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Full Paper

DEVELOPMENT OF MICROCONTROLLER-BASED SPEED CONTROLLER FOR THREE-PHASE INDUCTION MOTOR USING FUZZY LOGIC TECHNIQUE

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ABSTRACT

This paper presents an intelligent control technique based on fuzzy logic to control the speed of a three-phase induction motor. There are numerous applications of induction motors in the industry due to their features, such as simplicity in design, cost-effectiveness, and durability. Most of these industrial applications require intelligent control. The induction motor was modelled with a rotating reference frame. The fuzzy logic controller was designed with an MSP430F149 microcontroller for the application requiring speed control. The model of the induction motor was simulated using MATLAB/SIMULINK® version 2013a software. The system's performance was evaluated using a conventional PI controller and fuzzy logic controller. The simulation results show the transcendency of the fuzzy logic controller for indirect vector control of the speed of the three-phase induction motor.

Keywords: *Fuzzy-logic controller, field-oriented control, fuzzy inference system, membership functions*

1. INTRODUCTION

In order to implement conventional control methodologies, the system's model and control knowledge are necessary. Due to the non-linearity of motor dynamics, the usual method of computing the mathematical model of the induction motor is complicated. Recent trends reflect the widely used soft computation techniques in electrical drives generally and induction-motor drives specifically. Thus, the fuzzy logic technique is considered a viable alternative to conventional control methods. Due to their robust construction, simplicity in design, and cost-effectiveness, induction motors have increased in popularity. They have steady performance than direct current (DC) motors but have critical features such as time-varying and non-linear dynamics.

The advancement in power electronics research has significantly contributed to the development of voltage-frequency converters, making it possible to vary the Induction Motor's (IM) speed over a wide range (Kothari and Nagrath, 2004). However, the highly non-linear natures of the induction motor demand strenuous algorithms for the control of speed. Intelligent and variable speed controllers such as scalar-control and vector-control drives have been used to overcome these constraints (Han and Shapiro, 1967; Schittkowski, 1987). Vector Control or Field Oriented Control (FOC) was introduced in late 1960 (Han and Shapiro, 1967). In FOC, the magnitude, frequency, and momentary position of flux linkage vectors, current, and voltage are regulated and found justifiable for both steady-state and transient conditions.

The FOC strategies are categorized into the direct method of field orientation proposed by Blaschke (1972) and the indirect technique of field orientation recommended by Hasse (1969). The direct method depends on flux acquisition obtained by computation techniques using machine terminal quantities, whereas indirect methods use known parameters of the motor to determine the relevant slip speed of the motor to obtain the preferred flux position (Archana et al., 2012). The indirect method of FOC is more popular because it is easily implemented than the direct method (Koechli et al., 2004; Jazdzynski, 1989; Idir et al., 1997; Singh et al., 1993; Ramarathnam and Desai, 1971).

The types of conventional controllers that are used for the functions mentioned earlier could be numeric or neural, or fuzzy. The frequently used controllers are Proportional Integral Derivative (PID), Proportional Integral (PI), Proportional Derivative (PD), Fuzzy Logic Controller (FLC), or a combination of the different types of controllers. PID control is an efficient solution to many control problems in the real world. If PID controllers are tuned properly, they can provide a robust and reliable control (Mallesham and Rajani, 2006).

Variable Speed Drives (VSD) for IM needs a wide operating speed range and a swift torque response, regardless of the load variations, leading to modern means of control to meet the actual demand. Recently, computational intelligence such as Fuzzy Logic Set (FLS); Artificial Neural Network (ANN); Fuzzy-Neural Network (FNN); Genetic Algorithm Based system (GAB); Genetic Algorithm Assisted system (GAA) are being widely used in induction motor drives (and, in general, all other electrical drives). Fuzzy logic has been used in several motor control applications to subdue the complications of conventional controllers e.g., difficulty in controlling moving processes with time-delays, long testing time, etc. (Behrooz, 2018). Due to characteristics such as knowledge-based algorithm, improved non-linearity handling feature irrespective of the plant modelling, fuzzy logic has been used widely by many researchers. Fuzzy logic in its control algorithm imitates the human thought process. It has features such as better stability, high precision, reliability, and complex non-linear control to uncertain non-linear systems, thereby making it useful in industries.

