

FUZZY LOGIC BASED CONTROLLER FOR FIVE PHASE INDUCTION MOTOR DRIVE SYSTEM

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ABSTRACT

The area of multiphase variable-speed motor drives in general and multiphase induction motor drives in particular has experienced a substantial growth since the beginning of this century. Research has been conducted worldwide and numerous interesting developments have been reported in the literature. This paper presents fuzzy logic based controller for five-phase induction motor drives. The controller is based on indirect rotor field oriented control technique. The five-phase IM drive presents unique characteristics for enhancing the torque producing capability of the motor. The proposed controller is a suitable to high performance five-phase induction motor drives. The aim is to design and implement a speed control scheme of 5-phase induction motor drive system using fuzzy logic controller (FLC). In which, the system control parameters are adjusted by a fuzzy rule based system, which is a logical model of the human behavior for process control. The main advantages of FLC over the conventional controllers are that the design of FLC does not need the exact mathematical model of the system, and it can handle nonlinear functions of arbitrary complexity. The speed control algorithm is based on the indirect vector control. The elaborated aspects include advantages of multiphase induction machines, modeling of multiphase induction machines, basic vector control and direct torque control schemes and PWM control of multiphase voltage source inverters.

KEYWORDS: Five phase I.M, Fuzzy logic, Voltage source inverter, IFOC

I. INTRODUCTION

Induction motors have well known many advantages of simple construction, reliability, ruggedness and low maintenance which has led to their wide spread use in many industrial applications. Multiphase (more than three phase) systems are the focus of research recently due to their inherent advantages when we compared to their three-phase counterparts. The first record of a multiphase motor drive, known to the authors, dates back to 1969, when a five-phase voltage source inverter-fed induction motor drive was proposed [1]. A Five-phase motor drive possess many advantages when compared to conventional three-phase IM drives, such as reducing the amplitude and increasing the frequency of the torque pulsation, reducing the current per phase without increasing the voltage per phase, reducing the rotor harmonic currents, lowering the dc link current harmonics, providing higher power density, outputting more torque, and having higher reliability. The multiphase induction machines are normally applied for high power applications. Such as electric aircraft, ship propulsion, and electric/hybrid electric vehicles etc. a proper modulation technique needs to be designed to achieve high performance.

The limitation of multi-phase machine is that multi phase motor needs a power electronic converter for phase conversion because three-phase supply is only easily available. Earlier multiphase motor where not used widely because of the drawback that the supply for the multi phase motor was not available, because of the Advancement in Power Electronics, interest in Multi-phase machine has been increased tremendously as high power electronic devices are used as a switch in voltage source inverter (VSI) and the output of the VSI is given to the Multiphase machine. Voltage source inverters, despite their advantage of being able to use low cost induction machines, are still limited to the lower end of the high power range due to the limitations on gate-turn-off type semiconductor power device ratings. In the past decades, multi-level inverter fed electric machine drive systems have emerged as a

promising tool in achieving high power ratings with voltage limited devices. There are two approaches for supplying high power systems; one approach is the use of multi leg inverters supplying multiphase machines and the other approach is multilevel inverters supplying three-phase machines. However, in the last two decades, with the evolution of power semiconductor devices and power electronic converters, the Induction Motor (IM) [2] is also well established in the controlled-speed area. A survey of control schemes for asymmetrical six-phase induction motor drives and associated methods of VSI PWM control is given in [3]. Detailed modeling approach is discussed in [4]. It contains basic models, control schemes in developed form, and experimentally obtained illustrations of performance for various multiphase induction motor drives (asymmetrical and symmetrical six-phase, and five-phase machines). The induction motor control methods can be broadly classified into Vector and Scalar control. In the vector control magnitude and frequency but also instantaneous positions of voltage, current and flux space vectors are controlled. In contrast in scalar control only the magnitude and frequency of voltage, current and flux linkage space vectors are controlled. Recently scalar control of a five-phase induction machine is presented in [5] and the field oriented control for five-phase machine is illustrated in [6-7]. The space vector approach allows to simplify modeling and regulation of both the converter and the machine in traditional three-phase motor drive applications. On the other hand, the development of modern power electronic devices, makes it possible to consider the number of phases as a degree of freedom, i.e., as one of the design variables. However, when the machine is connected to an inverter supply, the need for a specific number of phases, such as three, disappears. Since apart from the fundamental spatial field harmonic, the space harmonic fields can be used to contribute to the total torque production then higher torque density in a multi-phase machine is possible. In a five-phase induction machine a third harmonic current injection can be used to enhance the overall torque production [8]. In a multi-phase machine, with five or more phases, there are additional degrees of freedom, which can be used to enhance the torque production through the injection of higher-order current harmonics. In [9], Toliyat et al. also mentioned that most multiphase motors are designed to have a non-sinusoidal back EMF voltage in order to increase the torque per ampere. However, five-phase motors have additional third space harmonics. The result of this space harmonic is a considerable harmonic current and phase current deformation. To solve this problem, [10] proposed DTC using space vector modulation (SVM). The DTC of an IM is a powerful control method for motor drives. Using DTC instead of field oriented control (FOC) provides simple implementation and good dynamic characteristics [10]. The FOC of a five-phase machine with concentrated winding on the stator with current control in the rotating reference frame has been reported [7].

Space vector pulse width modulation (SVPWM) is used to control a five-phase voltage source inverter feeding a drive. Only the outer large vectors are used to realize the SVPWM. However, this method has a complicated control structure and produces unwanted low order harmonics. Considering the above mentioned points, a five phase IM with a concentrated winding and an almost rectangular waveform back EMF, is designed. In order to inject a trapezoidal current waveform and achieve better dynamic performance, a new control method is proposed. The proposed control method is based on RFOC and DTC of five-phase IM drives. In order to exclude effect of the 3rd harmonic current the RFOC method is adapted during the steady state, and to maintain dynamic characteristics the DTC method is applied during the dynamic state. Among different methods, space vector pulse width modulation (SVPWM) is one of the most popular choices due to the easy digital implementation and because of a better utilization of the available dc bus voltage [11].

