Volume 3, Issue 4, October 2016 ISSN: 2348-8565 (Online)
International Journal of Modern Engineering and Research Technology
Website: http://www.ijmert.org Email: editor.ijmert@gmail.com

Efficiency Enhancement Using Fuzzy Based SVM - DTC Control Method

Shikha Yadav
M.Tech. Research Scholar
Takshshila Institute of Engineering & Technology
Jabalpur (M.P.), [INDIA]
Email:

Pramod Dubey
Assistant Professor
Department of Electrical & Electronics Engineering
Takshshila Institute of Engineering & Technology
Jabalpur (M.P.), [INDIA]
Email: pramoddubey@takshshila.org

Abstract

The induction motor is the most common electric motor in most applications of all the sectors. Induction motors fail due to many reasons, and many are rewound two or more times during their lifespan. It is assumed generally that efficiency of a rewound motor is not same as the original motor. Exact estimation of efficiency of a refurbished motor or any existing motor is essential in industries for energy auditing, savings and management. In most cases, the efficiency improvements can be obtained by the improved system efficiency, which very often, but not always, can be achieved with a variable-speed drive. The main function of a variable speed drive (VSD) is to control the power flow from the mains to the load. The combination of an electric motor with power electronic converter leads to the establishment of variable speed drives. The efficiency of the entire system can be optimized by introducing variable speed to the driven load, and so in this area that the greatest efficiency gains are possible.

Keywords:— *Induction motor, fuzzy logic, matlab, direct torque control, SVM.*

I. Introduction

Drive system efficiency is a complex function of the type of machine used, type of power semiconductor switches, converter topology, and the selected PWM algorithm. In addition, the control system has a reflective consequence on the drive efficiency. A drive system usually operating at rated flux provides the best transient response. However, rated flux operation causes too much core loss at light load conditions, thus harming the efficiency of the drive. Since most of the time drives work at light load, optimum efficiency can be attained by programming the flux. IMs perform well when they are driven with sinusoidal voltages and currents. This motor can provide smooth operation as the result of low torque ripple. To achieve this, most IMs consist of a slotted stator structure where the windings are placed in the slots with a sinusoidal winding distribution, resulting in a sinusoidal flux distribution in the air gap. In most cases, the efficiency of the motor can be increased by reducing the bar resistance of rotor. When the flux cut by the conductors a change in flux induces the voltage across the rotor bars, results flow of current in the rotor.

An induction motor is an asynchronous motor, the speed of which can be varied by altering the supply frequency. The control scheme to be implemented in any specific case will depend on a number of factors including load reliability, investment cost, and any special control necessities. Thus, for any particular application, a complete review of the load characteristics, the features required of the speed control system, historical data on process flows, the electricity tariffs and the investment costs would be a requirement to the selection of a speed control system.

II. Adjustable Speed Drives – Control Scheme

To save significant amounts of energy in process operations compared to traditional control methods Adjustable Speed Drives (ASD) can be used where the load or speed of the operation varies. AC Adjustable Speed Drives are among the most effectual types of speed control when used on variable torque loads like pumps, centrifugal fans, and compressors. As the motor decreases the operating speed of the fan, compressor the horsepower prerequisite to operating the system is greatly reduced. This is the main advantage of the ASD and one of the key reasons ASD's have become so prevalent in many process operations. An ideal choice for variable-speed applications is the three phase inverter topology. The speed of the motor can be controlled by simply varying the voltage and frequency of the applied waveform (scalar control). Alternately, speed can be controlled by covering a speed loop around a torque and flux loop integrating Direct Torque Control (DTC). The use of appropriately controlled power converters can decrease the drive total losses. For these reasons, the performance enhancement in the electrical drives for induction motors is today an important topic. A rise in the drive performance means, in one hand, a significant economic saving, and the other, a reduction in environment pollution.

