AI based design of a fuzzy logic scheme for speed control of induction motors using SVPWM technique

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Summary
The reliability and performance of the AC drives depends on the progress in power electronics, microelectronics, control methods, artificial intelligent techniques and so on. Fuzzy Logic Concept (FLC), one of the Artificial Intelligent methods has found high applications in most of the nonlinear systems like the electric motor drives. FLC can be used as controller for any system without requirement of the system mathematical model unlike that of the conventional electrical drive control, which uses the mathematical model. Due to the usage of the FLC concept, the efficiency, reliability & performance of the AC drives increases. In view of the previously mentioned concepts, this paper presents a rule-based fuzzy logic controller scheme designed and applied for the speed control of an induction motor by using the Space Vector Pulse Width Modulation (SVPWM) technique. The closed loop speed control of the induction motor using the above technique, thus provides a reasonable degree of accuracy. Instantaneous space voltage vectors applied by the inverter have redundancy characteristics, which provide some flexibility for selecting the inverter switching modes. Simulink based block model of induction motor drive is used for the simulation purposes & its performance is evaluated for the speed control. The inverter duty cycle can also be calculated using the space vector PWM techniques. The proposed method improves the dynamic performance of the induction machine compared to the conventional speed control of induction motor drives & has got a faster response time. The simulation results presented in this paper show the effectiveness of the proposed method, which has got a wide number of advantages.

Key words :
Artificial Intelligence, Electric drive, Induction machine, Space vector pulse width modulation, Fuzzy logic control, Torque, Speed, Simulink model.

1. Introduction

Induction motors are widely used in various industries as prime workhorses to produce rotational motions and forces. Generally, variable-speed drives for induction motors require both wide operating range of speed and fast torque response, regardless of load variations.

Usually, the classical control is used in majority of the electrical motor drives. Conventional control makes use of the mathematical model for the controlling system. When there are system parameters variation or environmental disturbance, behavior of system is not satisfactory [2]. In addition, usual computation of system mathematical model is difficult or impossible. The design and tuning of conventional controller increases the implementation cost and adds additional complexity in the control system & thus, may reduce the reliability of the control system. Hence, the fuzzy based techniques are used to overcome this kind of problems.

DC motors are controllable than AC motors but the implementation cost required is more. In addition, DC motors has got higher volume and weight compared to the AC motors. Induction motors (one type of AC motors) require low maintenance and are robust, have many applications in industry. Usually, the classical control used in motors drive design and implementation has many difficulties, which can be listed as follows. It is on the basis of the mathematical accurate model of system, that usual it is not known. Drives are nonlinear systems and classical control performance with this system decreases. Variation of machine parameters by load disturbance, motor saturation or thermal variations do not cause expectation performance. With the chosen coefficients, classical control cannot receive acceptable results [2].

Voltage source inverter-fed induction motors are most preferred for variable speed drive applications. The controller choice for a SVPWM drive is determined by the requirements of the type of application & is the most successful technique used in meeting the above requirements. Due to advances in power electronics and microprocessors, variable-speed drives for induction motors are commonly used nowadays. The SVPWM control has been widely used in many applications, such as AC servos, electric vehicle drive systems and so on.

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Using this type of control, a highly coupled, nonlinear, multivariable induction motor can be simply controlled through linear independent decoupled control of the torque and flux, similar to separately excited DC motors [3].

SVPWM method is an advanced, computation-intensive PWM method and possibly the best among all the PWM techniques for variable speed drives application. Because of its superior performance characteristics, it has been finding widespread application in recent years. With a machine load, the load neutral is normally isolated, which causes interaction among the phases. This interaction was not considered before in the PWM discussion. Recently, fuzzy logic control has found many applications in the past decades, which overcomes these drawbacks. Hence, fuzzy logic control has the capability to control nonlinear, uncertain systems even in the case where no mathematical model is available for the controlled system.

The structure of the work presented in this paper is organized in the following sequence. A brief literature survey of the related work was presented in the previous paragraphs. Section 2 presents about the overview of the block model of the induction motor with SVPWM technique. Design of the fuzzy logic control scheme is presented in section 3. The section 4 shows the simulink model for the speed control of the induction motor. The graphical results of the simulation & the discussion are presented in section 5. This is followed by the conclusions and the references.