The multiphase machine designs, various control schemes and different PWM methods are addressed in [12]. The design of post fault operating strategies and for multi-motor multiphase drives with single inverter supply has been covered and also discusses the potential of multiphase machines for electric energy generation is briefly addressed.

II. MODELING OF FIVE PHASE INDUCTION MOTOR

All the students of electrical engineering are aware, three phase induction motors will accelerate their loads from rest and after that they will run without producing a double line-frequency pulsating torque. Machines having more than three phases example 5 ph or 6 phases etc exhibit the same properties, but those with one or two phases it is not possible. A model of a five-phase induction

motor is initially developed in phase variable form. In order to simplify the model by removing the time variation of inductance terms, a transformation is applied on model and so-called d-q-x-y-0 model of the machine is design or constructed. A five-phase induction machine is build using ten phase belts, each of 36 degrees in that phases, along the circumference of the stator. The spatial displacement between phases is therefore ($\alpha=2\pi/n$ where n is a number of phases n=5) 72 degrees. The rotor winding is treated as an equivalent five-phase winding, of the same properties as the stator winding. It is assumed that the rotor winding has already been referred to stator winding, using winding transformation ratio. The built in induction motor in simpower block set cannot be used as it corresponds to three-phase only. Since the phase-variable model of a physical multiphase machine gets transformed using a mathematical transformation, the number of variables before and after transformation must remain the same. The machine model in original form is transformed using decoupling (Clarke's) transformation matrix [13], which replaces the original sets of n variables with new sets of n variables.

Equations for pairs of x-y components are completely decoupled from all the other components and stator to rotor coupling does not appear either [13]. Rotor x-y components are fully decoupled from d-q components and one from the other. Since rotor winding is short-circuited, neither x-y nor zero-sequence components can exist, Zero sequence component equations for both stator and rotor can be omitted from further consideration due to short-circuited rotor winding and star connection of the stator winding. A zero-sequence component does not exist in any star-connected multiphase system without neutral conductor for odd phase numbers, while only zero components can exist if the phase number is even. Finally vector control is applied (i.e. only d-q axis current components are generated), the equations for x-y components can be omitted from further consideration as well. This means that the model of the five-phase induction machine in an arbitrary reference frame becomes identical to the model of a three phase induction machine.

The mathematical model of five-phase motor given in [6-7] is used to simulate the five-phase induction machine, the data is provided in Appendix 1. The machine's voltage equations in the common reference frame:

$$\begin{aligned}
 v_{ds} &= R_s i_{ds} - \omega_a \psi_{qs} + P \psi_{ds} & v_{dr} &= R_r i_{dr} - (\omega_a - \omega) \psi_{qr} + P \psi_{dr} \\
 v_{qs} &= R_s i_{qs} + \omega_a \psi_{ds} + P \psi_{qs} & v_{qr} &= R_r i_{qr} + (\omega_a - \omega) \psi_{dr} + P \psi_{qr} \\
 v_{xs} &= R_s i_{xs} + P \psi_{xs} & v_{xr} &= R_r i_{xr} + P \psi_{xr} \\
 v_{ys} &= R_s i_{ys} + P \psi_{ys} & v_{yr} &= R_r i_{yr} + P \psi_{yr} \\
 v_{0s} &= R_s i_{0s} + P \psi_{0s} & v_{0r} &= R_r i_{0r} + P \psi_{0r}
 \end{aligned} \tag{1}$$

$$\begin{aligned}
 \psi_{ds} &= (L_{ls} + L_m) i_{ds} + L_m i_{dr} & \psi_{dr} &= (L_{lr} + L_m) i_{dr} + L_m i_{ds} \\
 \psi_{qs} &= (L_{ls} + L_m) i_{qs} + L_m i_{qr} & \psi_{qr} &= (L_{lr} + L_m) i_{qr} + L_m i_{qs} \\
 \psi_{xs} &= L_{ls} i_{xs} & \psi_{xr} &= L_{lr} i_{xr} \\
 \psi_{ys} &= L_{ls} i_{ys} & \psi_{yr} &= L_{lr} i_{yr} \\
 \psi_{0s} &= L_{ls} i_{0s} & \psi_{0r} &= L_{lr} i_{0r}
 \end{aligned} \tag{2}$$

$$\begin{aligned}
 T_e &= \frac{5P}{2} M (i_{dr} i_{qs} - i_{ds} i_{qr}) \\
 T_e &= P L_m [i_{dr} i_{qs} - i_{ds} i_{qr}]
 \end{aligned} \tag{3}$$

$$T_e - T_L = \frac{J}{P} \frac{d\omega}{dt}$$

The inputs to the motor are the five-phase voltage supply obtained from voltage source inverter.

III. VOLTAGE SOURCE INVERTER

Power circuit topology of a five-phase VSI, which was used probably for the first time by Ward and

Härer (1969). In multiphase inverter we can generate n number of phase, as each leg of the inverter represent the phase, thus by increase the number of leg in the inverter we can increase the number of phases. For the five phase motor we require five leg inverter. The basic power circuit topology of five phase VSI is shown below.

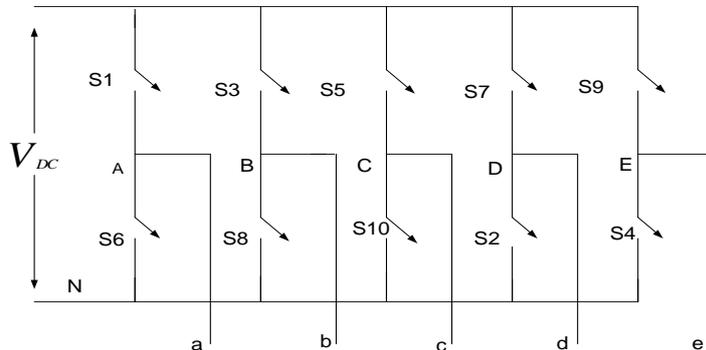


Figure 1. Five-phase voltage source inverter power circuit.

