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# Development of Fuzzy Logic-Based Speed Control of Novel Multilevel Inverter-Fed Induction Motor Drive

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**Abstract:** This paper presents the transformer-based multilevel inverter-fed induction motor drive. The development of new technology of power electronic switches and control techniques for inverter-based speed control of induction motor has led to the usage of induction motor in industrial and domestic applications. In this work, the stator winding of induction motor is fed through proposed five-level transformer-based symmetrical inverter, which consists of unidirectional and bidirectional switches, mid-point transformer and capacitors as voltage divider network to produce multilevel output voltage at the load side. The speed of the induction motor is varied by changing supply voltage of an induction motor by adjusting width of the pulse width-modulated signal. A speed controller has been implemented through fuzzy logic controller for performing closed loop operation of single phase induction motor drive. The ability of fuzzy-based speed controller can reduce the undesirable sustained oscillations in speed of induction motor drive and also provide better machine performance than conventional linear controller. The proposed controller performance of multilevel inverter-fed induction motor drive system is validated through MATLAB simulink environment.

**Keywords:** Multilevel Inverter, Induction Motor, Fuzzy Logic Controller, Sinusoidal Pulse Width Modulation, Fuzzy Set, Fuzzy Logic

## 1 Introduction

Induction motors are utilized for constant speed applications because conventional methods of their speed control have either been expensive or extremely inefficient. Availability of thyristors, power transistors, IGBT and GTO has authorized the growth of variable speed induction motor (IM) drives [8]. Compared to two-level inverter, multilevel inverters have several benefits along with decrease values of voltage on switches, Total Harmonic Distortion (THD), electromagnetic interference and many others [1–3]. However, the multilevel inverter circuit utilizes numerous number of switches and DC sources [4–7]. To overcome this problem, a new transformer-based multilevel inverter is presented which has ability to reduce the harmonics without filters along with reduced switch count.

In earlier days, speed control of induction motor has been implemented through classical controllers like PI, PD and PID controllers whose speed has been broadly used due to its easiness and robustness, however in some cases, the dynamics of drive system deviates with time or over load condition which deteriorates the quality of control [9]. The problems in linear PI, PD and PID controllers are the difficulty in designing a controller for non-linear dynamics of IM [10]. The conventional controllers should linearize the non-linear systems so one can calculate the parameters of the drive system [11–14]. The major drawbacks of conventional controller are poor dynamic response, torque and flux ripple which are reduced by the proposed fuzzy logic speed controller.

This work affords a control scheme for single phase induction motor with fuzzy logic based speed controller. A simple SPWM approach is implemented for a wide range of output voltage and it provides smooth speed control operation of the drive. In this paper, a FLC controller is modelled using MATLAB/SIMULINK.

## 2 Proposed Drive System

In this work, the stator winding of IM is fed through proposed five-level transformer-based symmetrical inverter, which consists of 3 unidirectional and one bidirectional switches, one mid-point transformer, two

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**Table 1:** Switching pattern of proposed 5-level inverter

| State | Switching State | | | | Inverter Output |
|---|---|---|---|---|---|
| | $S_1$ | $S_2$ | $S_3$ | $S_4$ | $V_{out}$ (V) |
| I | OFF | ON | ON | OFF | 240 |
| II | ON | OFF | ON | OFF | 120 |
| III | OFF | OFF | OFF | ON | 0 |
| IV | ON | OFF | OFF | ON | −120 |
| V | OFF | ON | OFF | ON | −240 |

capacitors as voltage divider network to produce five-level output voltage at the load side. The speed of the IM is varied by changing supply voltage of an induction motor by adjusting width of the PWM signal. A speed controller has been implemented through FLC controller for performing closed loop operation of single phase induction motor drive. The input of FLC is error of speed and its derivative, the output variable is single control signal for generating gating signal for regulating the speed of the motor. The ability of fuzzy logic-based speed controller can reduce the undesirable sustained oscillations in speed of IM drive and also provide better machine performance than conventional linear controller. The performance of the proposed controller-fed IM drive is validated through MATLAB simulink environment. The detailed operation of transformer-based five-level inverter is described below.