In addition to energy savings through matching the motor speed to application needs, ASDs can provide benefits related to energy efficiency:

- Improved process control, such as speeding up or slowing down a machine or process
- Inherent power factor correction
- Bypass capability in the event of an emergency
- Protection from overload currents

Direct Torque Control

Direct torque control (DTC) is one of the methods used in adjustable frequency drives to control the torque and thus finally the Speed of three-phase AC electric motors. This includes estimation of the motor's magnetic flux and torque based on the measured voltage and current of the motor. The Direct Torque Control method, allows direct and independent electromagnetic torque and flux control, making possible fast torque response, selecting an optimal switching vector, low harmonic losses and low inverter switching frequency. With DTC, it is possible to obtain direct flux and electromagnetic torque control, indirect voltage and current control, sinusoidal current and flux, superior torque dynamics and hysteresis band dependent inverter switching frequency. One of the common drawbacks of conventional DTC is high torque ripple and slow transient response to the step changes in torque during start-up.

DTC drives utilizing hysteresis comparators suffer from high torque ripple and variable switching frequency. The most common solution to this problem is to use fuzzy applications with Space Vector Modulation (SVM) or using a multilevel inverter. In this study fuzzy with Space vector modulation is used in direct torque control method.

Modelling of Induction Motor

A dynamic model of the induction machine subjected to control must be known in order to understand and design vector controlled drives. Due to the fact that every good control has to face any possible change of the plant, it could be said that the dynamic model of the machine could be just a good approximation of the real plant. Nevertheless, the model should incorporate all the important dynamic effects occurring during both steady state and transient operations. Such a model can be obtained by means of space vector phasor theory or two-axis theory of electrical machines.

The dynamic model of IM is derived by using a two-phase motor in direct and quadrature axes. This approach is desirable because of the conceptual simplicity obtained with the two sets of the windings, one on the stator and the other on the rotor. The stator of induction motor consists of three phase balanced distributed windings with each phase separated from other two windings by 120 degrees in space. When current flows through these windings, three phase rotating magnetic field is produced. The dynamic behavior of the induction machine is taken into account in an adjustable speed drive system using a power electronics converter. This machine constitutes an element within a feedback loop. Study of the dynamic performance of the machine is complex due to the coupling effect of the stator and rotor windings; also, the coupling coefficient varies with rotor position. So a set of differential equations with time-varying coefficients describe the machine model.

A balanced three phase supply is given to the motor from the power converter. For dynamic modeling of the motor two axes theory is used. According to this theory, the time varying parameters can be expressed in mutually perpendicular direct (*d*) and quadrature (*q*) axis. For their presentation of the *d-q* dynamic model of the machine, a stationary or rotating reference frame is assumed.

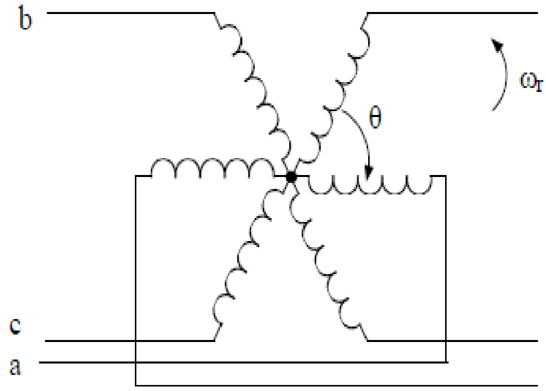

Figure 1. Coupling effect in stator and rotor winding of the motor

The dynamic performance of an AC machine is somewhat complex because the three-phase rotor windings move with respect to the three-phase stator windings as shown in Figure 1. Basically, it can be looked on as a transformer with a moving secondary, where the coupling coefficients between the stator and rotor phases change continuously with the change of rotor position θ_r correspond to rotor direct and quadrature axes. Note that a three-phase machine can be represented by an equivalent two-phase machine as shown in Figure 2, where $d_s \sim q_s$ correspond to stator direct and quadrature axes, and $d_r \sim q_r$ is corresponding to rotor.

