$$

In the above equation, Ω_{sl} is the slip speed, p_b is the number of pole pairs, and Ω_m is the angular speed of the rotor. The slip speed (Ω_{sl}), could be calculated from (4), (8), and (12).

$$\Omega_{sl} = \frac{1}{I_{sdc}} \frac{R_r}{L_r} I_{sqc} \tag{13}$$

The motor torque (M_e), could be obtained by product of the rotor flux magnitude and the stator current.

$$M_e = p_b \frac{m_s}{2} \frac{L_M}{L_r} \psi_r I_{sq} \tag{14}$$

The position of rotor flux linkage vector is:

$$\Omega_{sr} = \frac{d\gamma_{sr}}{dt} \tag{15}$$

The reference currents in rotating coordinate system I_{sdc}, I_{sqc} are calculated from the reference flux and torque values. Equations 10 and 11 at steady state for the reference currents can be written as follows:

$$I_{sdc} = \frac{1}{L_M} \psi_r \tag{16}$$

$$I_{sqc} = \frac{2}{p_b m_s} \frac{L_r}{L_M} \frac{1}{\psi_r} M_{ec} \tag{17}$$

In the Indirect Field Oriented Control method, mechanical speed, full information about motor state variable, load torque, and current controllers are required. The method is very sensitive to rotor time constant [15].

Fig.1 illustrates the block diagram of indirect vector control method. The speed error, with the help of a conventional PI and/or Fuzzy PID intelligent controller, is converted into a torque controlling current component (I_{sqc}). The field weakening block creates the reference current (I_{sdc}). The location of rotor flux linkage is obtained indirectly by reference values.

III. SPACE VECTOR MODULATION (SVM) METHOD

There are eight possible output voltage vectors in the SVM method; six active, and two zero vectors. These vectors can be formulated as [16]:

$$U_v = \begin{cases} \frac{2}{3} U_{dc} e^{j(v-1)\pi/3}, v = 1 \dots 6 \\ 0, v = 0, 7 \end{cases} \quad (18)$$

Any vector could be constructed by the combination of two active vectors and two zero vectors. In Fig.2, the reference vector U_c is constructed by switching of active vectors U_1 and U_2 as well as zero vectors U_0 and U_7 .

The duration of applying active vectors (t_1 & t_2), and zero vectors (t_0 & t_7) are given by [17]:

$$\begin{cases} t_1 = \frac{2\sqrt{3}}{\pi} MT_s \sin(\pi/3 - \alpha) \\ t_2 = \frac{2\sqrt{3}}{\pi} MT_s \sin(\alpha) \\ t_0 = t_7 = (T_s - t_1 - t_2)/2 \end{cases} \quad (19)$$

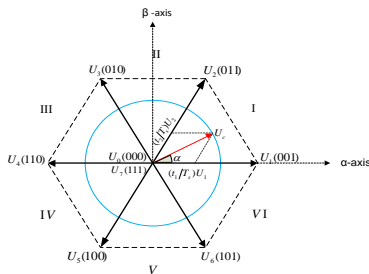


Figure 2. Construction of U_c by two active vectors U_1 and U_2 , and two zero vectors U_0 and U_7

In Fig.2, the maximum radius of the inner circle in the hexagon is $(\sqrt{3}/3)U_{dc}$. Therefore, compared to the six step method:

$$M = \frac{U_c}{U_1(\text{six-step})} = \frac{\frac{\sqrt{3}}{3} U_{dc}}{\frac{2}{\pi} U_{dc}} = 0.907 \quad (20)$$

The index M for PWM method is 0.7855. The higher value of the index M, shows the better utilization of the DC link. Switching vectors and output phase voltages in the SVM method are given in Table 2.