### *2.1 Proposed Five-Level inverter-fed IM Drive*

This proposed MLI topology has a feature of galvanic isolation between source and load, which enhances the reliability of the inverter. To generate five-level in the output voltage, this topology requires two level-modulated and two polarity-modulated switches along with capacitive voltage-divided network. The proposed inverter has five levels in the output voltage (120 V, 240 V, 0 V,−120 V,−240 V) with a single DC source of 240 V and the different input voltage pattern has been arrived through capacitor network. The modes of operation of the proposed inverter topology is shown in Fig. 1. The inverter output terminal is connected to the stator of single phase induction motor and the speed to be regulated by means of controlling inverter output voltage.

The speed error is attained by comparing the speed of the induction motor with reference speed. The mamdani rule-based FLC structure has been designed, which has two input variables; one as speed error and other one is derivative of speed error. The controller output signal decides the reference voltage magnitude. The working of this five-level inverter topology can be understood by using switching pattern as presented in Table 1.

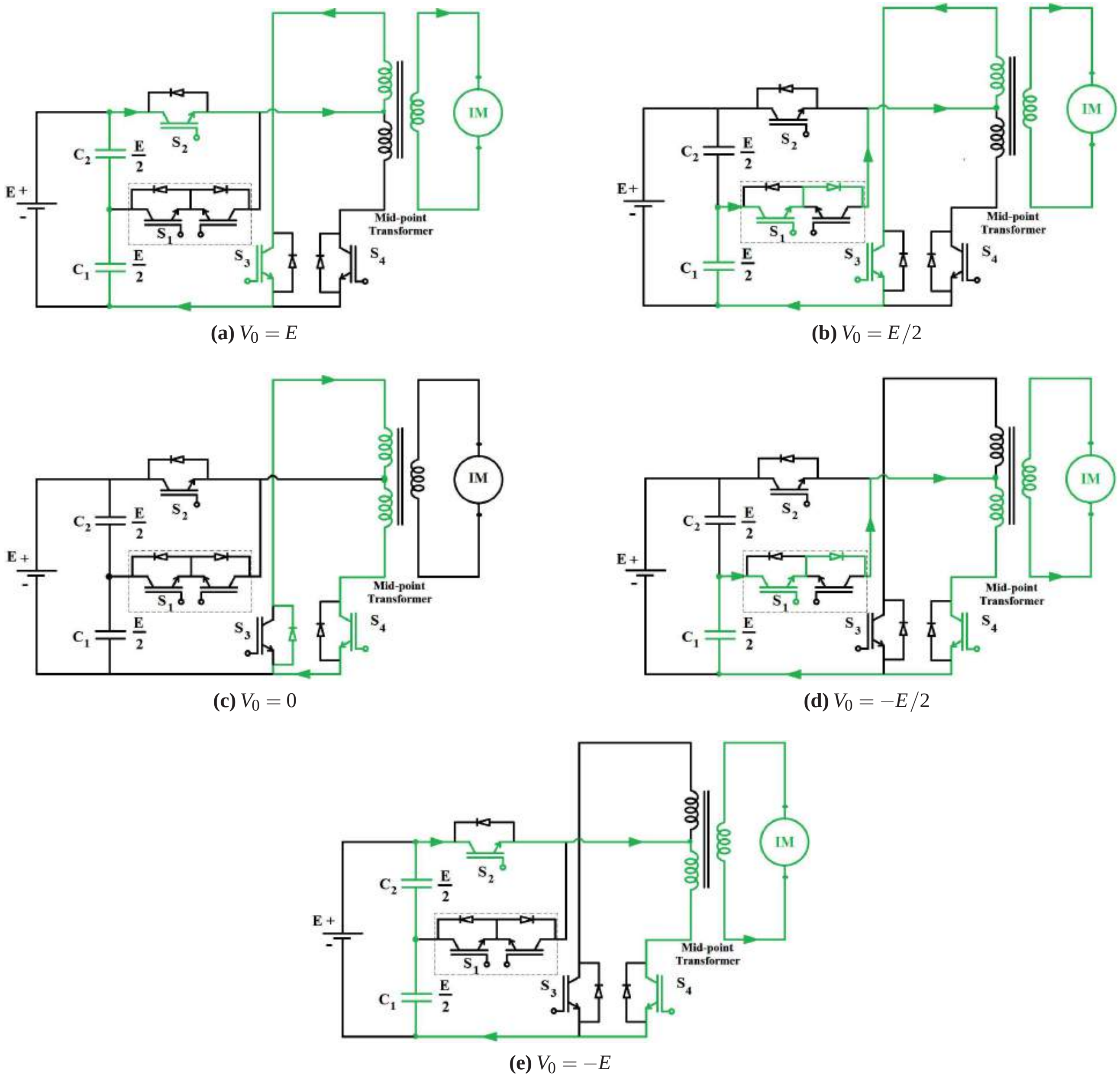
Here, a simple PWM method is used to generate the switching pulse for five-level inverter. This PWM scheme uses two fundamental frequency of sinusoidal wave as reference signal having equal magnitude with offset value and a single carrier signal having high frequency for generating control signal. The control signal is generated by comparing reference signal with carrier signal as presented in Fig. 2. The FLC output signal is multiplied with 2 reference signals and compared with carrier magnitude to regulate the inverter output voltage for performing closed-loop speed-control operation.