Each switch in the circuit consists of two power semiconductor devices, connected in anti-parallel. One of these is a fully controllable semiconductor, such as a bipolar transistor or IGBT, while the second one is a diode. The anti parallel diodes provides reverse current path such that when a particular IGBT is gated on, one output terminal and one input terminal will be connected. The input to the inverter is a dc supply voltage, which is regarded further on as being constant. The topology of five phase inverter with IGBT and Diode is shown below.

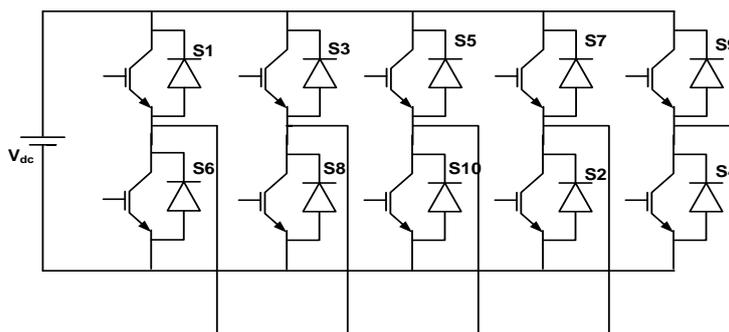


Figure 2. Line-to-line voltages of a five-phase star-connected load.

The inverter outputs are denoted in Fig.1 with lower case symbols (a, b, c, d, e), while the points of connection of the outputs to inverter legs have symbols in capital letters (A,B, In five phase inverter three switches from the upper switches and two from the lower switches are turned on at a time and vice versa. The two switches which form the leg of the inverter are complimentary to each other, for example when switch S1 is on Switch S6 is off so as to avoid short circuit.C,D,E).

The basic operating principles of the five-phase VSI are developed in what follows assuming the ideal commutation and zero forward voltage drop. Each switch is assumed to conduct for 180°, leading to the operation in the ten-step mode. Phase delay between firing of two switches in any subsequent two phases is equal to $360^\circ/5 = 72^\circ$.The switching sequence & the mode of operation of a five phase inverter are shown below

Table 1. Modes of operation of the five-phase voltage source inverter (ten-step operation).

Mode	Switches ON	Terminal Polarity
9	1,7,8,9,10	A ⁺ B ⁻ C ⁻ D ⁺ E ⁻
10	8,9,10,1,2	A ⁺ B ⁻ C ⁻ D ⁺ E ⁺
1	9,10,1,2,3	A ⁺ B ⁺ C ⁻ D ⁺ E ⁺
2	10,1,2,3,4	A ⁺ B ⁺ C ⁻ D ⁻ E ⁻
3	1,2,3,4,5	A ⁺ B ⁺ C ⁺ D ⁻ E ⁻
4	2,3,4,5,6	A ⁻ B ⁺ C ⁺ D ⁻ E ⁻
5	3,4,5,6,7	A ⁻ B ⁺ C ⁺ D ⁺ E ⁻
6	4,5,6,7,8	A ⁻ B ⁻ C ⁺ D ⁺ E ⁻
7	5,6,7,8,9	A ⁻ B ⁻ C ⁺ D ⁺ E ⁺
8	6,7,8,9,10	A ⁻ B ⁻ C ⁻ D ⁺ E ⁺

One complete cycle of operation of the inverter can be divided into ten distinct modes indicated in Fig. 3 and summarized in Table 1. It follows from Fig. 3 and Table 1 that at any instant in time there are five switches that are ‘on’ and five switches that are ‘off’. Phase-to-neutral voltages of the star connected load are most easily found by defining a voltage difference between the star point n of the load and the negative rail of the dc bus N.

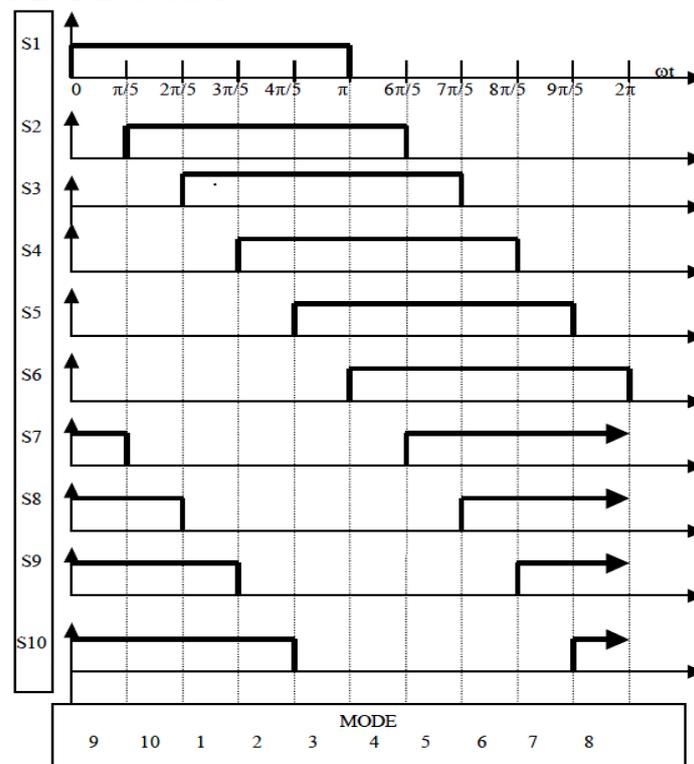


Figure 3. Driving switch signals of a five-phase voltage source inverter in the ten-step mode.

