

Comparative Analysis of Vector Control of Induction Motor using PI Controller with Fuzzy Logic Controller

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Abstract: *This paper presents a performance based comparative study of fuzzy logic controller (FLCs) with conventional PI Controller to control the speed of squirrel-cage induction motor (SCIM) by replacing the conventional proportional integral (PI) controller. The fuzzy logic based controller does not require any identification of motor dynamic to control its speed and also assures the disturbance rejection with high robustness. Performances of the fuzzy controllers are also compared with the conventional PI speed controller in terms of several performance measures such as peak overshoot (Mp%), settling time (ts), rise time (tr), peak time (tp) at specified value of load (torque). The simulation results show the effectiveness of the controllers based on fuzzy logic techniques. In this paper, an implementation of intelligent controller for speed control of an induction motor (IM) using direct vector control method has been developed and analyzed in detail. The paper simulates in MATLAB for studies a 50 HP (37KW), cage type induction motor has been considered. The comparative performance of Fuzzy Logic control technique has been presented and analyzed in this work. The fuzzy logic controller is found to be very useful techniques to obtain a high performance speed control. The indirect vector controlled induction motor drive involves decoupling of the stator current in to torque and flux producing components.*

Keywords: Adaptive Neuro Fuzzy logic controller, field-oriented control, proportional-Integral Controller, squirrel cage induction motor

1. Introduction

An induction motor is an asynchronous AC (alternating current) motor. The least expensive and most widely used induction motor is the squirrel cage motor. The interest in sensor less drives of induction motor (IM) has grown significantly over the past few years due to some of their advantages, such as mechanical robustness, simple construction, and less maintenance. These applications include pumps and fans, paper and textile mills, subway and locomotive propulsions, electric and hybrid vehicles, machine tools and robotics, home appliances, heat pumps

and air conditioners, rolling mills, wind generation systems, etc. So, Induction motors have been used more in the industrial variable speed drive system with the development of the vector control technology. This method requires a speed sensor such as shaft encoder for speed control.

However, a speed sensor cannot be mounted in some cases such as motor drives in a hostile environment and high-speed drives [1]. In addition, it requires careful cabling arrangements with attention to electrical noise. Moreover, it causes to become expensive in the system price and bulky in the motor size. In other words, it has some demerits in both mechanical and economical aspects. Thus current research efforts are focused on the so called "sensor less" vector control problem, in which rotor speed measurements are not available, to reduce cost and to increase reliability.

The control and estimation of ac drives in general are considerably more complex than those of dc drives, and this

complexity increases substantially if high performances are demanded. The main reasons for this complexity are the need of variable-frequency, harmonically optimum converter power supplies, the complex dynamics of ac machines, machine parameter variations, and difficulties of processing feedback signals in the presence of harmonics. The selection of drive for motor control is based on several factors such as [2]:

- One-, two- or four-quadrant drive,
- Torque, speed, or position control in the primary or outer loop, Single- or multi- motor drive,
- Range of speed control Does it include zero speed and field-weakening regions, Accuracy and response time,
- Robustness with load torque and parameter variations,
- Control with speed sensor or sensor less control,
- Type of front-end converter,
- Efficiency, cost, reliability, and maintainability consideration, and Line power supply, harmonics, and power factor consideration.

The performance at the high speed region is satisfactory but its performance at very low speed is poor. In many research, most of the methods are estimation of rotor flux angle and parameter tuning in field oriented vector control. The field orientation control, any controller is easily implemented and can approach desired system response. However, if the controlled electrical drives require high performance, i.e., steady state and dynamic tracking ability to set point changes and the ability to recover from system variations. Then a conventional PI, fuzzy and neural controller for such

drives lead to tracking and regulating performance simultaneously and then compared each other [3]. The control and estimation of induction motor drive constitute a vast subject, and the technology has further advance in recent years. Induction motor drives with cage-type machines have been the workhorses in industry for variable-speed application in a wide power range that covers from fractional horse power to multi-megawatts.