2. Induction motor model

The mathematical model of the system consists of space vector PWM voltage source inverter, induction motor, direct flux and the torque control. Direct Torque Control (DTC) uses an induction motor model to predict the voltage required to achieve a desired output torque [6]. By using only current and voltage measurements, it is possible to estimate the instantaneous stator flux and output torque.

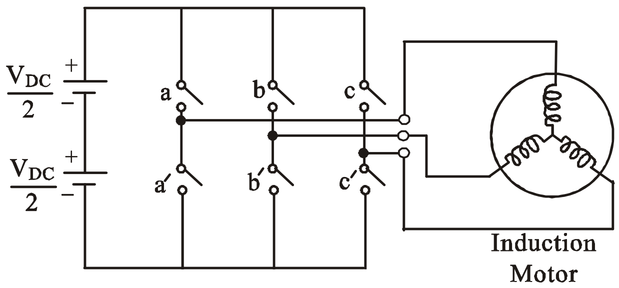

Figure 1. Power circuit connection diagram for the IM

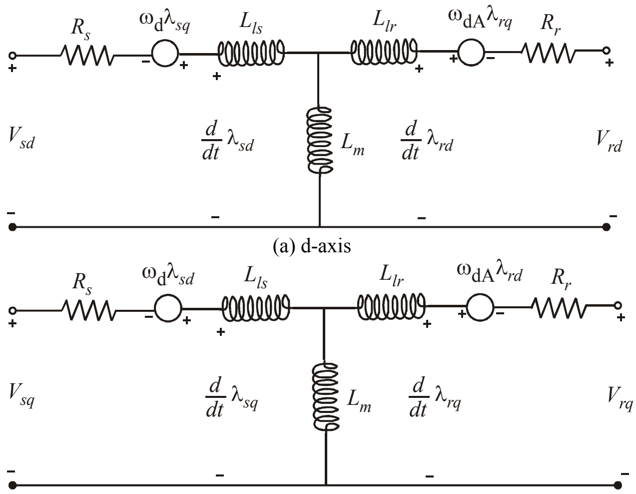

Figure 2. Equivalent circuit of induction motor in d-q frame

The power circuit of the induction motor is shown in the Fig. 1. The equivalent circuit used for obtaining the mathematical model of the induction motor is shown in the Fig. 2. An induction motor model is then used to predict the voltage required to drive the flux and torque to the demanded values within a fixed time period . This calculated voltage is then synthesized using the space vector modulation. The stator & rotor voltage equations are given by [9,11].

$$V_{sd} = R_s i_{sd} + \frac{d}{dt}\lambda_{sd} - \omega_d \lambda_{sq} \quad (1)$$

$$V_{sq} = R_s i_{sq} + \frac{d}{dt}\lambda_{sq} - \omega_d \lambda_{sd} \quad (2)$$

$$V_{rd} = R_r i_{rd} + \frac{d}{dt}\lambda_{rd} - \omega_{dA} \lambda_{rq} \quad (3)$$

$$V_{rq} = R_r i_{rq} + \frac{d}{dt}\lambda_{rq} - \omega_{dA} \lambda_{rd} \quad (4)$$

A squirrel-cage induction motor is considered for the simulation study in this paper, so the *d* and *q*-axis components of the rotor voltage are zero. The fluxes to currents are related by the equation [11].

$$\begin{bmatrix} \lambda_{sd} \\ \lambda_{sq} \\ \lambda_{rd} \\ \lambda_{rq} \end{bmatrix} = M \begin{bmatrix} i_{sd} \\ i_{sq} \\ i_{rd} \\ i_{rq} \end{bmatrix} ; M = \begin{bmatrix} L_s & 0 & L_m & 0 \\ 0 & L_s & 0 & L_m \\ L_m & 0 & L_r & 0 \\ 0 & L_m & 0 & L_r \end{bmatrix} \quad (5)$$