## 3 Design of Fuzzy Logic Controller

Soft computation technique is one of the solutions to solve the aforementioned issues of the design of controller for the induction motor drive systems [9]. The fuzzy logic concept is established by Zadah which is based on the fuzzy set theory. Fuzzy logic provides a systematic calculus to deal with such information linguistically, and it performs numerical computation by using linguistic labels stipulated by membership functions [10]. The development of fuzzy logic was motivated in large measure by the need for a conceptual framework which can address the issue of uncertainty and lexical imprecision [11]. Fuzzy control and modelling use only a small portion of the fuzzy mathematics that is available; this portion is also mathematically quite simple and conceptually easy to understand [12]. The fuzzy logic has provided a mathematical strength to capture the uncertainties associated with human cognitive processes, such as thinking and reasoning. Fuzzy logic provides an interface morphology that enables approximate human reasoning capabilities to be applied to knowledge-based systems [13,14].

The basic structure of a fuzzy inference system consists of three conceptual components: a rule base, which contains a selection of fuzzy rules; a database, which defines the membership functions used in the fuzzy rules; and a reasoning mechanism, which performs the inference procedure upon the rules and given facts to derive a reasonable output or conclusion. The basic configuration of a FLC is shown in Fig. 3. Fuzzy IF–THEN rules and fuzzy reasoning are the backbone of fuzzy inference systems, which are the most important modelling tool based on fuzzy set theory.

The basic fuzzy inference system can take either fuzzy inputs or crisp inputs, but the outputs it produces are almost always fuzzy sets. It is necessary to have a crisp output, in a situation where a fuzzy inference system is used as a controller. A method of defuzzification is needed to extract a crisp value that best represents a fuzzy set. With crisp inputs and outputs, a fuzzy inference system implements a nonlinear mapping from its input space to output space. This mapping is accomplished by a number of fuzzy IF–THEN rules, each of which describes the local behavior of the mapping. The defuzzifier converts the fuzzy quantities into crisp quantities from an inferred fuzzy control action by the inference engine. Hence fuzzy control does not require any mathematical model of the system and so it can be applied to nonlinear systems.




**(a)** $V_0 = E$ **(b)** $V_0 = E/2$

**(c)** $V_0 = 0$ **(d)** $V_0 = -E/2$

**(e)** $V_0 = -E$

**Fig. 1:** Modes of operation of the proposed MLI-fed IM drive

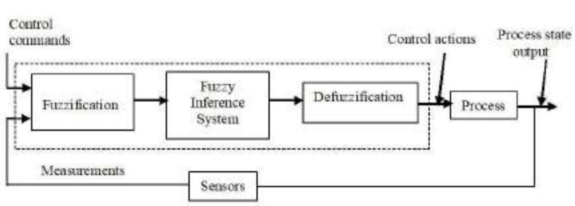



**Fig. 3:** Structure of fuzzy logic controller

Fuzzy conditional or fuzzy IF–THEN production rules are symbolically expressed as

$$\{\text{IF(premise } i\text{) THEN (consequent } i\text{)}\}_{i=1}^{D}$$

where $D$ is the number of rules.