Machines are so robust and inexpensive is that no external current is required inside the rotor to create the revolving magnetic field. An induction [4]. The major reason why these machine consists fundamentally of two parts: the stator (the stationary part) and the rotor (the moving part). For a three-phase induction machine (this will be used in this thesis project), three-phase sinusoidal voltages are applied to the windings of the stator. This creates a magnetic field. Because the voltages differ in phase by 120 degree with respect to each other, a revolving magnetic field is created that rotates in synchronism with the changing dominant poles around the cylindrical stator. The rotor, which, for a squirrel-cage rotor consists of copper bars in a cylindrical format 'follows' the created revolving magnetic field. As a consequence, a voltage is induced in the rotor bars that are proportional to the relative angular speed of the magnetic field (this is referenced to the angular speed of the rotor). Because a voltage is induced, magnetic fields are created around the rotor wires [5]. The two generated magnetic fields (in the rotor and stator) interact to generate a force that is also proportional in magnitude to the relative angular speed of the magnetic field. Torque is equal to force multiplied by the radius of the cylindrical stator. Therefore, the resultant torque applied by the rotor is proportional to the relative speed of the magnetic field with respect to the speed of the rotor [6].

2. Over View of Different Controlling Schemes for Speed Control Of Three Phase Induction Motor

2.1 Scalar Control

Scalar control as the name indicates, is due to magnitude variation of the control variable only, and disregards the coupling effect in machine. For example, the voltage of machine can be controlled to control the flux, and frequency or slip can be controlled to control the torque. However flux and torque are also function of voltage and frequency respectively. A scalar controlled drive gives somewhat inferior performance. Scalar control is easy to implement. Scalar controlled drives have been widely used in industry, but the inherent coupling effect (both torque and flux are function of voltage or current and frequency) gives sluggish response and system is easily prone to instability because of higher order (fifth order) system effect. To make it clearer, if torque is increased by incrementing the slip (the frequency), the flux tends to decrease .it has been noted that the flux variation is also sluggish [7]. Decreases in flux then compensated by the sluggish flux control loop feeding an additional voltage.

This temporary dipping of flux reduces the torque sensitivity with slip and lengthens the response time. However, their importance has diminished recently because of the superior performance of vector or Field orientated control (FOC) drives. To improve speed control performance of the scalar control method, an encoder or speed tachometer is required to feedback the rotor angle or rotor speed signal and compensate the slip frequency. However, it is expensive and destroys the mechanical robustness of the induction motor. So these are the limitation of scalar control which is overcome by Field orientated control (FOC) for induction motor drive [8]

2.2 Vector Control or Field Orientated Control (FOC)

Blaschke in 1972 has introduced the principle of field orientation to realize dc motor characteristics in an induction motor derive. For the same, he has used decoupled control of torque and flux in the motor and gives its name transvector control. In DC machine the field flux is perpendicular to the armature flux. Being orthogonal, these two fluxes produce no net interaction on one another. Adjusting the field current can therefore control the DC machine flux, and the torque can be controlled independently of flux by adjusting the armature current [9]. An AC machine is not so simple because of the interactions between the stator and the rotor fields, whose orientations are not held at 90 degrees but vary with the operating conditions. We can obtain DC machine-like performance in holding a fixed and orthogonal orientation between the field and armature fields in an AC machine by orienting the stator current with respect to the rotor flux so as to attain independently controlled flux and torque. Such a control scheme is called flux-oriented control or vector control. Vector control is applicable to both induction and synchronous motors.

The cage induction motor drive with vector or field oriented control offers a high level of dynamics performance and the closed-loop control associated with this derive provides the long term stability of the system. Induction Motor drives are used in a multitude of industrial and process control applications requiring high performances. In high-performance drive systems, the motor speed should closely follow a specified reference trajectory regardless of any load disturbances, parameter variations, and model uncertainties. In order to achieve high performance, field-oriented control of induction motor (IM) drive is employed. However, the controller design of such a system plays a crucial role in system performance. The decoupling characteristics of vector-controlled IM are adversely affected by the parameter changes in the motor. So the vector control is also known as an independent or decoupled control [10].