The electrical part of an induction motor can thus be described by a fourth-order model [11], which is given in (6), by combining equations (1) - (5):

$$\begin{bmatrix} i_{sd} \\ i_{sq} \\ i_{rd} \\ i_{rq} \end{bmatrix} = \frac{1}{L_m^2 - L_r L_s} \times \left(A \begin{bmatrix} i_{sd} \\ i_{sq} \\ i_{rd} \\ i_{rq} \end{bmatrix} + \begin{bmatrix} L_s & 0 & L_m & 0 \\ 0 & L_s & 0 & L_m \\ L_m & 0 & L_r & 0 \\ 0 & L_m & 0 & L_r \end{bmatrix} \begin{bmatrix} V_{sd} \\ V_{sq} \\ V_{rd} \\ V_{rq} \end{bmatrix} \right) \quad (6)$$

where, A is given by [11]

$$A = \begin{bmatrix} L_r R_s & \omega_{dA} L_m^2 - \omega_s L_r L_s & -L_m R_r & -L_r L_m (\omega_s - \omega_{dA}) \\ -(\omega_{dA} L_m^2 - \omega_s L_r L_s) & L_r R_s & L_r L_m (\omega_s - \omega_{dA}) & -L_m R_r \\ -L_m R_s & L_s L_m (\omega_s - \omega_{dA}) & L_s R_r & \omega_s L_m^2 - \omega_{dA} L_r L_s \\ -L_s L_m (\omega_s - \omega_{dA}) & -L_m R_s & -(\omega_s L_m^2 - \omega_{dA} L_r L_s) & L_s R_r \end{bmatrix} \quad (7)$$

The instantaneous torque developed in the induction motor is given by [11]

$$T_{em} = \frac{P}{2}\left(\lambda_{rq} i_{rd} - \lambda_{rd} i_{rq}\right) \quad (8)$$

The electromagnetic torque expressed in terms of inductances is given by [11]

$$T_{em} = \frac{P}{2} L_m \left(i_{sq} i_{rd} - i_{sd} i_{rq}\right) \quad (9)$$

The mechanical part of the motor is modeled by the equation [11]

$$\frac{d}{dt}\omega_{Mech} = \frac{T_{em} - T_L}{J_{eq}} = \frac{\frac{P}{2} L_m \left(i_{sq} i_{rd} - i_{sd} i_{rq}\right) - T_L}{J_{eq}} \quad (10)$$

where,

$J_{eq} =$ Equivalent MI, $\omega_{dA} = \omega_{slip} = \omega_s - \omega_m$

$\omega_m = \frac{P}{2}\omega_{mech}$, $\omega_d = \omega_s$, $L_s = L_{sl} + L_m$

$L_r = L_{rl} + L_m$

A 3-phase bridge inverter has 8 permissible switching states as shown in Fig. 3. The table 1 gives the summary of the switching states and the corresponding phase-to-neutral voltage of isolated neutral machine [9, 11].

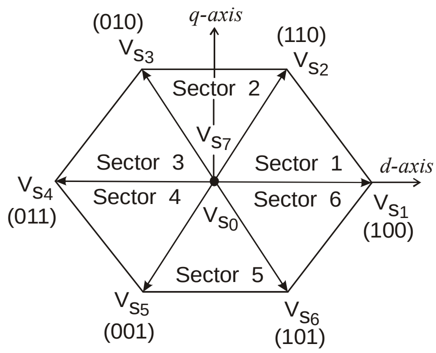

Figure 3. Space vector sequence

Table 1 : Switching states

V	a	b	c	V_{An}	V_{An}	V_{An}
V_0	0	0	0	0	0	0
V_1	1	0	0	$2V_{DC}/3$	$-V_{DC}/3$	$-V_{DC}/3$
V_2	1	1	0	$V_{DC}/3$	$V_{DC}/3$	$-2V_{DC}/3$
V_3	0	1	0	$-V_{DC}/3$	$2V_{DC}/3$	$-V_{DC}/3$
V_4	0	1	1	$-2V_{DC}/3$	$V_{DC}/3$	$V_{DC}/3$
V_5	0	0	1	$-V_{DC}/3$	$-V_{DC}/3$	$2V_{DC}/3$
V_6	1	0	1	$V_{DC}/3$	$-2V_{DC}/3$	$V_{DC}/3$
V_7	1	1	1	0	0	0

3. Design of the fuzzy logic control scheme

Fuzzy controllers have got a lot of advantages compared to the classical controllers such as the simplicity of control, low cost and the possibility to design without knowing the exact mathematical model of the process. Fuzzy logic is one of the successful applications of fuzzy set in which the variables are linguistic rather than the numeric variables.