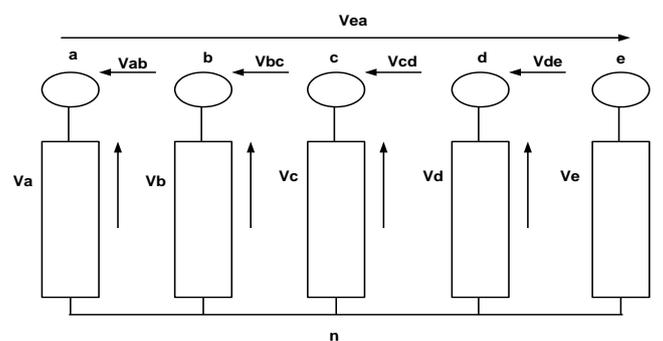


Figure 4. line-to-line voltages of a five-phase star-connected load.

The following correlation then holds true:

$$\begin{aligned}
 v_A &= v_a + v_{nN} \\
 v_B &= v_b + v_{nN} \\
 v_C &= v_c + v_{nN} \\
 v_D &= v_d + v_{nN} \\
 v_E &= v_e + v_{nN}
 \end{aligned} \tag{4}$$

Since the phase voltages in a star connected load sum to zero, summation of the equations (5) yield

$$v_{nN} = \left(\frac{1}{5}\right)(v_A + v_B + v_C + v_D + v_E) \tag{5}$$

Substitution of (6) into (5) yields phase-to-neutral voltages of the load in the following form:

$$\begin{aligned}
 v_a &= \left(\frac{4}{5}\right)v_A - \left(\frac{1}{5}\right)(v_B + v_C + v_D + v_E) \\
 v_b &= \left(\frac{4}{5}\right)v_B - \left(\frac{1}{5}\right)(v_A + v_C + v_D + v_E) \\
 v_c &= \left(\frac{4}{5}\right)v_C - \left(\frac{1}{5}\right)(v_A + v_B + v_D + v_E) \\
 v_d &= \left(\frac{4}{5}\right)v_D - \left(\frac{1}{5}\right)(v_A + v_B + v_C + v_E) \\
 v_e &= \left(\frac{4}{5}\right)v_E - \left(\frac{1}{5}\right)(v_A + v_B + v_C + v_D)
 \end{aligned} \tag{6}$$

The relationship between phase-to-neutral voltages of the inverter and the dc link voltage, given in (6) in terms of leg voltages, can be expressed using switching functions for the five individual inverter legs. Where suffix with small letter indicates phase-to-neutral voltages and the suffix with capital letters represents leg voltages. The component modeling is done using the simpower system block sets. The IGBT based power module is utilized. Each IGBT block represents one inverter leg incorporating both the upper and lower power switch along with the snubber circuit.

IV. CONTROL SCHEME

Methods of speed control of multiphase induction machines are in principle the same as or three-phase induction machines. These methods are namely as constant voltage per hertz V/f control, vector control, and direct torque control (DTC). Constant V/f control was extensively studied in the early days of the multiphase variable-speed induction motor drive development in conjunction with voltage source inverters operated in the conduction mode. In the recent times, the emphasis has shifted to vector control and direct torque control (DTC). Since the cost of implementing more sophisticated control algorithms is negligible compared to the cost of multiphase power electronics and the multiphase machine itself.

4.1 Vector Control Of Multiphase Induction Machines

The basis of vector control is the selection of the speed of the common reference frame. In rotor flux oriented control scheme the speed of the reference frame is selected as equal to the speed of the rotor flux space vector. The rotor flux space vector is kept aligned at all times with the real axis (d-axis) of the common reference frame, while q-axis is perpendicular to it. As the rotor flux space vector is aligned with the real axis its imaginary component always remains equal to zero. For a symmetrical multiphase induction machine with sinusoidally distributed stator winding, the same vector control schemes for a three-phase induction machine are directly applicable regardless of the number of phases. The only difference is that the coordinate transformation has to produce an n-phase set of stator current or stator voltage references, depending on whether current control is stationary or in synchronous rotating reference frame. Indirect rotor flux oriented control (FOC) schemes for multiphase induction machine using these two types of current control. Assuming the stator winding has a single neutral point, the scheme of Fig.5 utilizes (m-1) stationary current controllers. The torque producing current component is calculated from:

$$\psi_r + T_r \frac{d\psi_r}{dt} = L_m i_{ds} \tag{7}$$

$$(\omega_r - \omega) \psi_r T_r = L_m i_{qs} \tag{8}$$

$$\omega_{sl} = \frac{L_m i_{qs}}{T_r \psi_r} \tag{9}$$

$$T_e = p \frac{L_m}{L_r} \psi_r i_{qs} \tag{10}$$

Where $T_r = L_r/R_r$ It can be seen from (7) - (10) that the flux and torque producing currents in five-phase machines are only d-q components, thus the vector control scheme for a current fed five-phase machine is identical to the scheme for a current fed three-phase machine. The only difference is that the co-ordinate transformation now generates five phase current references instead of three. The configuration of the indirect vector controller for operation in the base speed region is illustrated in Fig. 5 for the five-phase induction machine. Constants in Fig. 5 are determined with the following expressions (which are in essence identical to those for a three-phase induction machine with indirect rotor flux oriented control):

$$i_{qs}^* = K_1 T_e^* = K_1 = i_{qs}^* / T_e^* = \frac{1}{p} \frac{L_r}{L_m} \frac{1}{\psi_r^*}$$

$$i_{qs}^* / T_e^* = \frac{1}{p} \frac{L_r}{L_m} \frac{1}{i_{ds}^*}$$

$$\omega_{sl}^* = K_2 i_{qs}^* = K_2 = \omega_{sl}^* / i_{qs}^* = \frac{L_m}{T_r \psi_r^*} = \frac{1}{T_r i_{ds}^*}$$