TABLE II

SWITCHING VECTORS AND OUTPUT VOLTAGES IN SVM METHOD

NAME	A	B	C	U_A	U_B	U_C
U_0	0	0	0	0	0	0
U_1	0	0	1	$2U_{dc}/3$	$-U_{dc}/3$	$-U_{dc}/3$
U_2	0	1	1	$U_{dc}/3$	$U_{dc}/3$	$-2U_{dc}/3$
U_3	0	1	0	$-U_{dc}/3$	$2U_{dc}/3$	$-U_{dc}/3$
U_4	1	1	0	$-2U_{dc}/3$	$U_{dc}/3$	$U_{dc}/3$
U_5	1	0	0	$-U_{dc}/3$	$-U_{dc}/3$	$2U_{dc}/3$
U_6	1	0	1	$U_{dc}/3$	$-2U_{dc}/3$	$U_{dc}/3$
U_7	0	0	0	0	0	0

IV. FUZZY PID CONTROLLER

The determination of the PI controller coefficients is possible in systems with the available and linear transformation function by various methods for instance, Ziegler-Nichols method, or Bode diagram [18], [19].

In nonlinear systems, the determination of controller gain is difficult. As a result of applying the approximation and system nonlinearity, no appropriate result will be achieved. The Intelligent controllers are more applicable in nonlinear systems [20]. Fig. 3 indicates the Fuzzy PID controller block. Fuzzy block inputs are speed error and its derivative. The output has a permanent error. In order to decrease that permanent error, an integrator block is designed and placed after the Fuzzy logic controller (FLC). Hence, the whole of Fig. 3 is named PID Fuzzy controller.

The Membership Functions for two inputs and one output are designed according to Fig.4. The membership functions are symmetric and they are limited between 1 and 0

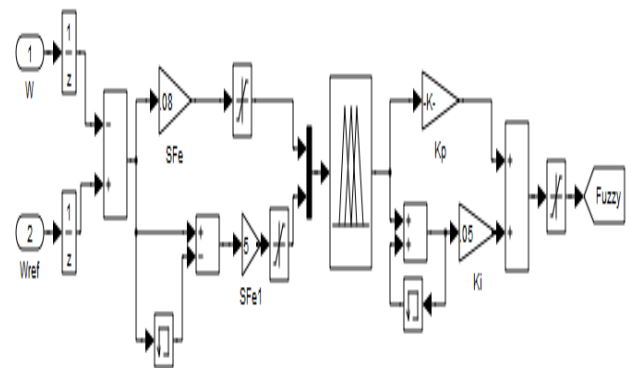
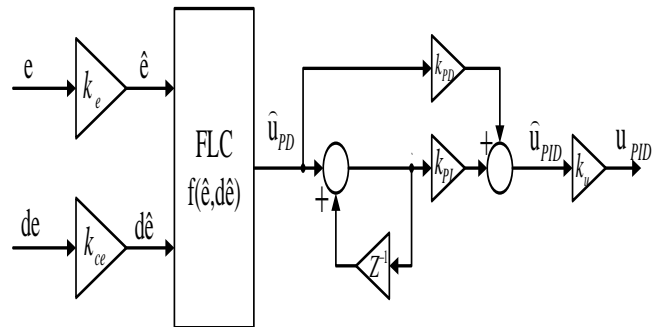
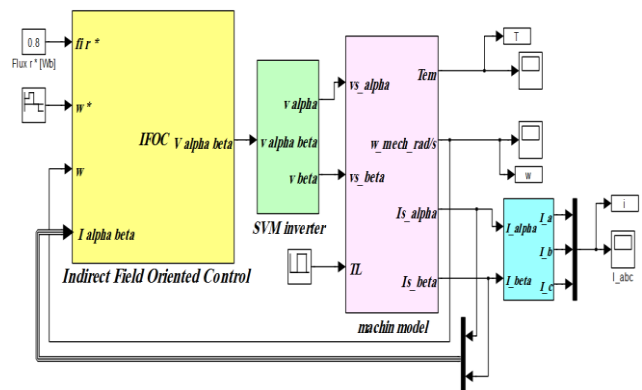