Linguistic variables, defined as variables whose values are sentences in a natural language (such as large or small), may be represented by fuzzy sets. Fuzzy set is an extension of a ‘crisp’ set where an element can only belong to a set (full membership) or not belong at all (no membership). Fuzzy sets allow partial membership, which means that an element may partially belong to more than one set. A fuzzy set A of a universe of discourse X is represented by a collection of ordered pairs of generic element $x \in X$ and its membership function $\mu : X \rightarrow [\ 0$

1], which associates a number $\mu_A(x): X \rightarrow [\,0 \quad 1]$, to each element x of X.

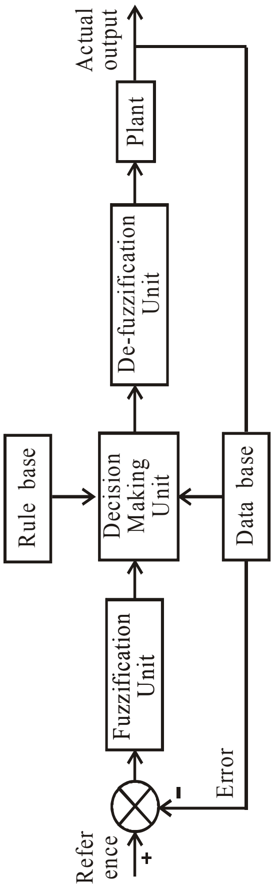

Figure 4. A diagrammatic view of a fuzzy logic controller

A fuzzy logic controller is based on a set of control rules called as the fuzzy rules among the linguistic variables [7]. These rules are expressed in the form of conditional statements. Our basic structure of the fuzzy logic controller to control the speed of the induction motor consists of 4 important parts, viz., fuzzification, knowledge base, decision-making logic and the defuzzification. The internal structure of the controller is shown in the Fig. 4. The necessary inputs to the decision-making unit blocks are the rule-based units and the data based block units. The fuzzification unit converts the crisp data into linguistic formats. The decision making unit decides in the linguistic format with the help of logical linguistic rules supplied by the rule base unit and the relevant data supplied by the data base [8, 5]. The error & the change in error is modeled using the equation (11) as

$$e(k) = \omega_{ref} - \omega_r$$
$$\Delta e(k) = e(k) - e(k-1) \tag{11}$$

where ω_{ref} is the reference speed, ω_r is the actual rotor speed, $e(k)$ is the error and $\Delta e(k)$ is the change in error.

The output of the decision-making unit is given as input to the de-fuzzification unit and the linguistic format of the signal is converted back into the numeric form of data in the crisp form [5]. The decision-making unit uses the conditional rules of 'IF-THEN-ELSE'. In the first stage, the crisp variables $e(k)$ and $\Delta e(k)$ are converted into fuzzy variables [7]. The fuzzification maps the error, and the error changes to linguistic labels of the fuzzy sets. The proposed controller uses following linguistic labels: {NB Negative Big), NM Negative Medium), NS (Negative Small), ZE (Zero), PS (Positive Small), PM (Positive Medium), PB(Positive Big)}. Each fuzzy label has an associated membership function. The membership functions of triangular type are shown in the Fig. 5.