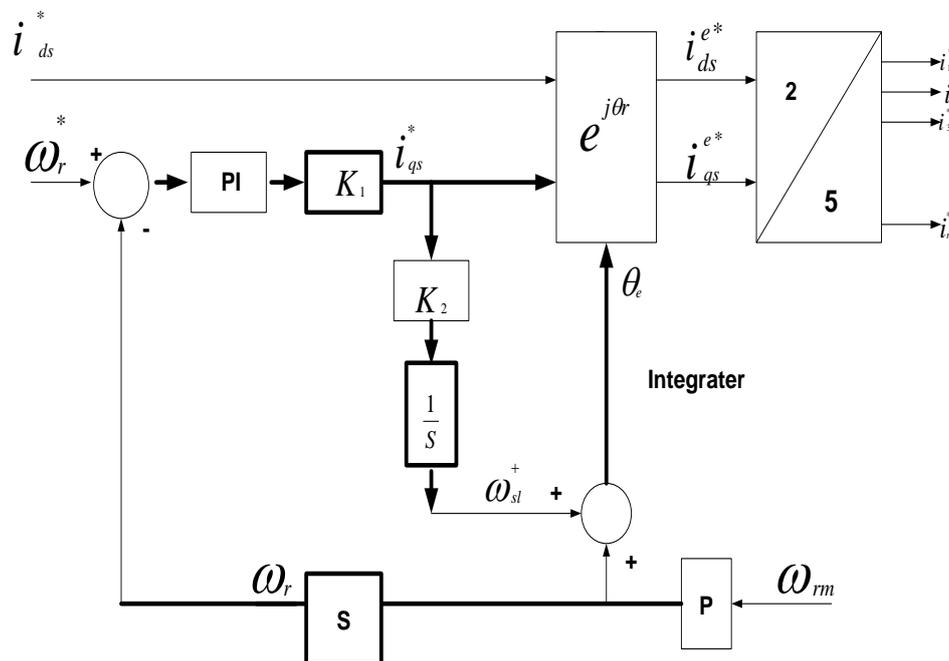


Figure 5. Indirect vector control of a five-phase induction machine in the base speed region.

The parameter and symbols shown in Fig. 5(a) are defined as follows

$$K_1 = \frac{1}{T_r i_{ds}^*} \tag{11}$$

$T_r = \frac{L_r}{r_r}$ is the rotor time constant

ω_r is the electrical rotor speed, ω_{rm} is the mechanical rotor speed, ω_{sl}^* is the electrical slip speed, ω_r^* is

the reference rotor speed i_{qs}^* is the reference q-axis stator current i_{ds}^* is the reference d-axis stator current, PI stands for proportional integral controller, θ_e is the instantaneous rotor flux space vector position $i_1^*, i_2^*, \dots, i_n^*$ are the reference stator phase currents. Either phase currents or phase current components in the stationary reference frame can be controlled an the standard ramp comparison current control method offers the same quality of performance as with three phase induction motor drives.

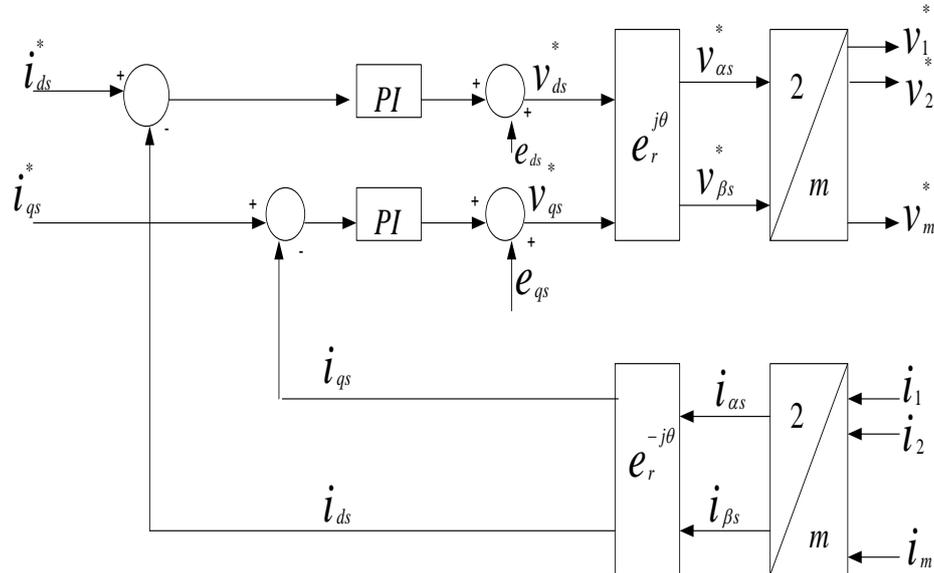


Figure 6. Indirect rotor field oriented control of a multiphase induction machine.

The current control of Fig. 6 is in the rotating reference frame. The stator q and d axis reference currents and rotor flux position are obtained as in Fig.5 Some of the defining equations for the system of Fig. 6 are

$$e_{qs} = \omega_e L_{\sigma} i_{ds} + \omega_r \frac{L_m}{L_r} \lambda_{dr}' \tag{12}$$

$$e_{ds} = -\omega_e L_{\sigma} i_{qs} + \frac{\gamma_r L_m}{L_r'^2} \lambda_{dr}' \tag{13}$$

Where $\omega_e = \frac{d\theta_e}{dt}$ (14)

$$L_{\sigma} = L_s - \frac{L_m^2}{L_r} \tag{15}$$

Where L_s is the stator self inductance, L_r' is the rotor self inductance referred to stator side L_m is the magnetizing inductance, $V_1^*, V_2^*, \dots, V_n^*$ are the reference stator phase voltages, i_1, i_2, \dots, i_n are the stator phase currents, V_{α}^* and V_{β}^* are the α and β axis reference stationary voltages, Respectively i_{α} and i_{β} are the α and β axis reference stationary currents, respectively i_{qs} and i_{ds} are the q and d axis currents, respectively, in the synchronous reference frame V_{qs}^* and V_{ds}^* are the q and d axis reference voltages, respectively, in the synchronous reference frame i_{qs}^* and i_{ds}^* are the q and d axis reference currents, respectively, in the synchronous reference frame. λ_{dr}' is the rotor d -axis flux linkage.