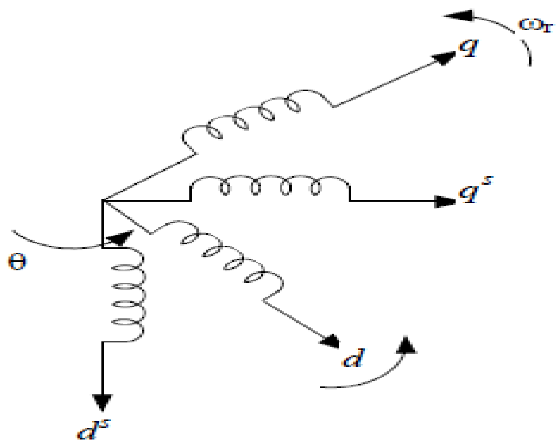

Figure 2. Equivalent two-phase machine

Axes transformation

Three phase to two phase transformation

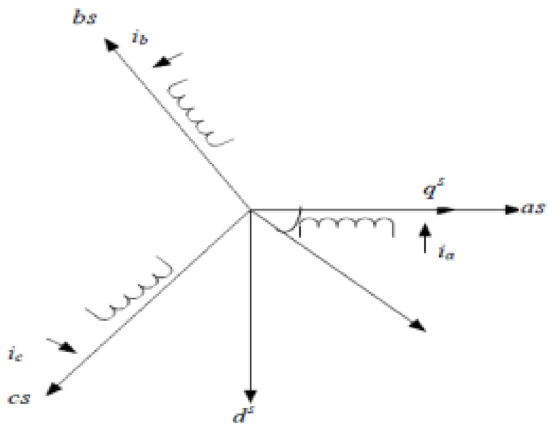

Figure 3. Stationary frame abc to $ds-qs$ axes transformation.

The voltages V_{as}, V_{bs}, V_{cs} are the voltages of as, bs, cs phases respectively. Now assuming that the stationary $d_s - q_s$ axes are oriented at θ angle as shown and the voltages along $d_s - q_s$ axes to be V_{ds}^s, V_{qs}^s respectively, the stationary two phase voltages can be transformed to three phase voltages according to the following equations:

$$V_{as} = V_{qs}^s Cos\theta + V_{ds}^s Sin\theta$$

$$V_{bs} = V_{qs}^s Cos(\theta - 120^\circ) + V_{ds}^s Sin(\theta - 120^\circ)$$

$$V_{cs} = V_{qs}^s Cos(\theta + 120^\circ) + V_{ds}^s Sin(\theta + 120^\circ)$$

The phase voltages in matrix form can be written as:

$$\begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 1 \\ \cos(\theta-120) & \sin(\theta-120) & 1 \\ \cos(\theta+120) & \sin(\theta+120) & 1 \end{bmatrix} \begin{bmatrix} V_{qs}^s \\ V_{ds}^s \\ V_{0s}^s \end{bmatrix}$$

By inverse transformation, V_{ds}, V_{qs} can be written in terms of three phase voltages in matrix form as follows:

$$\begin{bmatrix} V_{qs}^s \\ V_{ds}^s \\ V_{0s}^s \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & \cos(\theta-120) & \cos(\theta+120) \\ \sin\theta & \sin(\theta-120) & \sin(\theta+120) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \end{bmatrix}$$

Where V_{0s} = zero sequence component which may or may not present.

For convenient q_s axis is aligned with the as - axis i.e. θ = 0 and zero sequence component is neglected. So the transformation relations are reduced to

$$V_{as} = V_{qs}^s$$

$$V_{bs} = -\frac{1}{2}V_{qs}^s - \frac{\sqrt{3}}{2}V_{ds}^s$$

$$V_{cs} = -\frac{1}{2}V_{qs}^s + \frac{\sqrt{3}}{2}V_{ds}^s$$

$$V_{qs}^s = V_{as}$$

$$V_{ds}^s = -\frac{1}{\sqrt{3}}(V_{bs} - V_{cs})$$

Two phase stationary to two phase synchronously rotating frame transformation

The stationary $d_s - q_s$ axes are transformed to synchronously rotating $d_e - q_e$ reference frame which is rotating at speed ω_e with respect to $d_s - q_s$ axes with the help of Figure 3.