2. FUZZY LOGIC CONTROLLER TECHNIQUE

Fuzzy logic depends on fuzzy logic set theory, which comprises variables having 0-1 degree of membership. Fuzzy logic uses word descriptions instead of mathematical equations to prescribe the rules that decide a system's behaviour.

The fuzzy-logic controller comprises three essential segments: fuzzification block or fuzzifier; inference system, and defuzzification block or defuzzifier. In order to design a fuzzy logic controller, the first step is to choose appropriate inputs that ultimately represent the dynamic system. These inputs are in the form of numerical variables (crisp sets) converted into fuzzy sets called linguistic variables by the fuzzifier. The fuzzy inference system consists of a rule-based database and reasoning mechanism. The rule base is made up of several “If-Then” rules, which are similar to the human thought process. The 'If side' is the antecedent, and the 'Then side' is the consequence. The rules are simple to fathom and write, thereby making fuzzy logic controller programming very simple. The reasoning mechanism carries out inference procedures on the data given and the rules to give a good output.

The defuzzifier converts the fuzzy variable obtained after processing the input into crisp sets. This is important because other systems in the real world take crisp values as input. There are three architectures of defuzzification which include the Mamdani fuzzy model, Takagi-Sugeno fuzzy model, and Tsukamoto fuzzy model. The Mamdani model is used in this study since it strictly supports the compositional rule of inference in its mode of reasoning (jang *et al.*, 1997). The fuzzy output can be defuzzified with seven different methods: Centroid method; Max-membership principle; Mean-max membership; weighted average method; Centre of sums; First of maxima or last of maxima; Centre of the largest area. The centroid method, also called the centre of area method, among others, is widely used.

3. METHODOLOGY

Figure 1 shows the block diagram of the FLC for indirect vector control (IVC) of a three-phase induction motor. For designing the fuzzy-logic controller, two system dynamic input parameters were selected: change in error and speed error, while the output parameter is a control signal as illustrated in Figure 1. The two inputs, which are numerical parameters, were fuzzified, converted into linguistic variables. The membership functions associated with the input variables and output were triangular and Gaussian shapes (Tables 1 and 2). The universe of discourse was selected for the inputs and outputs and divided into seven overlapping fuzzy sets of linguistic variables Negative small (NS), Negative medium (NM), Negative big (NB), Zero (Z), Positive big (PB), Positive small (PS) and Positive medium (PM).

The output variables and input variables were related by 49 “If-Then” rules due to seven fuzzy sets in each input (Table 3). Fuzzy operator AND was applied to the two inputs to produce an output. If and then rules were formed between the inputs (antecedents) and the output (consequence). The consequence was calculated based on the antecedents rules.

The output was defuzzified using Mamdani architecture, where the output membership function was cut short at the height of the value that correlates with the degree of fulfilment. The consequences were then accumulated to produce the final fuzzy output. Centroid defuzzification, expressed in eqn. (1), was used to defuzzify the resultant fuzzy output into actual physical form.

$$z^* = \frac{\int \mu_c(z) z dz}{\int \mu_c(z) dz} \qquad (1)$$

where

$\int$ is used for algebraic integration
z^* = resultant control signal
$\mu_c(z)$ = Output membership function
z = control signal

Table 1: Fuzzy Rule Table for Output Control Signal (I)