There exist two major types of fuzzy rules: Mamdani and Takagi-Sugeno fuzzy rules. A Mamdani fuzzy controller uses fuzzy sets as rule consequent. So, fuzzy rules are more intuitive and can more easily be extracted from expert knowledge and experience. Hence, a

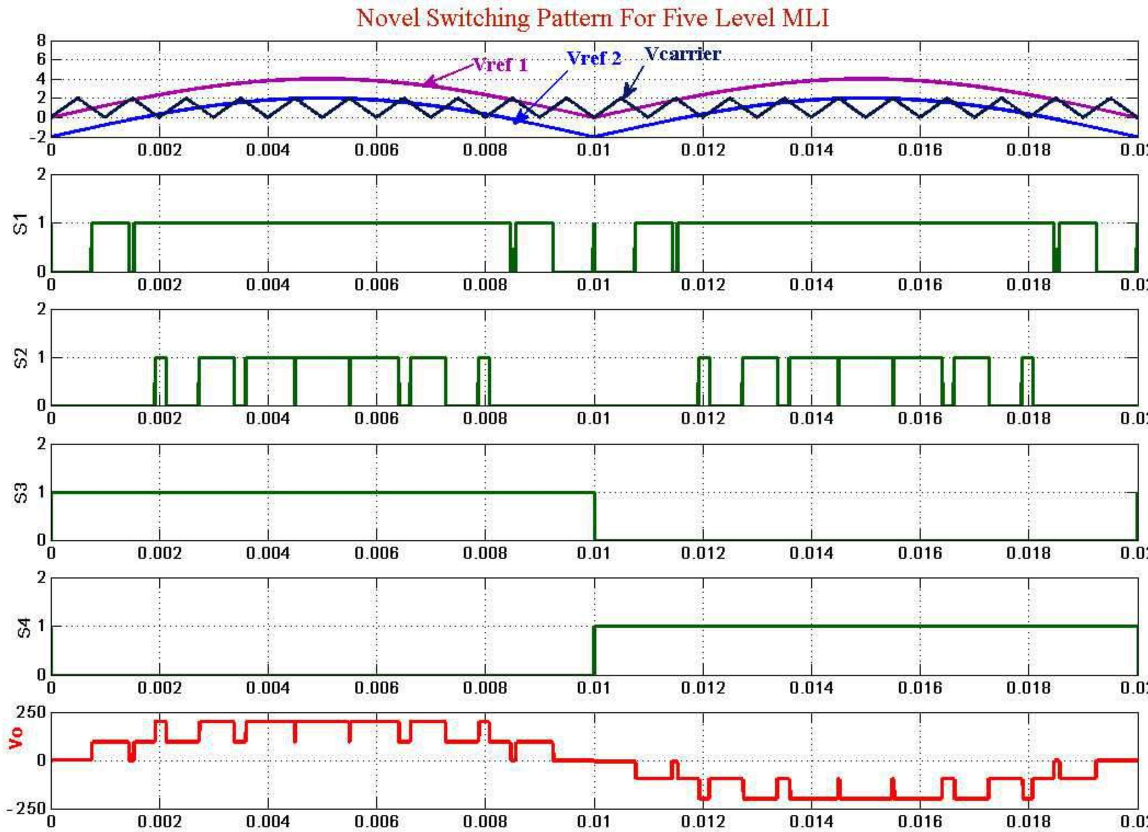



**Fig. 2:** A simple PWM scheme for proposed MLI-fed IM drive

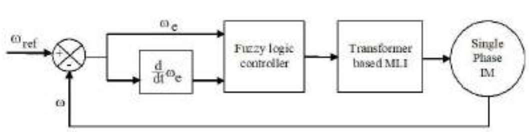



**Fig. 4:** Block diagram of fuzzy controller-based IM drive

Mamdani-type inference system is commonly used because of its advantage of intuition, wide acceptance and suitability to human input. Defuzzification is a mapping from a space of fuzzy control action defined by fuzzy sets on an output universe of discourse into nonfuzzy (crisp) control actions. This process is necessary because crisp control action is required to actuate the control. Among the various defuzzification methods, the most commonly used method is the centroid technique.