Figure 3. Fuzzy PID Controller Block



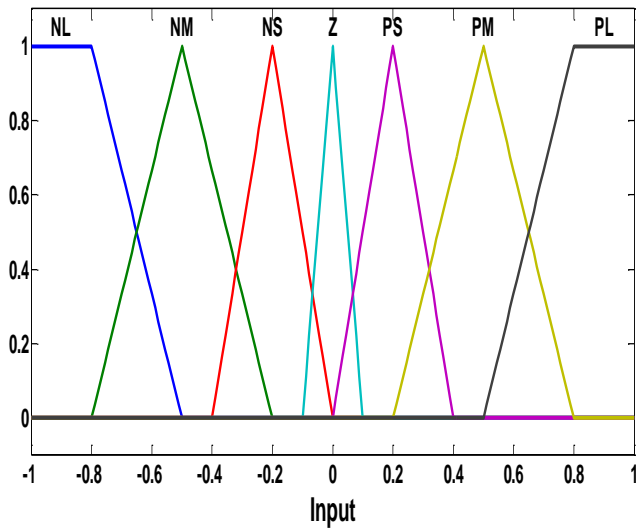


Figure 4. Membership Functions

Abbreviations in Fig. 4 are: NL: Negative Large, NM: Negative Medium, NS: Negative Small, Z: Zero, PL: Positive Large, PM: Positive Medium, and PS: Positive Small. Fuzzy rules are defined by a 7×7 matrix (Table 3) with 49 Fuzzy rules and Mamdani inference [21].

TABLE III
FUZZY-RULE-BASED MATRIX

$\begin{matrix} e \\ c_e \end{matrix}$	NL	NM	NS	Z	PS	PM	PL
NL	NL	NL	NL	NL	NM	NS	Z
NM	NL	NL	NL	NM	NS	Z	PS
NS	NL	NL	NM	NS	Z	PS	PM
Z	NL	NM	NS	Z	PS	PM	PL
PS	NM	NS	Z	PS	PM	PL	PL
PM	NS	Z	PS	PM	PL	PL	PL
PL	Z	PS	PM	PL	PL	PL	PL

V. VECTOR CONTROL STRATEGY

As shown in the Fig.1 in the direct axis, there is a flux controller and the reference signal of which is reduced above the base speed to achieve field weakening. The rotor flux reference also served to reduce the torque limit at high speed. The output of field weakening block is rotor flux reference. Field weakening block decreases magnetizing current for speeds more than the nominal speed, thus the motor would work in the constant power region. The output of speed controller is used as a reference electromagnetic torque. Reference torque in high speeds (higher than the nominal speed) decreased by the rotor flux reference.

VI. SIMULATION RESULTS

Simulations for PI controllers and Fuzzy PID controllers for different speeds and torques are done. Fig. 5 shows the block diagram of the simulation indirect field oriented control. The parameters of the studied induction motor are given in Table 4.

TABLE IV
PARAMETERS OF THE INDUCTION MOTOR

Power	$P_N=15$ kW
Voltage	$U_N=380$ V
Current	$I_N=28.9$ A
Frequency	$f_N=50$ Hz
Base speed	$\Omega_N=1460$ rpm
Number of pole pairs	$P=2$
Moment of inertia	$J=0.875$ kgm ²
Nominal torque	$M_N=98$ N.m
Nominal stator flux	$\psi_{s0}=0.98$ wb
Stator winding resistance	$R_s=0.28$ Ω
Rotor winding resistance	$R_r=0.26$ Ω
Stator inductance	$L_s=63.5$ mH
Rotor inductance	$L_r=63.5$ mH
Mutual inductance	$L_M=58.1$ mH

Fig.6 shows transient responses of speed and torque when reference speed steps from 0 to 25rad/s. Comparison between the performance of the Fuzzy PID and conventional PI controllers confirms the superiority of the Fuzzy PID controller.