2.3 Proportional – Integral (PI) Control

In this project complete mathematical model of FOC induction motor is described and simulated in MATALAB for studies a 50 HP(37KW) induction motor has been considered .The performance of FOC drive with proportional plus integral (PI) controller are presented and analyzed. One common linear control strategy is proportional-integral (PI) control.

The Maintenances of the systems, Therefore, preliminary results can be obtained within a short development period. Fuzzy control is based on fuzzy logic, which provides an efficient method to handle in exact information as basis reasoning. With fuzzy logic it is possible to convert knowledge, which is expressed in an uncertain form, to an exact algorithm. In fuzzy control, the controller can be represented with linguistic if-then rules [13]. Control law used for this strategy is given by

$$T = K_p e(t) + K_i \int e(t) dt \dots\dots\dots(1)$$

Its output is the updating in PI controller gains (K_p and K_i) based on a set of rules to maintain excellent control performance even in the presence of parameter variation and drive nonlinearity. The use of PI controllers for speed control of induction machine drives is characterized by an overshoot during tracking mode and a poor load disturbance rejection. This is mainly caused by the fact that the complexity of the system does not allow the gains of the PI controller to exceed a certain low value. At starting mode the high value of the error is amplified across the PI controller provoking high variations in the command torque. If the gains of the controller exceed a certain value, the variations in the command torque become too high and will destabilize the system. To overcome this problem we propose the use of a limiter ahead of the PI controller [11]. This limiter causes the speed error to be maintained within the saturation limits provoking, when appropriately chosen, smooth variations in the command torque even when the PI controller gains are very high. The motor reaches the reference speed rapidly and without overshoot, step commands are tracked with almost zero steady state error and no overshoot, load disturbances are rapidly rejected and variations of some of the motor parameters are fairly well dealt with [20]. In the next chapter we will discuss about the PI controller and designing of PI controller.

2.4 Fuzzy Logic Control

Due to continuously developing automation systems and more demanding small Control performance requirements, conventional control methods are not always adequate. On the other hand, practical control problems are usually imprecise. The input output relations of the system may be uncertain and they can be changed by unknown external disturbances. New schemes are needed to solve such problems. One such an approach is to utilize fuzzy control. Since the introduction of the theory of fuzzy sets by L. A. Zadeh in 1965, and the industrial application of the first fuzzy controller by E.H. Mamadani in 1974, fuzzy systems have obtained a major role in engineering systems and consumer's products in 1980s and 1990s. New applications are presented continuously. A reason for this significant role is that fuzzy computing provides a flexible and powerful alternative to contract controllers, supervisory blocks, computing units and compensation systems in different application areas [12]. With fuzzy sets nonlinear control actions can be performed easily.

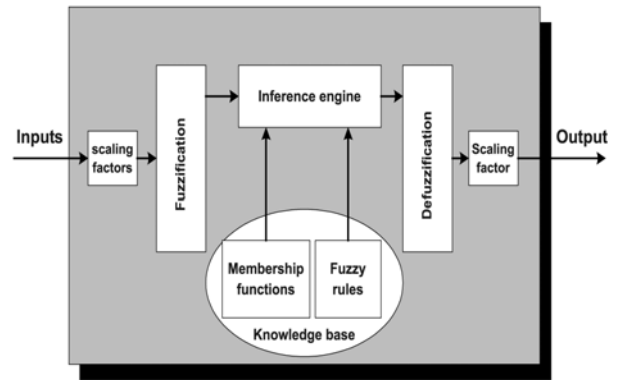


Figure 1. Block Diagram of Fuzzy Logic Controller

3. Design of Speed Controllers

Fuzzy logic based techniques have been recognized in recent years as powerful tools for dealing with the modelling and control of complex systems for which no easy mathematical descriptions can be provided [14], [22] . In fact, expert controllers have been successfully applied in recent years to a wide range of control applications characterized by difficult modelling and ill-definedness of the operating environment. The basic structure of fuzzy logic controller is shown in Fig. 2 which depicted the essential blocks i.e. fuzzification, defuzzification, inference engine and knowledge base. The output equation for a PD like fuzzy controller is given as follows:

For PI like fuzzy controller, the control output equation is evaluated as:

$$u(t) = K_p \int e(t)dt + K_i e(t) \quad (2)$$

where K_p and K_i are the proportional and integral gain factors respectively.