The scheme of Fig. 6 has only two current controllers. However, since an n -phase machine essentially has $(m-1)$ independent currents, utilization of this scheme will suffice only if there are not any winding and /or supply asymmetries within the m -phase stator winding and / or supply. This scheme also requires an adequate method of inverter PWM control to avoid creation of an unwanted low-order stator voltage harmonics. Field Oriented Control provides the smooth motion at slow speeds as well as efficient operation at high speeds. Sinusoidal commutation produces smooth motion at slow speeds, but is inefficient at high speeds. Trapezoidal commutation can be relatively efficient at high

speeds, but causes torque ripple at slow speeds. Field Oriented Control provides the best of both worlds.

4.2 Fuzzy Logic Controller

Fuzzy logic is a convenient way to map an input space to an output space. Fuzzy logic is conceptually easy to understand. A fuzzy logic controller consists typically of three steps. The first step is to take the inputs and determine the degree to which they belong to each of the appropriate fuzzy sets via membership functions. In second step is once the inputs have been fuzzified, we know the degree to which each part of the antecedent has been satisfied for each rule. If the antecedent of a given rule has more than one part, the fuzzy operator is applied to obtain one number that represents the result of the antecedent for that rule. In third step the input for the defuzzification process is a fuzzy set (the aggregate output fuzzy set) and the output is a single number crispness recovered from fuzziness at last. As much as fuzziness helps the rule evaluation during the intermediate steps, the final output for each variable is generally a single crisp number. So, given a fuzzy set that encompasses a range of output values, we need to return one number, thereby moving from a fuzzy set to a crisp output.



Figure 7. Fuzzy controller.

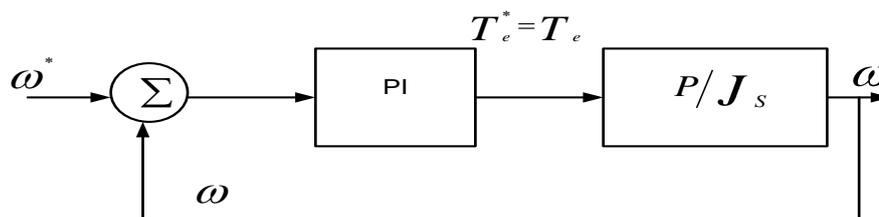


Figure 8. Structure of the speed control loop.

PI speed controller is considered next. Two different speed controllers are designed, a continuous one and a discrete one. Both speed controllers are used in simulations further on. The type of the speed controller used in conjunction with any specific simulation will be indicated in the corresponding section with simulation results. The design of continuous speed controller is presented first. For this purpose, and having in mind that the inverter current control will be performed in the stationary reference frame using hysteresis or ramp comparison technique, the whole current control loop is approximated with unity gain and zero time delay. The structure of the speed control loop is then as shown in Fig. 8.

V. SIMULATION & RESULTS

A simulation program is written using MATLAB/SIMULINK software for an indirect rotor flux oriented five-phase induction motor drive. The motor is simulated using developed d-q model in the stationary reference frame. The machine is fed by a PWM voltage source inverter and hysteresis current control is exercised upon motor phase currents. The drive is operated in closed loop speed control mode with discrete anti-windup PI speed controller. The anti-windup feature restricts the saturation of the integral part of the controller while working in the limiting region. The torque is limited to twice the rated value (16.67 Nm).