Modern electric drive system needs to monitor the shaft speed of the motor continuously to ensure that the desired speed can be achieved by employing intelligence-based controller-like fuzzy. As shown in Fig. 4, the desired speed of the motor is the set point and the measured speed is from the feedback signal. Thus, the anticipated speed of the motor is achieved by the operation of closed loop control system. The error signal is obtained by subtracting actual speed from the desired speed. The FLC block receives two input signals of error signal and its derivatives of error signal. The output of FLC is sent to PWM generator which in turn produces a PWM signal proportional to the set speed voltage of induction motor, and hence the speed is maintained constant.

The input variables of FLC are the speed error, $\omega_e$ and change in error, $\omega_{ec}$ signals defined as:

$$\omega_e(n) = \omega_{\text{ref}}(n) - \omega(n) \tag{1}$$

$$\omega_{ec}(n) = \omega_e(n) - \omega_e(n-1) \tag{2}$$

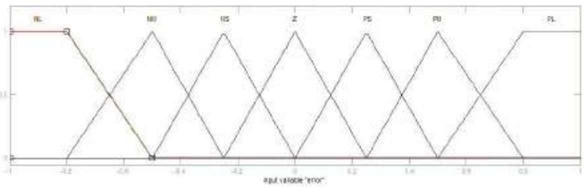
where $\omega$ represents the rotor mechanical angular speed, $\omega_e$ represents error in angular speed, $\omega_{\text{ref}}$ is set speed, $\omega_{ec}$ change in error signals. The corresponding output $Y_f$ is

$$Y_f(t) = f(\omega(t), \omega_{ec}(t)) \tag{3}$$

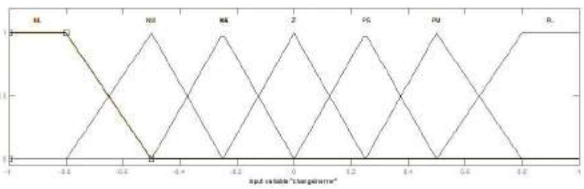
Usually, an odd number of membership functions is used in fuzzy logic applications to partition a region.

In this problem, seven membership functions were chosen and the range of each variable lies in the range of:

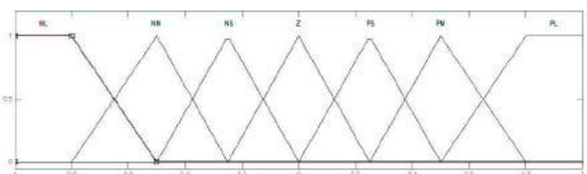
**Fig. 5:** Simulink diagram of FLC



**(a)** Input membership function "Error"



**(b)** Input membership function "Change in Error"



**(c)** Output membership function "Control Signal"

**Fig. 6:** Representation of Input–Output membership function

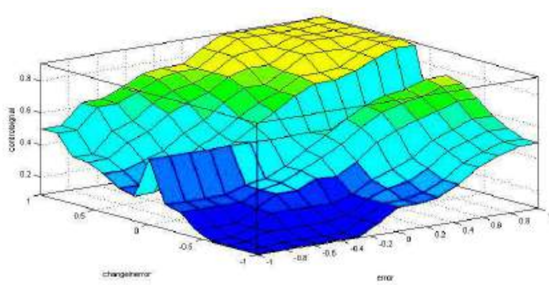


**Fig. 7:** Surface plot of FLC response

Negative Large (NL), Negative Medium (NM), Negative Small (NS), Zero (Z), Positive Small (PS), Positive Medium (PM) and Positive Large (PL), which is used to determine the required control signal to obtain the desired inverter output voltage to track the set speed of the motor. The rule base consists of IF–THEN statements which direct the input–output relationship like IF (speed error is NL) AND (change in speed error is NS) THEN (change in control value is NL). In this design, forty-nine rules were considered to make effective control function to stabilize the speed and improve dynamics of the system, the rules tables are presented in Table 2

The simulink diagram of fuzzy logic controller is shown in Fig. 5. The whole fuzzy set along with their triangular membership function for inputs, output variable and control signal are shown in Fig. 6. All input and output variables are normalized to fit the range of ($-1$ to 1). Fig. 7 shows the surface plot of the FLC response.