Fuzzy set	Set Description (Speed Error)	Range	Membership Function

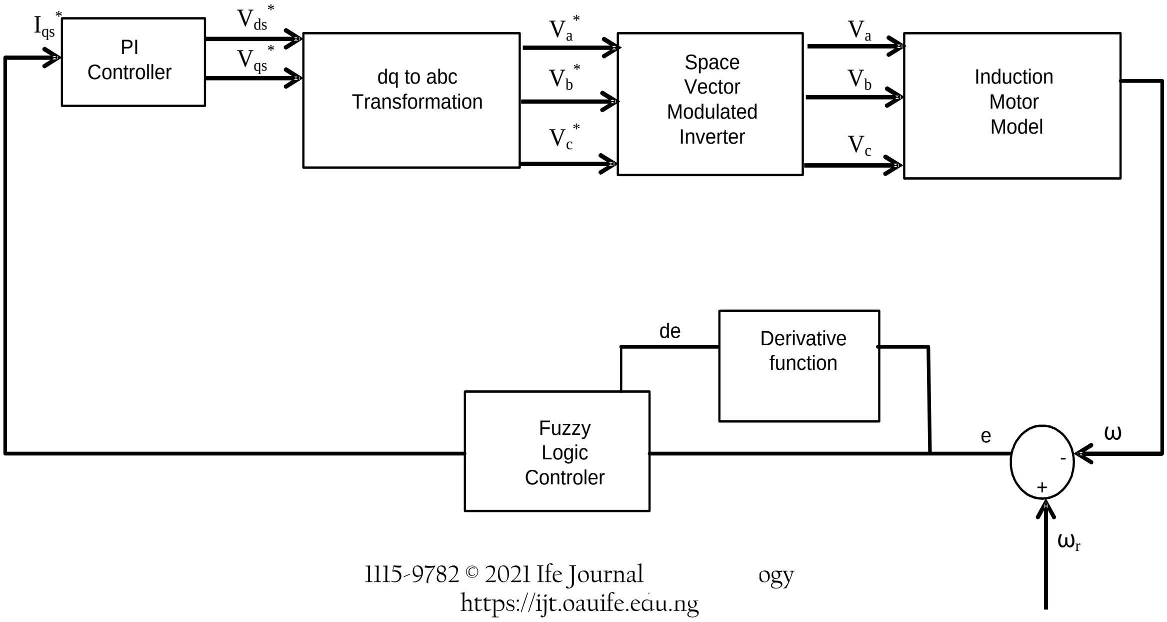

Figure 1: Block Diagram of FLC for IVC of Three-Phase Induction Motor

NB (Negative Big)	Negatively High	-500 - 0 0 - 500	Triangular
NM (Negative Medium)	Negatively Medium	0 - 500 500 - 1000	Triangular
NS (Negative Small)	Negatively Small	500 - 1000 1000 - 1500	Triangular
Z (Zero)	Around Zero	1000 - 1500 1500 - 2000	Triangular
PS (Positive Small)	Positively Small	1500 - 2000 2000 - 2500	Triangular
PM (Positive Medium)	Positively Medium	2000 - 2500 2500 - 3000	Triangular
PB (Positive Big)	Positively High	2500 - 3000 3000 - 3000	Triangular

Table 2: Fuzzy Set and Representative Membership Functions for Change in Speed Error (de) and Speed Error (e)

Fuzzy Set	Set Description (Speed Error)	Range	Membership Function
NB	Negatively High	27.4 to -99.72	Gaussian
NM	Negatively Medium	-100 to -66.67 -66.67 - 0	Triangular
NS	Negatively Small	-100 to -33.33 -33.33 to 33.33	Triangular
Z	Around Zero	-66.67 to 0 0 to 66.67	Triangular
PS	Positively Small	-33.33 to 33.33 33.33 to 100	Triangular
PM	Positively Medium	0 to 66.67 66.67 to 100	Triangular
PB	Positively High	27.67 to 100	Gaussian