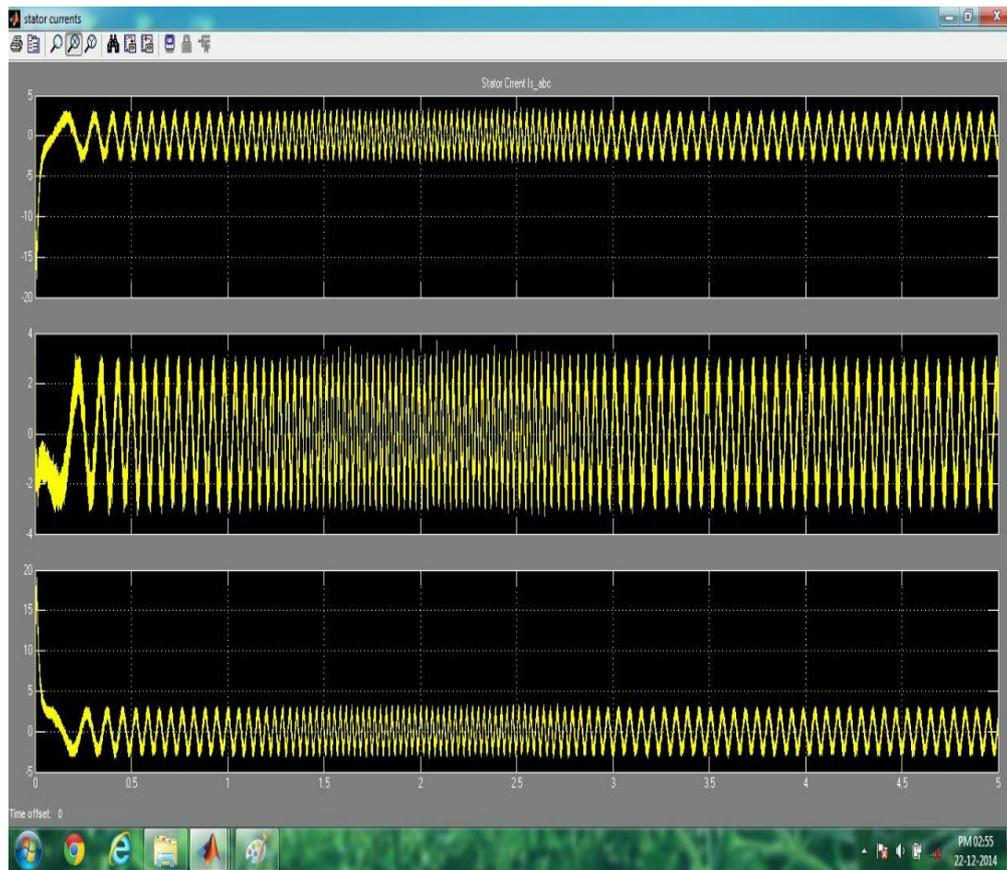


Figure 9. Stator Current.

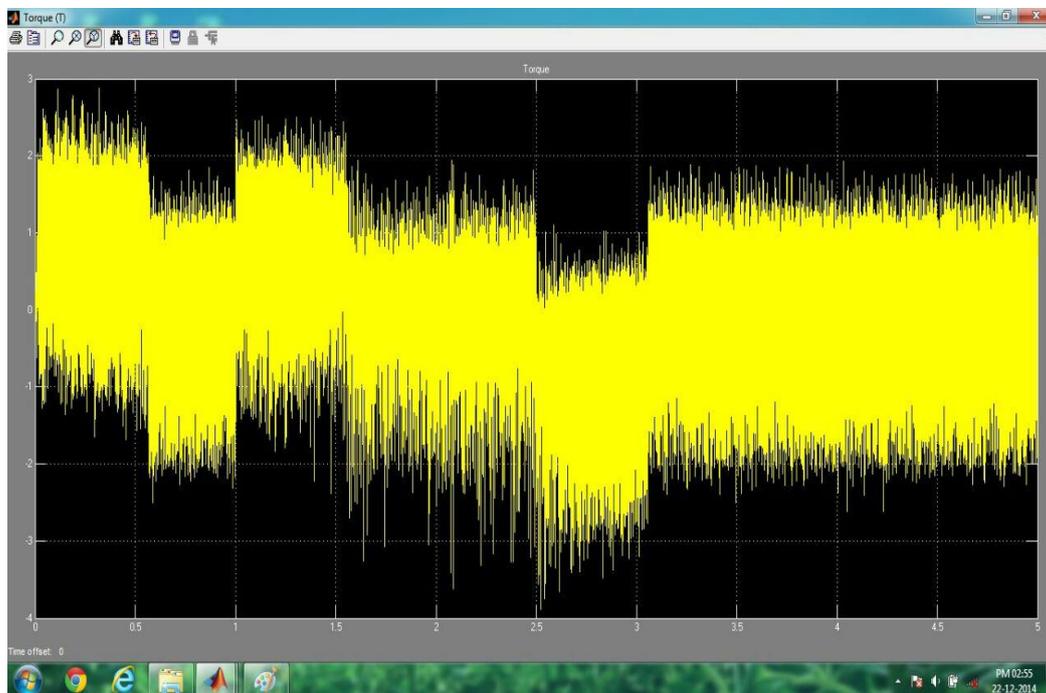


Figure 10. Torque.