**Table 2:** Fuzzy rule base for speed control of IM

| $\frac{d\omega_e}{dt}$ | $\omega_e$ | | | | | | |
|---|---|---|---|---|---|---|---|
| | NL | NM | NS | Z | PS | PM | PL |
| NL | NL | NL | NL | NM | NM | NS | Z |
| NM | NL | NL | NM | NM | NS | Z | PS |
| NS | NL | NM | NM | NS | Z | PS | PM |
| Z | NM | NM | NS | Z | PS | PM | PM |
| PS | NM | NS | Z | PS | PM | PM | PL |
| PM | NS | Z | PS | PM | PM | PL | PL |
| PL | Z | PS | PM | PM | PL | PL | PL |

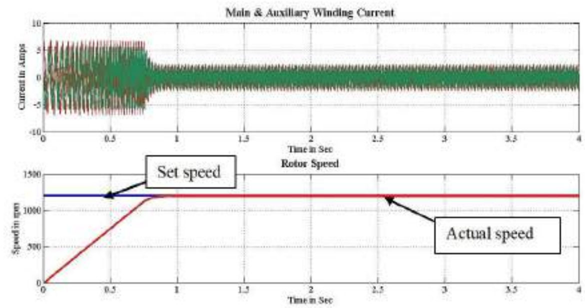



**Fig. 10:** No load response of proposed inverter-fed IM drive

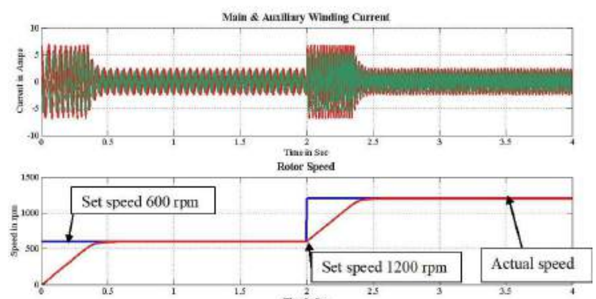