The angle between d_s and d_e axes is $\theta_e = \omega_e t$. The voltages V_{ds}, V_{qs} can be converted to voltages, on $d_e - q_e$ axis according to the following relations:

$$V_{ds} = V_{qs}^s \cos\theta_e - V_{ds}^s \sin\theta_e$$

$$V_{qs} = V_{qs}^s \sin\theta_e + V_{ds}^s \cos\theta_e$$

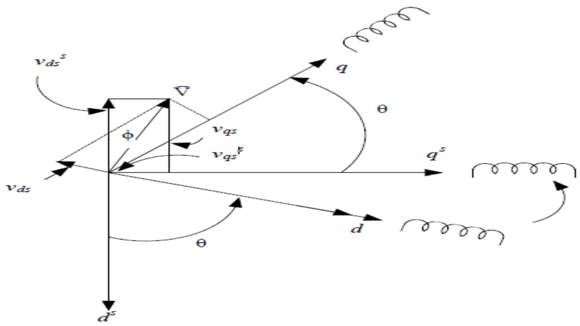

Figure 4. Stationary d-q frame to synchronously rotating frame transformation

The transformation of rotating frame parameters to stationary frame is according to the following relations:

$$V_{qs}^{s} = V_{qs}\cos\theta_e + V_{ds}\sin\theta_e$$

$$V_{ds}^{s} = -V_{qs}\sin\theta_e + V_{ds}\cos\theta_e$$

Assuming that the three phase voltages are balanced and sinusoidal given by following

$$V_{as} = V_m \cos(\omega_e t + \phi)$$

$$V_{bs} = V_m \cos(\omega_e t + \phi - 2\pi/3)$$

$$V_{cs} = V_m \cos(\omega_e t + \phi + 2\pi/3)$$

$$V_{qs}^{s} = V_m \cos(\omega_e t + \phi)$$

$$V_{ds}^{s} = -V_m \sin(\omega_e t + \phi)$$

$$V_{qs} = V_m \cos\phi$$

$$V_{ds} = -V_m \sin\phi$$

From above equations it is clear that sinusoidal quantities in a stationary frame appear as dc quantities in a synchronously rotating reference frame.

Motor dynamic model in stationary frame

Machine model in stationary frame by Stanley equations substituting ωe= 0. The stator circuit equations are written as:

$$V_{qs}^{s} = R_s i_{qs}^{s} + \frac{d}{dt}\psi_{qs}^{s}$$

$$V_{ds}^{s} = R_s i_{ds}^{s} + \frac{d}{dt}\psi_{ds}^{s}$$

$$0 = R_r i_{qr}^{s} + \frac{d}{dt}\psi_{qr}^{s} - \omega_r \psi_{dr}^{s}$$

$$0 = R_r i_{dr}^{s} + \frac{d}{dt}\psi_{dr}^{s} + \omega_r \psi_{qr}^{s}$$

Where

ψ_{qs}^{s} , ψ_{ds}^{s} = q-axis and d-axis stator flux linkages

ψ_{qr}^{s} , ψ_{dr}^{s} = q-axis and d-axis rotor flux linkages

ω_r = rotor speed and

R_s , R_r = stator and rotor resistances

The electromagnetic torque is developed by the interaction of air gap flux and rotor mmf which can be expressed in general vector form as

$$T_e = \frac{3}{2}\frac{P}{2}(\overline{\psi_m}) * (\overline{I_r})$$

The torque equations can be written in stationary frame with corresponding variables as

$$T_e = \frac{3}{2}\frac{P}{2}(\psi_{dm}^{s} i_{qr}^{s} - \psi_{qm}^{s} i_{dr}^{s})$$

$$= \frac{3}{2}\frac{P}{2}(\psi_{dm}^{s} i_{qs}^{s} - \psi_{qm}^{s} i_{ds}^{s})$$

$$= \frac{3}{2}\frac{P}{2}(\psi_{ds}^{s} i_{qs}^{s} - \psi_{qs}^{s} i_{ds}^{s})$$

$$= \frac{3}{2}\frac{P}{2}L_m(i_{dr}^{s} i_{qs}^{s} - i_{qr}^{s} i_{ds}^{s})$$

$$= \frac{3}{2}\frac{P}{2}(\psi_{dr}^{s} i_{qr}^{s} - \psi_{qr}^{s} i_{dr}^{s})$$

III. MODELING AND ANALYSIS OF SVPWM SCHEME FOR DIRECT TORQUE CONTROL DRIVE

Direct flux and torque control with space vector modulation (DTC-SVM) schemes are proposed in order to improve the classical DTC. The DTC-SVM strategies operate at a constant switching frequency. In the control structures, the space vector modulation (SVM) algorithm is used. The type of DTC-SVM strategy depends on the applied flux and torque control algorithm. Basically, the controllers calculate the required stator voltage vector and then it is realized by space vector modulation technique.