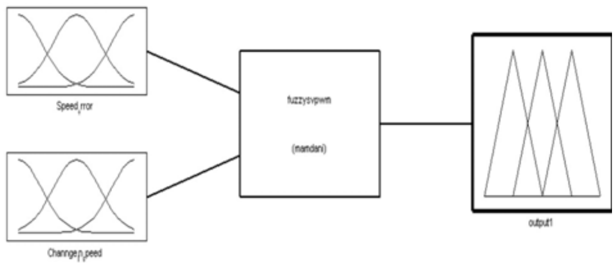

Figure 5. FIS Fuzzy editor with 2 inputs and 1 outputs developed simulink model

The rule base for the decision-making unit is written as shown in the table 2.

Table 2 : Rule base for controlling the speed

ΔE \ E	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NM	NM	NS	ZE	PS
NS	NB	NM	NS	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PS	PM	PB
PM	NS	ZE	PS	PM	PM	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

4. Development of the simulink model

The design of the fuzzy logic controller is developed using the fuzzy logic toolbox available in Matlab / Simulink. In this paper, fuzzy logic controller employs the speed error and the change of speed error as the inputs [5]. The change in the speed component of current that drives the induction motor is obtained as the output. The developed simulink model in MATLAB is shown in the Fig. 6.

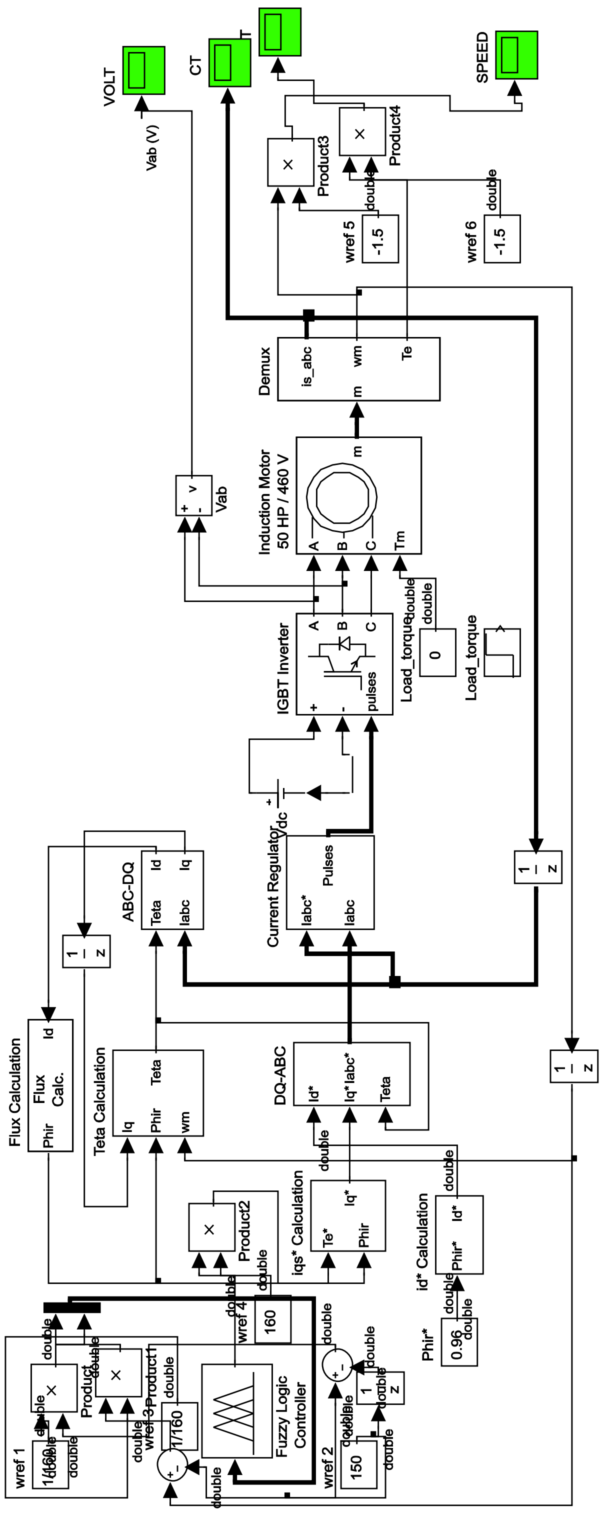

Figure 6. Developed simulink model

5. Simulation results & discussions

Simulations are carried out in Matlab. The response curves of voltage, stator current, torque & the speed v/s time are shown in the Figs. 7 - 10 respectively. The surface plot of the error, change in error and the speed is shown in the Fig. 11. From the results, it is observed that the stator current does not exhibit any overshoots & undershoots & the response of the speed curve takes less time to settle & reach the desired value.