3.1. Design and simulation of Fuzzy Logic Controller for the Induction Motor

The fuzzy logic controller was implemented using the MSP430F149 device for the motor speed control application. Figure 2 shows the application block schematic. An 8 MHz crystal sources the MSP430 to produce a high-resolution clock source used to generate pulse width modulation for the inverter and measurement of the motor speed. The clock system of the MSP430 and the peripheral were set up. The actual speed was determined by Timer A. The capture event was triggered by Timer A capture/compare block 0 using the rising edge of the port pin P2.2. The unique hardware-generated stamp was read out and processed in the associated ISR function. This value was passed through a moving average filter, and the freshly computed speed value was kept in the variable current. The capture/compare block 1 was set to compare mode and offer a time-out mechanism for measuring speed. Implementing this time out, the variable current speed becomes updated, and the control procedure continued working. Timer A worked in continuous mode to mitigate the effect of software latency which affects the measurements. Timer B's capture/compare block number 2 was set to compare mode and used for pulse width modulation (PWM) signal generation. Timer B was activated in up-mode and operated by the 8 MHz clock source setting the period register to 3999; the operational PWM output frequency was 8 MHz / (3999+1) = 2 kHz. This setup gave a fine granularity for motor power adjustment, which results in smoother control.

The watchdog module was set as interval times. Its ISR function was called 244 times per second to waken the CPU from a mode of low power. This principle offers the time interval between each of the control cycles. The actual control loop was realized after setting up the peripheral, lower power mode was activated, thereby switching off the CPU and ending the execution of the program while awaiting the wake-up initiated by the watchdog timer ISR.

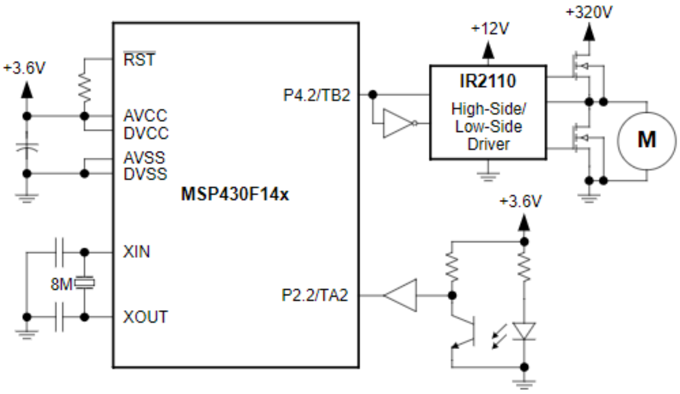

Figure 2: Hardware Block Schematic

On wakeup, the absolute 'Error' and differential control loop error 'Change in Error' were calculated based on the reference speed, current speed, and previous error value. These errors were changed into fuzzy values e and de through fuzzification. Forty-nine (49) “If-Then” rules were then applied to the inputs to generate an output. The output vector was converted into a single control loop value and added to the duty cycle of the current PWM thereby closing the control loop. The motor duty cycle is regulated within the range provided by the PWM_Min and PWM_Max. This is therefore adjusted based on the application and load conditions. The PWM signal triggers the inverter to generate a three-phase voltage. This voltage was supplied to the IM running at a speed that follows the reference.

Table 3: Fuzzy Rule Table for Output

	Speed Error (e)						
Change in Error (de)	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NM	NM	NS	NS	Z
NM	NB	NB	NM	NS	NS	Z	NS
NS	NB	NM	NS	NS	Z	PS	PM
Z	NM	NM	NS	Z	PS	PM	PM
PS	NM	NS	Z	PS	PS	PM	PB
PM	NS	Z	PS	PS	PM	PB	PB
PB	Z	PS	PS	PM	PM	PB	PB

Several simulation tests were carried out on the induction motor using the PI controller and FLC to control the speed. Simulations were carried out varying the reference speed and the load torque. The command of the reference speed was applied to start with an acceleration rate that corresponds to the speed of 900 rpm and suddenly changed to 1500 rpm. Comparing PI controller and FLC performance, the response of motor speed, torque, and current were observed.

4. RESULTS AND DISCUSSION

Figure 3 shows the three-phase output voltage waveform fed to the induction motor (without filter), while Figure 4 shows the output voltage waveform (with filter).