**Fig. 11:** Step change in increased speed response at no load operation

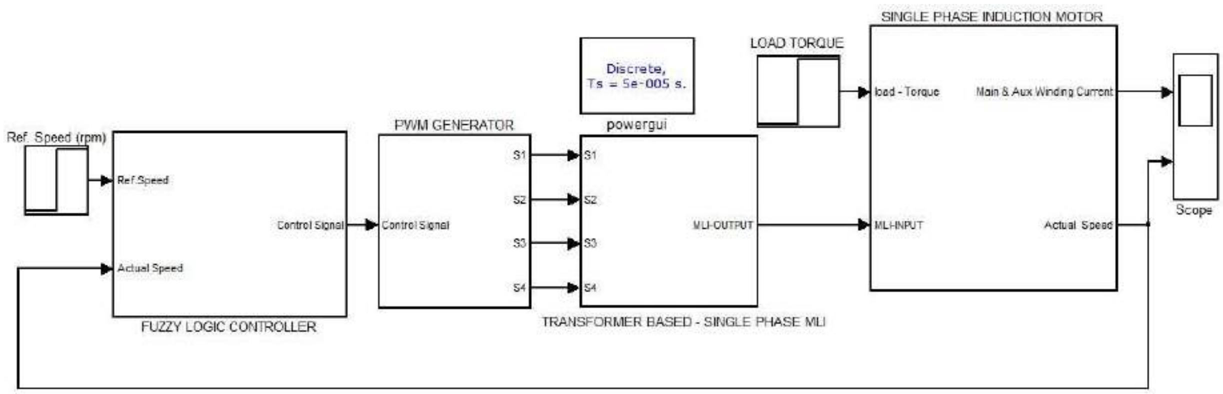



**Fig. 8:** Sub system model of FLC-based speed control of IM drive

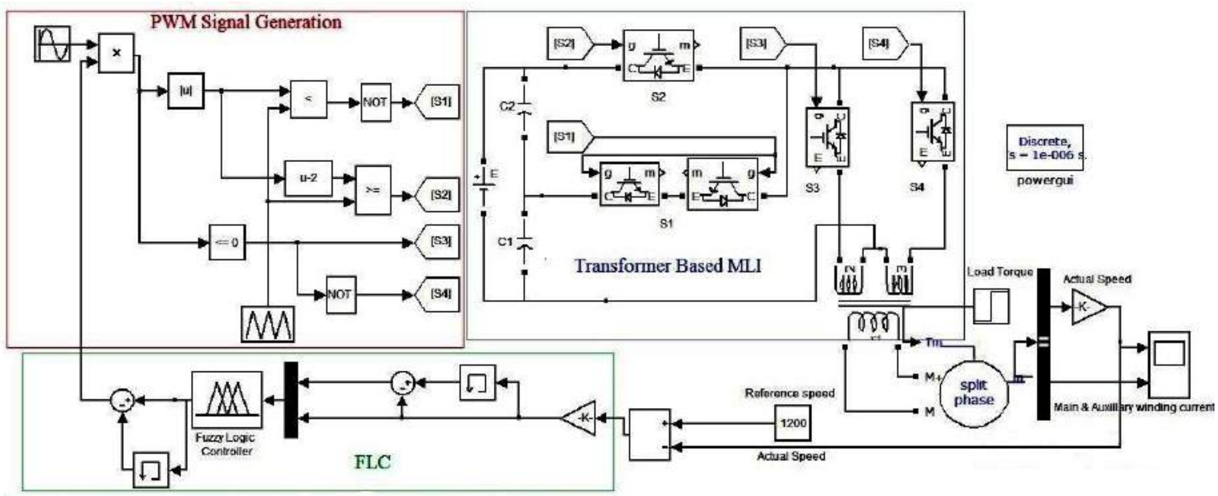



**Fig. 9:** Simulink model of proposed MLI-fed IM drive with FLC

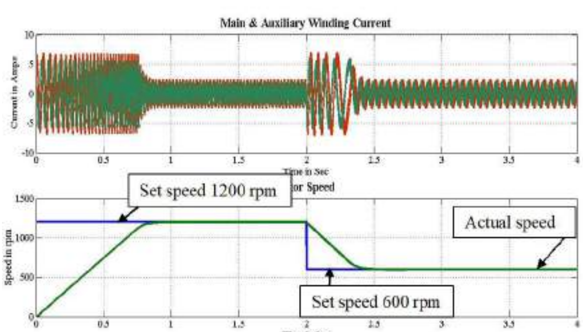



**Fig. 12:** Step change in decreased speed response at no load operation

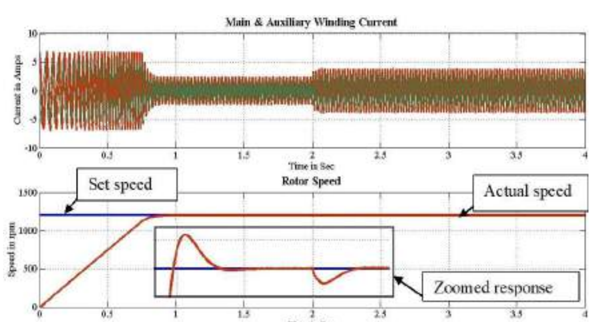



**Fig. 13:** Step change increase in load response from no load to load ($T = 1$ N-m) at 2 s

## 4 Investigation of Simulation of Proposed Drive System

The proposed work has been simulated in MATLAB/SIMULINK environment to validate the