A fuzzy logic controller (FLC) can be regarded as a mapping a set of antecedent fuzzy sets into consequent set. Formally, it is a mapping from $U = U_1 \times U_2 \times \dots \times U_n$, where $U_i \subseteq \mathbb{R}$; $i = 1, 2, \dots, n$, into $V \subseteq \mathbb{R}$ and consists of four main components:

- Fuzzification Interface;
- Knowledge Base;
- Inference Engine;
- Defuzzification Interface

First, the FLC fuzzifies its crisp valued input vector $x = (x_1; \dots; x_n)^T \in U$, by mapping it into a fuzzy set in U . This is achieved by the means of the membership functions stored in the knowledge base. The if - then rules, also stored in the knowledge base, and the composition rule of inference are then used by the inference engine to map sets in U into sets in V . The if - Then rules are in the form of $R(l): \text{if } x_1 \text{ is } A(l) \text{ and } x_n \text{ is } A(l)_n \text{ then } y \text{ is } B(l)$ where $y \in V$ is the output of the FLC, A_i ; $i = 1, 2, \dots, n$, and $B(l)$ are fuzzy sets in U_i and V , respectively, and $l = 1, 2, \dots, L$, where L

denotes the total number of rules. Finally, the defuzzification process maps a fuzzy set in V to a crisp point value in V .

All membership functions (MFs) for: 1) two controller inputs, i.e., error (e) and change of error (Δe) and 2) single control output (u) are defined on the separate interval $[-200, 300]$ and $[-200, 150]$. A desired number of asymmetric triangles (except the two MFs at the extreme ends) with different base and overlap with neighbouring MFs are used in the fuzzy inference. The two inputs and one output of the fuzzy controller is partitioned and represented linguistically in seven and nine membership functions respectively (i.e. for two inputs as NB = negative big, NM = negative medium, NS = negative small, Z = zero, PS = positive small, PM = positive medium, PB = positive big and for single output as NB = negative big, NM = negative medium, NS = negative small, NVS = negative very small, Z = zero, PVS = positive very small, PS = positive small, PM = positive medium, PB = positive big).

A fuzzy system is characterized by a set of linguistic statements based on expert knowledge. The expert knowledge is usually in the form of if-then rules, which are easily implemented by fuzzy conditional statements in fuzzy logic. The collection of fuzzy control rules that are expressed as fuzzy conditional statements forms the rule base or the rule set of an FLC.

In Takagi-Sugeno, method of fuzzy inference the first two parts of the fuzzy inference process (i.e. fuzzifying the inputs and applying the fuzzy operator) are exactly the same as Mamdani method. The main difference between Mamdani and Sugeno is that the Sugeno output membership functions are either linear or constant. A typical rule in a Sugeno fuzzy model has the form if Input 1 (e) is zero and Input 2 (Δe) is zero, then Output is $z = a * e + b * (\Delta e) + c$.

Where a , b and c are all constants. For a zero-order Sugeno model, the output level z is a constant ($a = b = 0$). The output level z_i of each rule is weighted by the firing strength w_i of the rule. For example, for an AND rule with Input 1 = e and Input 2 = Δe , the firing strength is $w_i = \text{AND Method}(F1(x); F2(y))$, where $F1(x); F2(y)$ are the membership functions for Inputs 1 and 2. The final output of the system is the weighted average of all rule outputs, computed as

$$\text{Final output} = \frac{\sum_{i=1}^N w_i z_i}{\sum_{i=1}^N w_i}$$

Where N is the number of rules. This is a very often used rule base designed with a two-dimensional phase plane in mind where the FLC drives the system into the so-called sliding mode. The rule base contains 25 rules and the control surfaces (control output versus e and Δe) are depicted. The performance parameters are evaluated on the basis of same rule base used in all the fuzzy speed controller.