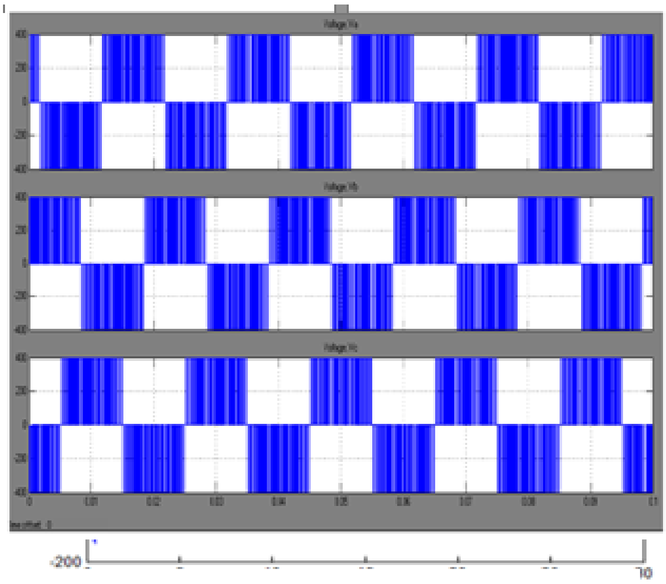

Figure 3: Three-phase Output Voltage Waveform (without a Filter)

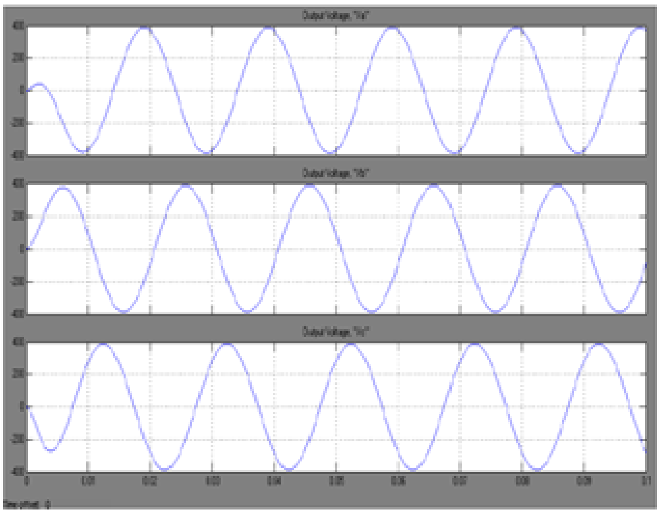

Figure 4: Three-phase Output Voltage Waveform (with a Filter)

The speed response of the motor using PI and Fuzzy controller is shown in Figure 5 and Figure 6, respectively.