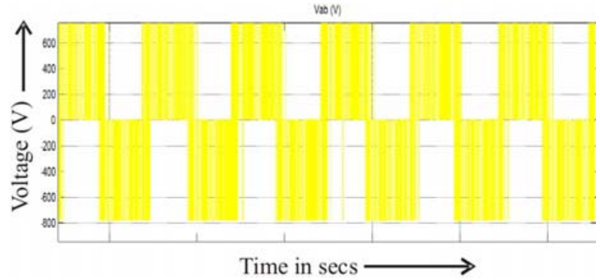

Figure 7. Plot of control voltage v/s time

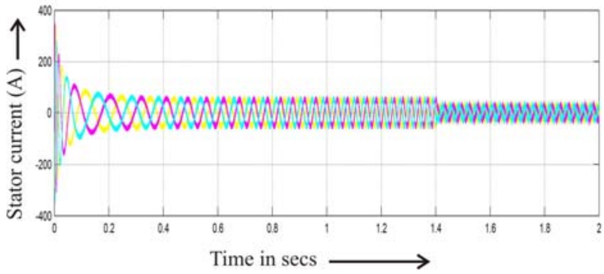

Figure 8. Plot of stator current v/s time

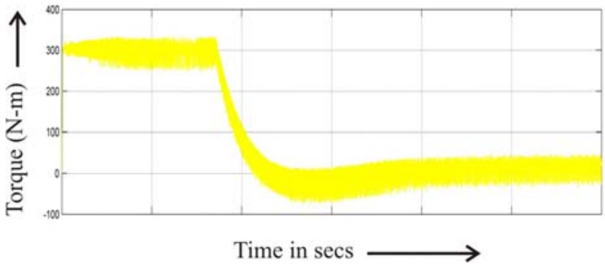

Figure 9. Plot of torque v/s time

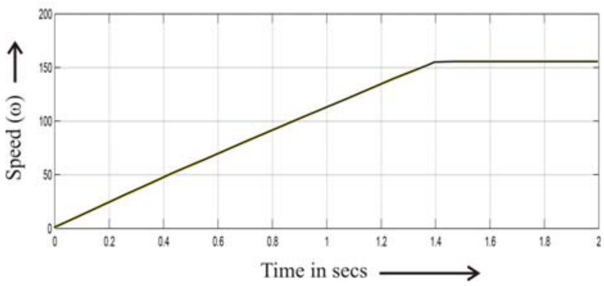

Figure 10. Plot of speed v/s time

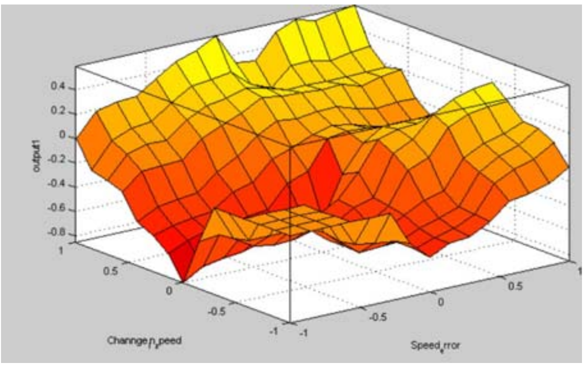

Figure 11. Surface plot of error, change in error with speed

6. Conclusion

The speed control of an induction motor drive by means of the AI based fuzzy technique using SVPWM concept has been investigated in this paper. Under reference speed trajectory the fuzzy controller has shown good performances. The settling time of the torque & the speed matched with the desired values that were taken during the simulations. By the method presented in this paper, the efficiency, performance and reliability of induction motor drive increases. Steady state error in speed control is acceptable and there is not any overshoot.

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