The features of the DTC-SVM method can be summarized as follows:

- Good dynamic control of flux and torque,
- Constant switching frequency,
- Unipolar voltage thanks to using of PWM block (SVM),
- Low flux and torque ripple,
- Sinusoidal stator currents.

In principle, the DTC method selects one of the six nonzeroes and two zero voltage vectors of the inverter on the basis of the instantaneous errors in torque and stator flux magnitude. In spite of its simplicity, DTC allows good torque control in both steady and transient state. Its main characteristic is the good performance, obtaining results as good as the classical vector control. DTC method still required further research in order to improve the motor's performance, as well as achieve a better behavior regarding environment compatibility (Electro Magnetic Interference and Energy), that is desired nowadays for all industrial applications.

Direct flux control

In stationary reference frame the stator flux equation can be written as:

$$\overline{\psi_s} = \int (\overline{V}_s - \overline{i}_s R_s) dt$$

If the stator resistance drop is neglected for simplicity, the stator flux varies along the direction of applied voltage vector and the equation will be reduced to

$$\Delta\overline{\psi_s} = \overline{V_s}\Delta t$$

Which means, by applying stator voltage vector $\overline{V}s$ for a time increment Δt , $\overline{\psi_s}$ can be changed incrementally. Each sector has a different set of voltage vector to increase or decrease the stator flux. The command flux vector rotates in anticlockwise direction in a circular path and the actual stator flux vector $\overline{\psi_s}$ tracks the command flux in a zigzag path but constrained to the hysteresis band.

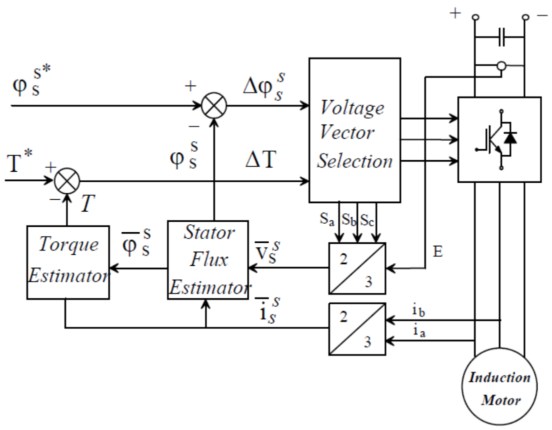

Figure 5: Block diagram of direct torque control

Direct torque control

The electromagnetic torque produced due to interaction of stator and rotor flux is given by the following equation

$$T_e = \frac{3}{2}(\frac{P}{2})\frac{L_m}{L_s^{'}L_r}\overline{\psi_s} * \overline{\psi_r}$$

$$= \frac{3}{2}(\frac{P}{2})\frac{L_m}{L_s^{'}L_r}\psi_s\psi_r \sin\gamma$$

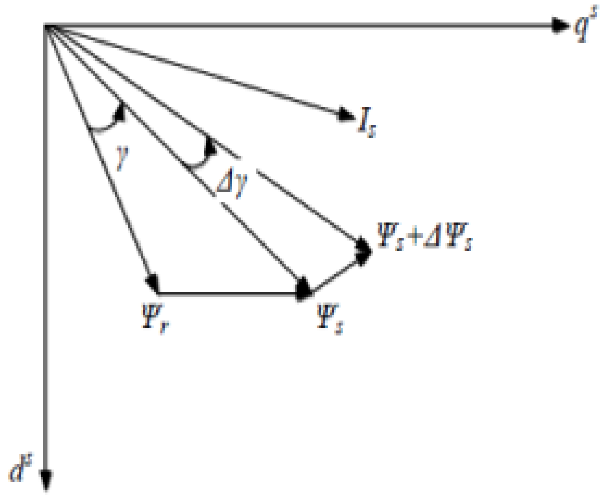

Figure 6: Stator flux, rotor flux and stator current vectors in ds-qs reference plane