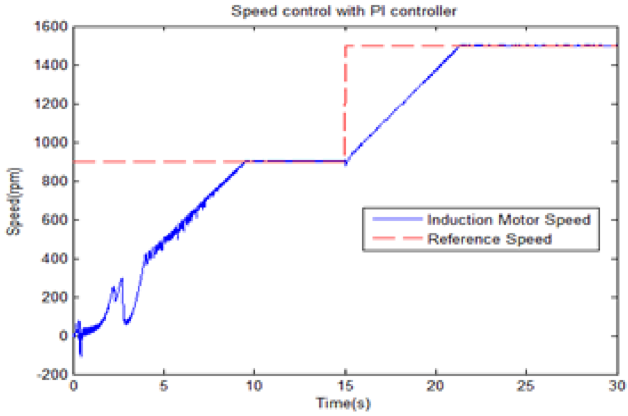

Figure 5: Speed Response with PI-Controller

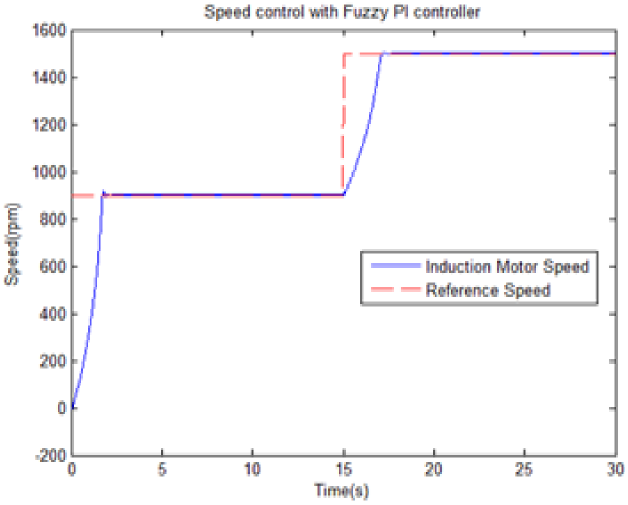

Figure 6: Speed Response with Fuzzy Controller

Using PI-Controller, the IM speed took about 10s to reach the 900 rpm reference speed, and when the speed was suddenly changed to 1500 rpm, the controller took another 5 seconds to attain the speed. The result of the fuzzy controller showed far better improvement compared to the PI controller, with 2.8s to attain 900rpm and 2.3s to attain 1500rpm. A load was applied at time = 2 s, while another load was applied at time = 15 s. The second load had a greater effect on the motor speed. As a result., the control signal is proportional to the variation in load. After a short time of load variation, the actual motor speed was maintained equal to the reference speed. The overshoots attained using FLC are less significant as compared to when the PI Control was used. The settling time was also less in the case of the FLC. Therefore, the FLC gives an enhanced response with a change in load torque and speed references. It moves toward the new speed reference faster with relatively minimum overshoot. However, the PI significantly deviates from the new speed reference and fails in attaining a steady state when its difference with base speed is high.

The torque response using PI and the fuzzy controller is shown in Figure 7 and Figure 8, respectively. The response with PI-controller has inherent overshoots of 0.75% and oscillation when transients occur. The overshoot and significant pulsations in the torque observed result in oscillations in the speed and gives a long settling time. Using FLC, the torque was observed to be constant with only slight oscillation. The FLC-based drive has 0.33% torque overshoot for just 2 seconds each time the speed was varied, thereby reducing torque ripple. It gives a robust performance in the presence of induction motor speed variation. There was a distortion in the current envelope using the PI controller, as shown in Figure 8, while with the fuzzy controller, a distortion in the current waveform is observed at start-up before the drive reaches a steady state, as shown in Figure 10. The inevitable transient at the induction motor start-up is responsible for this distortion. Otherwise, the current was completely sinusoidal and steady. The results obtained from all simulations conform to expected performance and thus validates the IM speed control employing the FLC technique over PI.

The three-phase IM performance was analysed with the IVC technique using Fuzzy Controllers and PI in MATLAB/SIMULINK® version 2013a. Based on set point (reference) and feedback from the induction motor, the Fuzzy Logic Controller produced a proper control signal used by the inverter to regulate the speed of the IM. Simulation results showed better performance of the Fuzzy Logic Controller over the conventional PI-Controller in the speed control process. The implementation is simple, and the design flexibility and modification are provided for a wide range of applications.