4. Matlab Simulation of VCIM Based of PIController

We have simulated in matlab by use of Proportional - Integral controller based model as shown in figure. The reference speed 100 and feedback is given to summer, output of summer error given to PI controller which change the in output for better result [17].

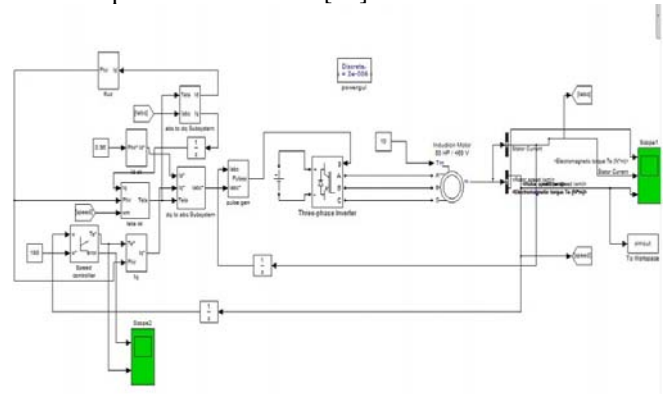


Figure 2. Matlab Simulink block diagram of direct vector control using P-I controller

5. Matlab Simulation of VCIM Using Fuzzy Logic Controller

We have simulated in matlab by use of Fuzzy Logic controller based model as shown in figure. Fuzzy logic controller block is used which have two input Error and rate of change in error and one output.

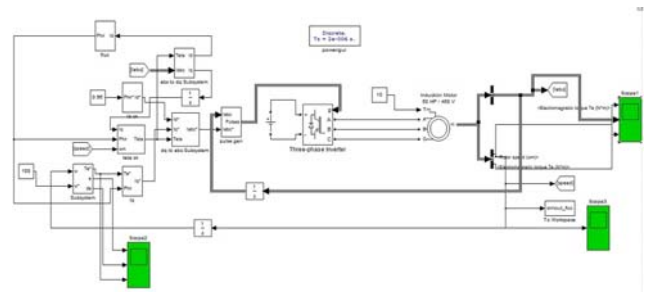


Figure 3. Matlab Simulink block diagram of direct vector control using Fuzzy Logic controller

6. Experimental Result

6.1 Performance of direct Vector Control IM Using P-I Control

Fig 4 shows the performance characteristic of a 50 hp, 460 V, 60 Hz IM, operating at no load with a PI speed controller. The reference speed is 100 rad/sec. It is observed that motor pick up the speed 115 rad/sec at starting. If the gains of the controller exceed a certain value, the variations in the motor torque become too high and will destabilize the system. Induction motor current (I_{abc}), motor torque (T_e) and time (t) are shown in fig 4

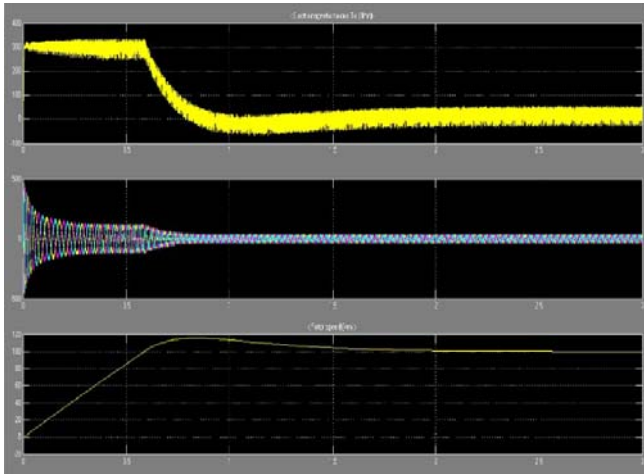


Figure 4. Performance of VCIM using PI control at 10 N-M load with reference speed 100 rad/sec

Table I Results of PI Controller

	Peak Time (T_p)	Max. Overshoot (M_p)	Rise Time (T_r)	Settling Time (T_s)
PI Controller	0.845 sec	15.524	0.588 sec	2.593 c

6.2 Performance of Indirect Vector Control IM Using Fuzzy Control

Fig 5 shows the performance characteristic of a 50 hp, 460 V, 60 Hz IM, operating at no load with a fuzzy logic speed controller. The reference speed is 100 rad/sec.