Switching Selection

A high-performance torque control can be established due to the decoupled control of stator flux and torque in DTC. Optimum switching vector selection table given by table 3 shows the optimum selection of the switching vectors in all sectors of the stator flux plane. This table is based on the value of stator flux error status, torque error status and orientation of stator flux for counterclockwise rotation of the shaft.

The sectors of the stator flux space vector are denoted from S1 to S6. Stator flux modulus error after the hysteresis block (Φ) can take just two values. Torque error after the hysteresis block (τ) can take three different values. The zero voltage vectors V0 and V7 are selected when the torque error is within the given hysteresis limits, and must remain unchanged.

Table 3: Applied selected voltage vectors

$d\Psi$	dT_e	S(1)	S(2)	S(3)	S(4)	S(5)	S(6)
1	1	V_2	V_3	V_4	V_5	V_6	V_1
	0	V_7	V_0	V_7	V_0	V_7	V_0
	-1	V_6	V_1	V_2	V_3	V_4	V_5
0	1	V_3	V_4	V_5	V_6	V_1	V_2
	0	V_0	V_7	V_0	V_7	V_0	V_4
	-1	V_5	V_6	V_1	V_3	V_3	V_7

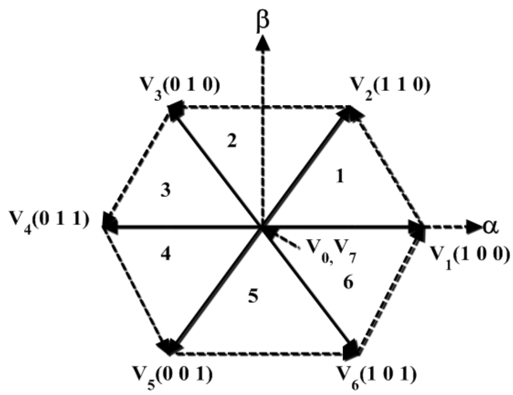

Figure 7: Inverter switching state vectors

Decoupled control of the stator flux modulus and the torque is achieved by acting on the radial and tangential components respectively of the stator flux linkage space vector in its locus. These two components are directly proportional (Rs =0) to the components of the same voltage space vector in the same directions. Figure 7 shows the possible dynamics locus of the stator flux, and its different variation depending on the VSI states chosen. The possible global locus is divided into six different sectors signaled by the discontinuous line.

When three phase supply is given to the stator of the induction machine, a three phase rotating magnetic field is produced. Due to this field flux, a three phase rotating voltage vector is generated which lags the flux by 90º. This field can also be realized by a logical modeling of the system very arduous.

2. The analytical form of the system is not provided, instead, a linguistic form is provided.
3. The precise identification of the system parameters.
4. The system behavior has a vague characteristic under precisely defined conditions.
5. The conditions themselves are vague.

Inference System

The inference system of a Fuzzy Logic Controller consists of the following three paradigms:

1. **Rule Base**: - It consists of a number of If-Then rules. The If side of the rule is called the antecedent and the Then side is called the consequence. These rules are very much similar to the Human thought process and the computer uses the linguistic variables, derived after fuzzification for execution of the rules. They very simple to understand and write and hence the programming for the fuzzy logic controller becomes very simple. The control strategy is stored in more or less the normal language.

2. **Database**: - It consists of the all the defined membership functions that are to be used by the rules.

3. **Reasoning Mechanism**: - It performs the inference procedure on the rules and the data given to provide a reasonable output. It is basically the codes of the software which are process the rules and the all the knowledge based on a particular situation. It exercises a human brain type of attribute to methodically carry out the inference steps for processing the information.