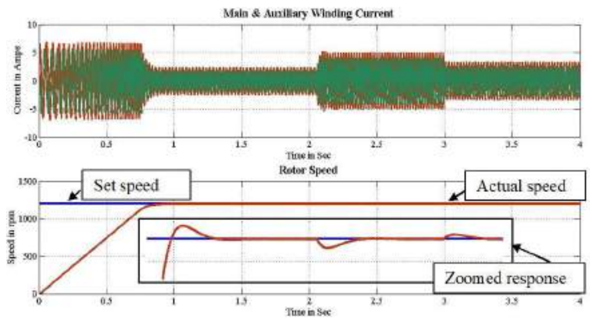



**Fig. 14:** Step change in load at various conditions (Load $T = 1.5$ N-m at 2.1 s and load $T = 1$ N-m at 3 s)

effectiveness of the proposed MLI-fed induction motor drive at different operating conditions. The simulink model of the block diagram is shown in Fig. 8 which consists of fuzzy logic controller, PWM generator, and transformer-based MLI and single phase induction motor. The complete simulink structure of proposed drive system is shown in Fig. 9. A single phase split phase type induction motor is considered as a load and the parameters are: rated power $P = 180$ W, main winding resistance $R_s = 2.02$ $\Omega$, main winding inductance $L_s = 7.4$ mH, auxiliary winding resistance $R = 7.14$ $\Omega$, auxiliary winding inductance $L = 8.5$ mH, Inertia $J = 0.0146$ kgm$^2$, pole pairs 2, turns ratio 1.18. The following figures illustrate the speed response of FLC-based induction motor drive for certain reference speeds and load disturbance. Fig. 10 shows the no-load speed response of the proposed control system when the reference speed is set as 1200 rpm. Fig. 11 illustrates that a step change in increase of speed with no-load condition. It was applied at 2 s, the output of FLC control signal went up to compensate the increase in speed, during the transition period, the stator current changes from minimum to maximum and settles down when the rotor speed reaches a steady state speed. Similarly, in Fig. 12, a step change in decrease in speed with no load condition, at the same instant of 2 s, the FLC controller has to maintain the set speed to achieve such case by drawing more stator current during transient period and settle down to minimum current when the rotor speed reaches the steady state speed. The following two figures show the load response of FLC system while applying two loads with time interval between them. A change in load from no load to a load value of 1 Nm is applied at time 2 s; the speed response is shown in Fig. 13. In Fig. 14, a multi reference load (no load, 1.5 Nm and 1 Nm) are applied without change in reference speed at time 2 s and at time 3 s respectively. As noticed in the both figures, because of load disturbance the actual motor speed is sustained equal to the reference speed after a short time of

**Table 3:** Time domain specification of the PID, PI and FLC-based drive

| Time Domain Specification (s) | PID | PI | Fuzzy Logic Controller |
|---|---|---|---|
| Delay time | 0.0769 | 0.07645 | 0.07612 |
| Rise time | 0.6111 | 0.61105 | 0.6108 |
| Settling time | 1.678 | 1.456 | 1.348 |

change. It is concluded that, a FLC controller shows a good response in both rise time and settling time to this sudden change of load and set speed. Even after the removal of the applied load, the control signal goes down and maintains the desired speed with relatively very low overshoot, steady-state error and fast response. Finally, it is concluded that, usage of MLI provides the improved quality of the output voltage waveform. The smoothness of the sine wave depends on the elimination of harmonic components. Hence, tests have been done using simulation to analyze the harmonic components of the output voltage. The proposed inverter does not employ additional filter and it provides a features of lesser THD values than conventional two level inverter, which are considered as acceptable harmonic distortion according to IEEE standards. The results obtained from the simulation show that the FLC controller has significantly better performance.

The proposed FLC drive system is compared with PID and PI controller to prove the superiority of the proposed drive.

From Table 3, it can be observed that the delay time, setting time, rise time of the FLC drive system are minimum compared to classical PI, PID controller fed drive. Hence, the FLC fed IM drive is suitable for all the practical applications.

## 5 Conclusion

A transformer-based five-level inverter-fed induction motor drive with fuzzy logic-closed loop speed controller is investigated. The five-level inverter structures consist of lesser number of power electronic switches with single DC voltage source. The operation and performance of the proposed inverter-fed IM drive with FLC model is validated through the MATLAB simulation. The static and dynamic performances of FLC-based speed controller have been assessed under a variety of operating conditions of the drive system, and the results exhibit the effectiveness of this controller configuration. Based on the performance study, it can be shown that FLC-based proposed drive system gives better high speed performance with improved time domain response in terms of minimum delay, rise, and setting time.

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