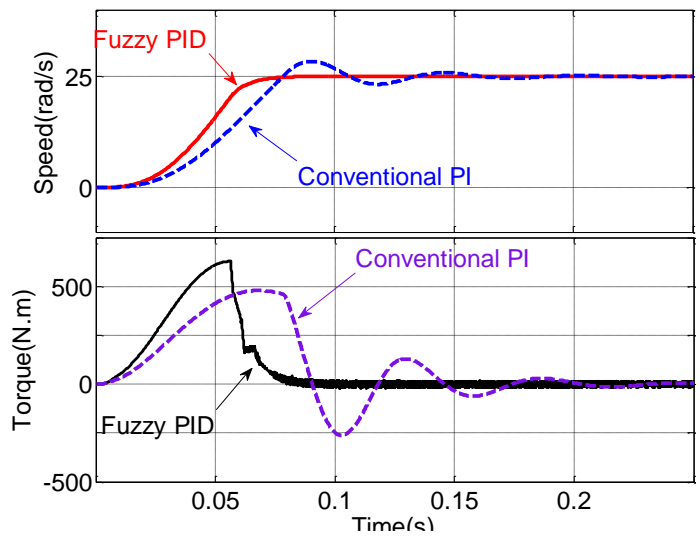


Figure6. Speed and Torque responses to the speed change command

Overshoot and settling time for the PI controller are 1.15% and 0.14s, respectively. For the Fuzzy controller those values are 0% and 0.06s, respectively. Moreover, the torque diagram reveals that the Fuzzy PID controller has a higher starting torque which is limited by the maximum tolerable torque. Fig. 7 shows motor response to the step change in speed from 25 to 50 rad/s at t=0.5s, and step change in torque from 0 to 50 N.m at t= 0.7s. Percent overshoots (M_p) and settling times (T_s) for two controllers are given in Table 5. Now, the performances of two controllers are examined at low speeds.

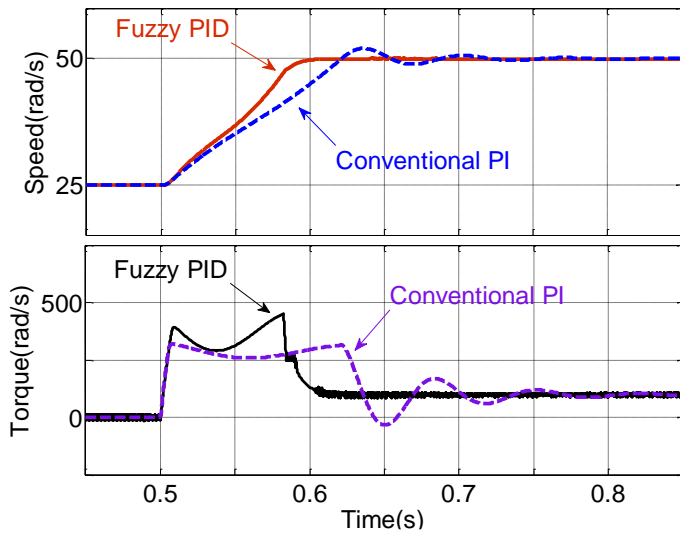


Figure7. Torque and speed response for step changes in speed and torque

Fig. 8 shows two system responses when the speed decreased to zero, while torque is kept constant. Fig. 8 shows that Fuzzy PID controllers leads to less torque oscillations as well as fast response to the changes. In steady state, there is the torque oscillations because of its high frequency compared with the nominal torque. Of course it is not a problem, because it practically damps. However, these oscillations can produce high-frequency sounds with damaging impact on some industrial equipment such as ultrasonic sensors.

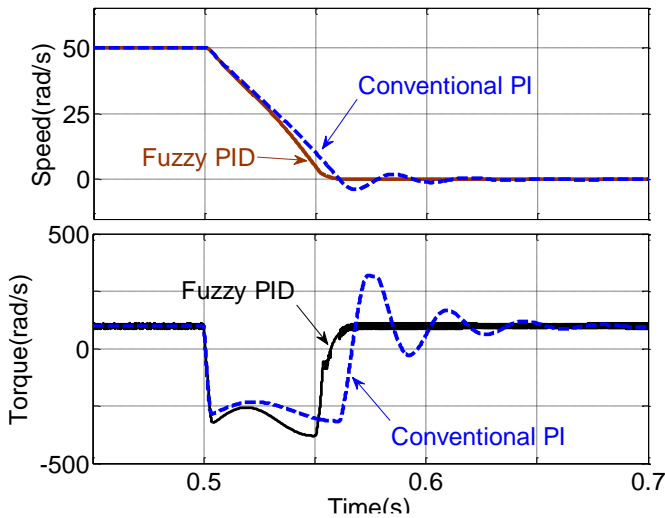


Figure8. Torque and speed responses when speed decreased to zero while torque is kept constant

Fig. 9 shows the situation in which speed is kept constant at 10rad/s while the torque command steps from 0% to 60% of its nominal value. This figure also confirms the superiority of Fuzzy PID controller to the conventional PI controller.