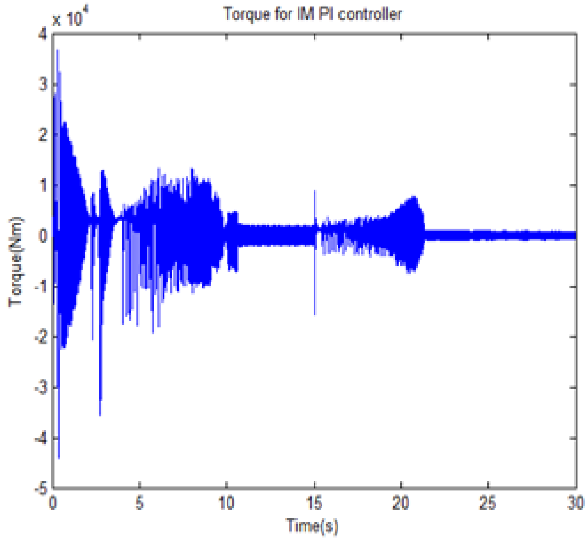

Figure 7: Torque Response with PI-Controller

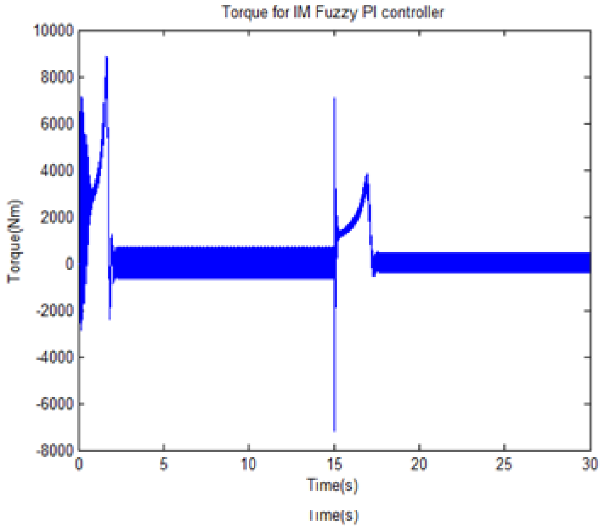

Figure 8: Torque Response using Fuzzy Controller

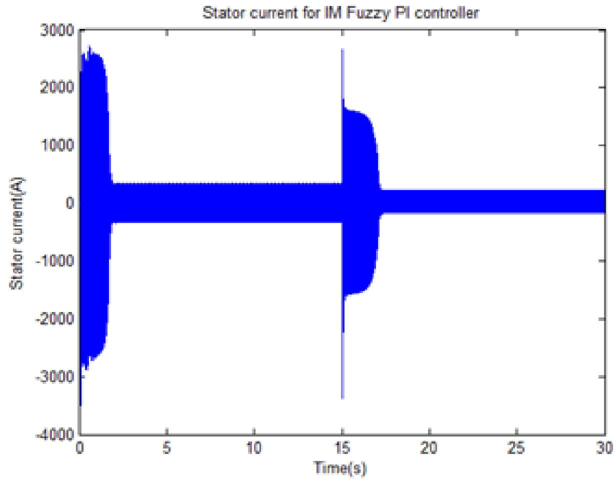

Figure 9: Current Response using Fuzzy Controller

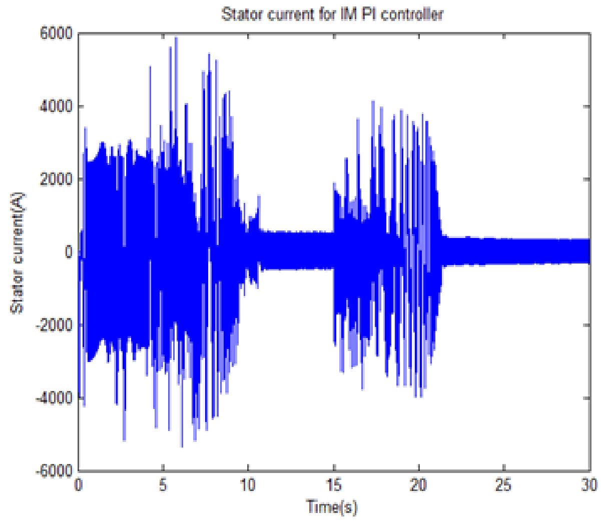

Figure 10: Current Response using PI-Controller

5. CONCLUSION

The behaviour of indirect vector control of the three-phase induction motor was analysed using PI and fuzzy controller. Based on the reference speed and feedback from the induction motor, the fuzzy logic controller produced a proper control signal. Results from simulation showed that fuzzy logic controller has a better performance in speed control process over PI controller. Once designed, the implementation of fuzzy logic can be adapted to various applications.

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