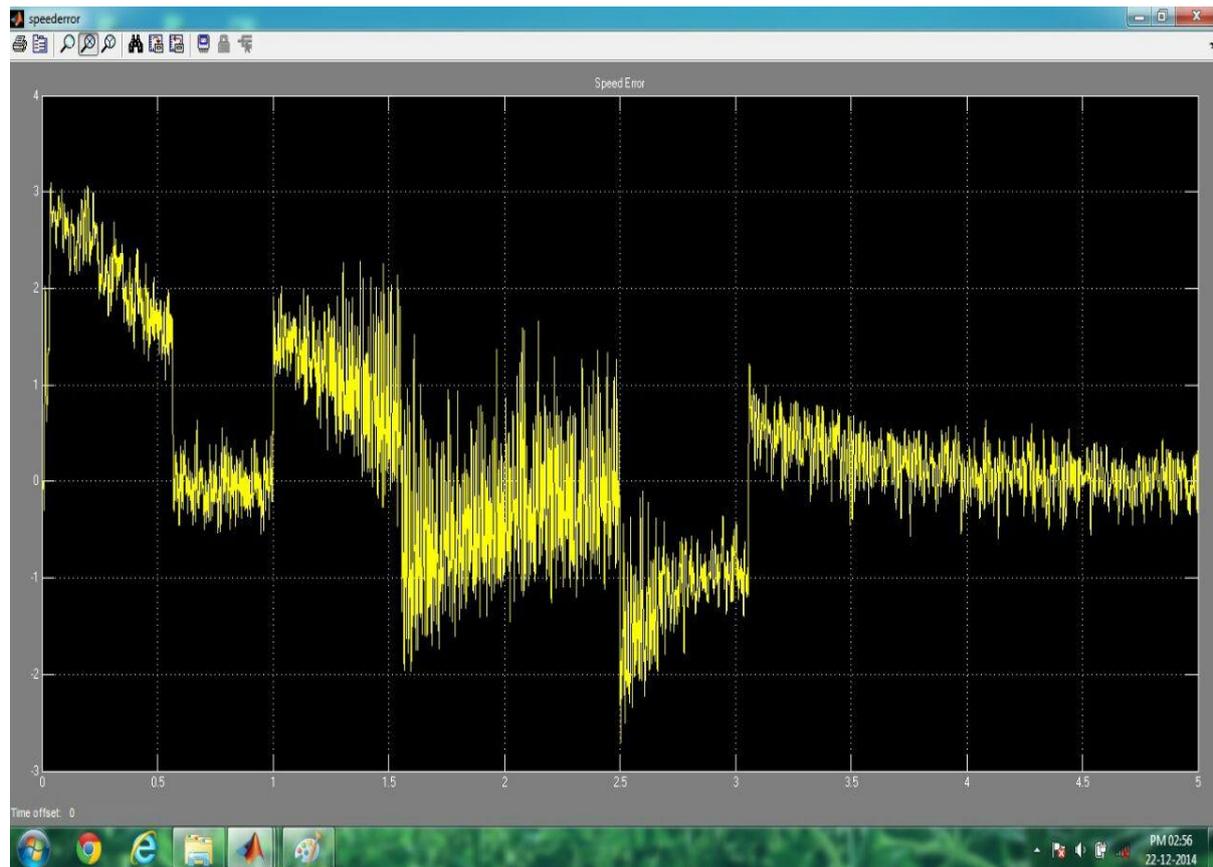


Figure 11. Speed Error.

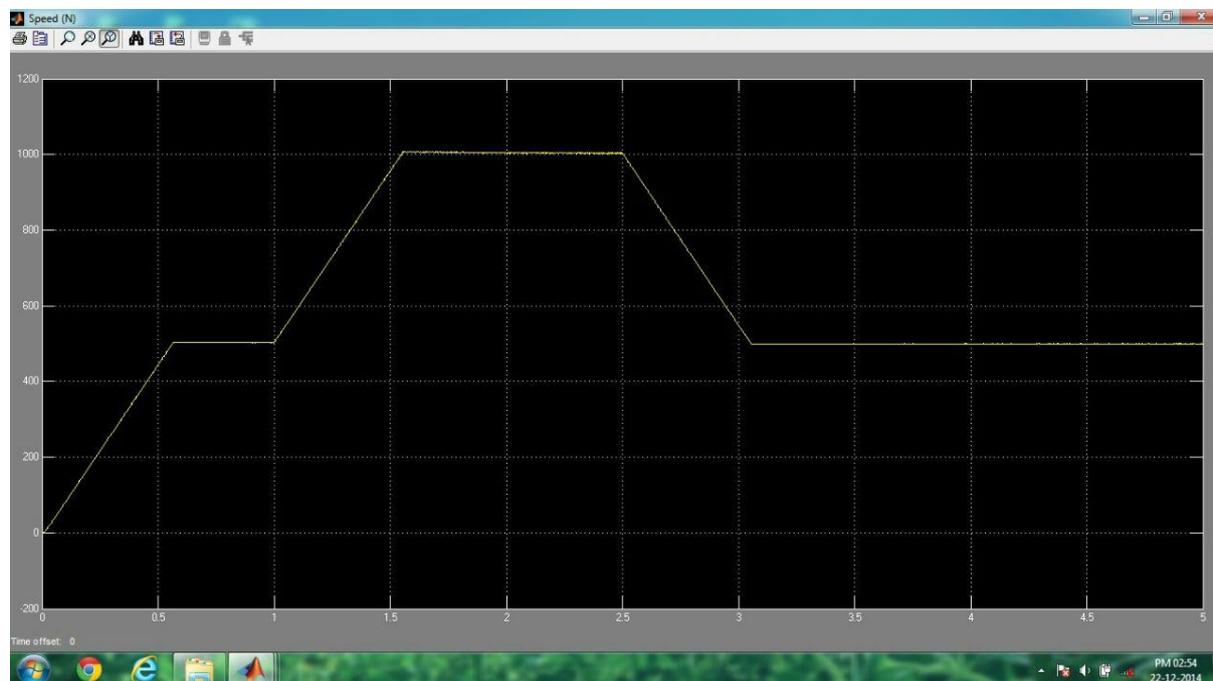


Figure 12. Speed.

Rotor flux reference (i.e. stator d-axis current reference) is ramped from $t = 0$ to $t = 0.01$ s to twice the rated value. It is further reduced from twice the rated value to the rated value in a linear fashion from $t = 0.05$ to $t = 0.06$ s. and it is then kept constant for the rest of the simulation period. Once the rotor flux has reached steady state, a speed command of 1200 rpm (or 1500 rpm) is applied at $t = 0.3$ s in

ramp wise manner from $t = 0.3$ to $t = 0.35$ s. The inverter dc link voltage is set to $415\sqrt{2} = 586.9$ V. A step load torque, equal to the motor rated torque (8.33 Nm), is applied at $t = 1$ s and the machine is allowed to run for sufficient time so as to reach the steady state condition. A speed reversal is then initiated in the ramp-wise manner (ramp duration from $t = 1.2$ to $t = 1.25$ s). Rotor flux and rotor flux reference for the complete duration of the transient, as well as motor speed response, torque response and reference and actual current during the acceleration transient. Rotor flux settles to the reference value after initial transient and then it remains constant throughout the simulation period (2 seconds), indicating that full decoupling between rotor flux and torque control has been achieved. During acceleration motor torque and speed follow the commanded value. Acceleration takes place with the maximum allowed value of the motor torque. Actual motor phase current tracks the reference very well. Consequently, torque response closely follows torque reference. There is sufficient voltage reserve to enable the complete acceleration transient to take place in the torque limit

VI. CONCLUSION

The project demonstrates the versatile application of fuzzy theory for the control of five-phase induction motor drive system. A simple structure of fuzzy logic controller has been proposed. This structure has been derived from the dynamic model of five-phase induction motor drive system using the vector control technique. The effectiveness of the fuzzy logic controller has been established by performance prediction of a simulation of five-phase induction motor drive over a wide range operating conditions. The simulation results showed better dynamic performance of the induction motor when using the FLC as compared with fixed PI controller. The FLC has improved the speed control of 5-ph IM over a wide range of operating conditions.

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