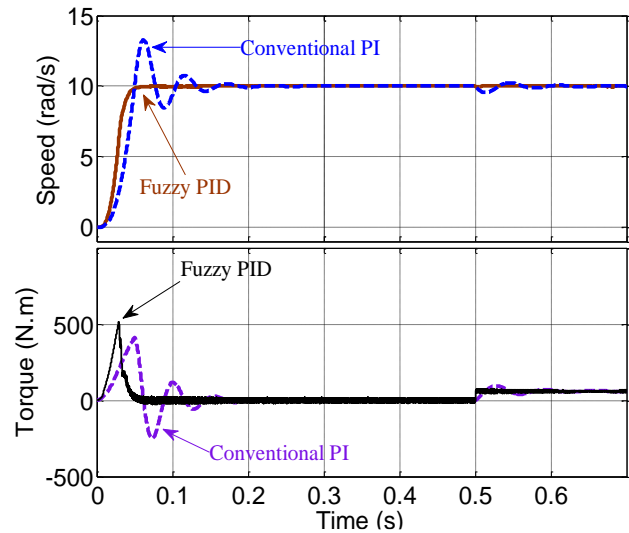


Figure9. Applying 60% of the nominal torque when speed is kept constant at 10 rad/s

Results of comparison between the performances of the PI controller and Fuzzy PID controller based upon Fig.6 to Fig. 9 are gathered in Table 5.

TABLE V
COMPARISONS OF CONTROLLERS PERFORMANCE

Controller	PI Controller		Fuzzy PID Controller	
	$%M_p$	T_s	$%M_p$	T_s
Speed, Load				
0-25 rad/s, no load	1.15	0.14	0	0.06
25-50 rad/s, no load	1.13	0.14	0	0.06
50-0 rad/s, 50 N.m	1.073	0.2	0	0.1
0-25 rad/s, 50 N.m	1.15	0.16	0	0.06
0-10 red/s, no load	1.33	0.15	0	0.057
10 rad/s, 60 N.m	1.06	0.086	0	0.01

Fig. 10 shows motor performances with two controllers by applying arbitrary step changes in both speed and torque commands. According to the table 4 and the figure 10, we can investigate the accuracy of equations and simulations. The current and torque limiters are adjusted on their 7 rated values at the time of starting and the direction change of the motor. According to the figure 10, fuzzy controller can use motor ability more effectively.

Torque-to-current curves are calculated and shown in that figure. It is assumed that the maximum current is 7 times greater than the nominal current of the motor. Fig. 10 reveals that the torque-to-current ratio of Fuzzy PID controller is better than the PI controller, especially in sudden changes in the speed command. This implies that it would be easier to change the motor speed or change the direction of rotation by Fuzzy PID controller.