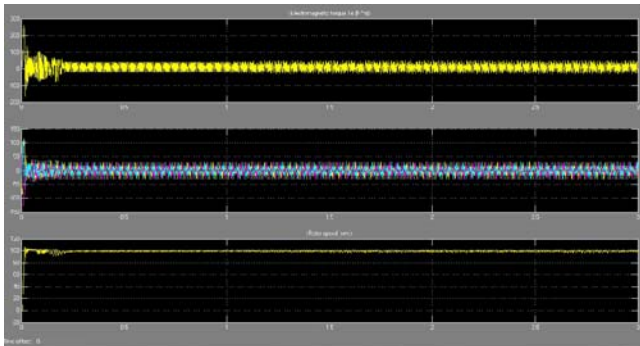


Figure 5. Performance of VCIM using Fuzzy Logic controller at 10 N-M load with reference speed 100 rad/sec

Table II Results of PI Controller

	Peak Time (T_p)	Max. Overshoot (M_p)	Rise Time (T_r)	Settling Time (T_s)
Fuzzy Controller	0.046 sec	1.218	0.026 sec	0.82 c

6.3 Comparative Results of PI Controller and Fuzzy logic Controller

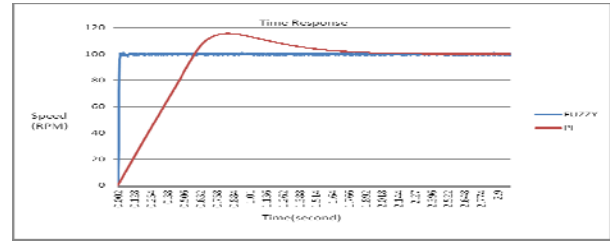


Figure 6. Comparative Result PI Controller and Fuzzy Logic controller at 10 N-M load with reference speed 100 rad/sec

Table III Comparative Results of PI Controller and Fuzzy Logic Controller

	Peak Time (T_p)	Max. Overshoot (M_p)	Rise Time (T_r)	Settling Time (T_s)
PI Controller	0.845 sec	15.524	0.588 sec	2.593 sec
Fuzzy Controller	0.046 sec	1.218	0.026 sec	0.082 sec

7. Conclusion & Future Scope

This paper has successfully demonstrated and a properly designed PI, Fuzzy logic controller. We have study and compared two controllers for speed control of vector control induction motor drive. At given result and their data of induction motor current, motor torque, and speed at 10 N-m load performances are better with the Fuzzy logic controller Based on simulation results verification, the following conclusions are made.

- The Fuzzy logic controller is more robust than the PI and when load disturbances occurred.
- The Fuzzy logic controller performance when certain motor parameters (i.e. current and motor torque) were increased by a factor was still quite good and far better than the PI performance when the same parameters.
- The fuzzy logic controller base makes the superior to PI control techniques

Nomenclature

- P- Number of poles.
- J_{eq} - inertial constant.
- I_d, I_q - direct- and quadrature-axis components of the induction motor armature current.
- V_d, V_q - direct and quadrature-axis components of the induction motor armature voltage.
- R_s - Stator resistance.
- R_r - rotor resistance.
- L_s - stator inductance.
- L_r - rotor inductance.

- L_m - mutual inductance.
- ω_{mech} - rotor speed, in actual (mechanical) radians per second.
- ω_s - supply frequency.
- T_{em} - electromagnetic torque.
- T_L - load torque.

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