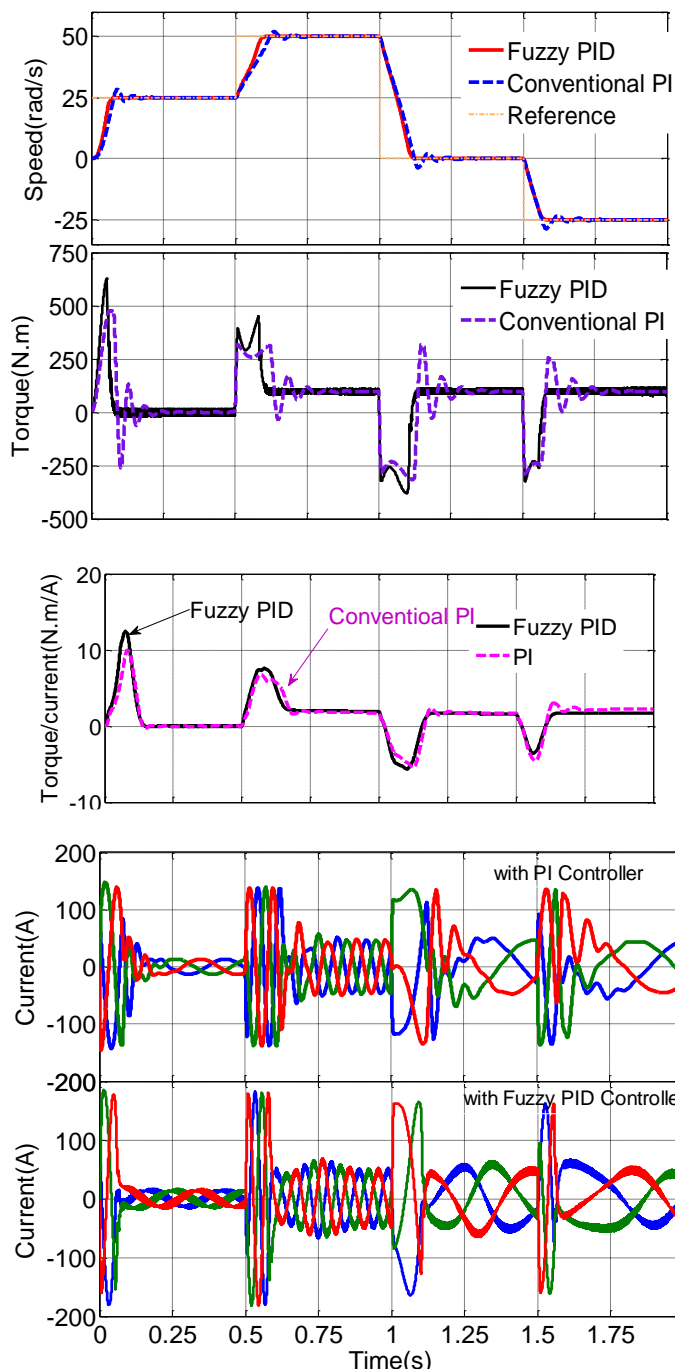


Figure10. Motor responses to some arbitrary step changes in the speed and torque commands

The rotor resistance changes due to the temperature change. By changing rotor resistance, rotor time constant will be changed. That change affects the performance of conventional controllers. Fig. 11 shows the motor speed response with PI controller with 20% increase in the rotor resistance. Fig. 12 shows that response in the same situation but with Fuzzy PID controller. Comparison between Fig. 11 and Fig. 12 reveals the negligible effect of rotor resistance increase on the performance of Fuzzy PID controller.

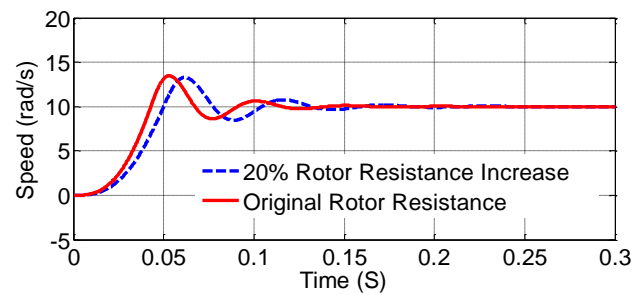


Figure11. Investigating the effect of rotor resistance increase on the performance of PI controller

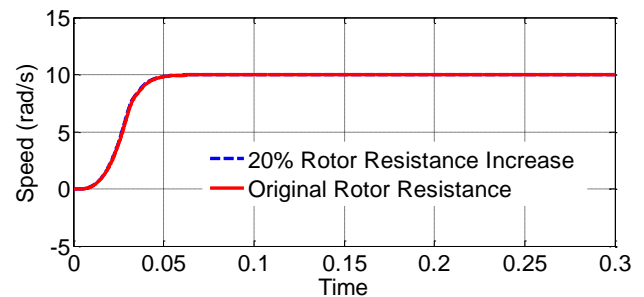


Figure12. Investigating the effect of rotor resistance increase on the performance of Fuzzy PID controller

VII. CONCLUSION

In this manuscript, the SVM-based indirect vector-controlled induction motor drive was replicated by employing both Fuzzy PID controller and conventional PI, along with the concept of fuzzy logic. The simulation results unveiled that the FLC resolves rapidly and depicts better results as compared to the PI controller. As an outcome of this research study, the comparison and analysis of both controllers under the dynamic conditions were under-taken.

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