Defuzzification Block or Defuzzufier

A defuzzifier performs the exact opposite function of a fuzzifier. It transforms the fuzzy variables (which are obtained as output after processing of the inputs) to crisp sets. The defuzzifier is necessary because in the real world the crisp values can only be taken as inputs to the other systems. Even though the fuzzy sets resemble the human thought process, their functionality is limited only to the above processes. A defuzzifier is generally required only when the Mamdani Fuzzy Model is used for designing a controller. There are other types of architectures that can be used are:

1. Tagaki-Sugeno Fuzzy Model.
2. Tsukamoto Fuzzy Model.

Mamdani model is preferred here because it follows the Compositional Rule of Inference strictly in its fuzzy reasoning mechanism. Unlike the Mamdani model, the outputs are defined with the help of a specific function for the other two models (first order polynomial in the input variables) and hence the output is crisp instead of fuzzy. This is counterintuitive since a fuzzy model should be able to propagate the fuzziness from inputs to outputs in an appropriate manner.

The proposed fuzzy-based SVM-DTC method includes a fuzzy logic controller block to produce optimum control vector. The optimum control vector angle is calculated by the fuzzy logic controller with using instantaneously flux and torque errors. On this calculation, fuzzy logic rates flux and torque errors and produces necessary change in stator flux vector angle for next step. Then, calculated optimum vector angle applied to discrete space vector pulse width modulation block SVPWM and it generates switching signals.

V. Design of Fuzzy Logic Controller

The design of a Fuzzy Logic Controller needs the choice of Membership Functions. The membership functions should be chosen such that they cover the whole universe of discourse. It should be taken care that the membership functions overlap each other. This is done in order to avoid any kind of discontinuity with respect to the minor changes in the inputs. To achieve finer control, the membership functions near the zero regions should be made narrow. Wider membership functions away from the zero regions provide faster response to the system. Hence, the membership functions should be adjusted accordingly. After the appropriate membership functions are chosen, a rule base should be created. It consists of a number of Fuzzy If-Then rules that completely define the behavior of the system. These rules very much resemble the human thought process, thereby providing artificial intelligence to the system.

For the proposed FLC, the speed error and change of the speed error are considered as the input linguistic variables and the torque-producing current component is considered as the output linguistics variable. Thus, the functional relation of the FLC can be expressed as

$$i_q(n) = \int_{discrete} \Delta i_q(n) = f(\Delta e(n), \Delta\omega_r(n))$$

where $\Delta e(n) = \Delta\omega_r(n) - \Delta\omega_r(n-1)$ is the change of speed error, $\Delta\omega_r(n) = \omega_r^*(n) - \omega_r(n)$ is the present sample of speed error, $\Delta\omega_r(n-1)$ is the post sample of speed error, $\Delta\omega_r(n)$ is the present sample of actual speed, $\omega_r^*(n)$ is the present sample of command speed, and f denotes the nonlinear function. The main goal of the control system is to track the command speed by providing the appropriate torque- producing current component i_q depending upon theoperating conditions. In real time, the motor position information and output of the fuzzy, which is considered as the command q-axis current i_q^*, as well as the command d-axis current i_d, are compared to the quadrature current (i_q, i_d)to get the quadrature stator voltage (v_q^*, v_d^*).

Membership Function Design Input linguistic variable

The inputs to the Fuzzy Logic Controller are:

1. Speed Error (e).
2. Change in Error (Δe) or derivative of speed error.

Output linguistic variable

The output from the fuzzy logic controller is:

Torque- producing the current component.

Fuzzy sets or label for the membership functions are defined as:

- Negative big
- Negative small
- Positive small
- Positive big

Rule Base Design

The Rule Base for deciding the output of the inference system consists of If-Then rules in this case since there are 4 fuzzy sets in each of the inputs. The table representing the rule base is as follows:

Table.4. Fuzzy Rule Table for Output

e/ce	NB	NS	PS	PB
NB	PB	PS	NS	NB
NS	PB	PS	NS	NB
PS	NB	NS	PS	PB
PB	NB	NS	PS	PB

The rules have the following format-

IF error is NB AND change of error is NB THEN output is NB

IF error is NS AND change of error is PS THEN output is NS

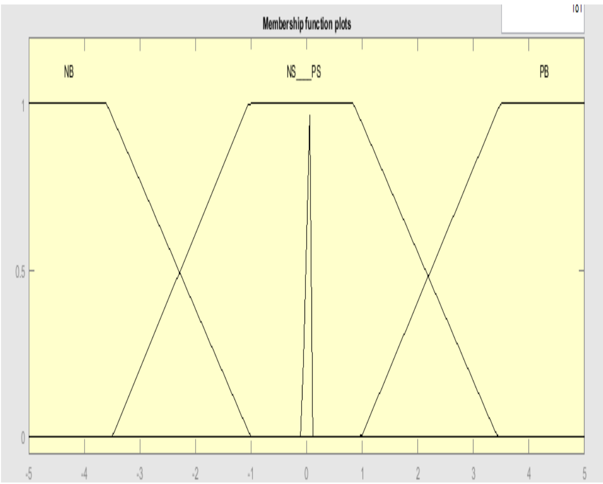

Figure 8. Membership function plots for input signal speed error

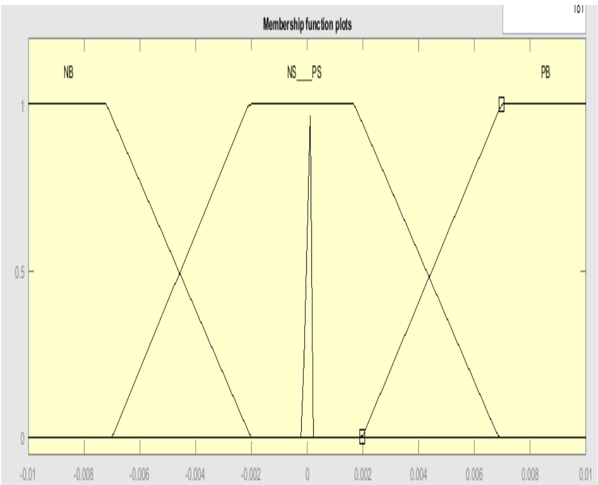

Figure 9. Membership function plots for input signal-change in speed error

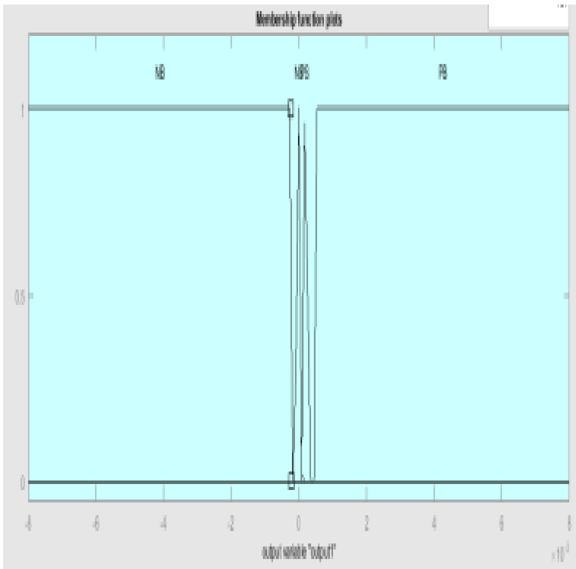

Figure 10. Membership function plots for output signal

The MF used for the input and output fuzzy sets show in Figure 10 The trapezoidal function are used as membership function for all fuzzy sets except the fuzzy set ZE (zero) of input vectors. The trapezoidal membership functions are used for all fuzzy set ZE of the input vectors and all the fuzzy sets of the output vector. The trapezoidal membership function is used to reduce the computation for online implementation. For this study, Mamdani-type fuzzy inference is used. The values of the constants, MF, input, output variables of linguistic variables, and the rules used in this study are selected by trial and error to obtain the optimum drive performances.

Results and Discussion

The implementation of the DTC technique of induction motor using fuzzy logic control is performed in MATLAB/ Simulink environment. Figure 12 shows the simulation diagram of Fuzzy logic controller based DTC technique of induction motor. The speed control performance of the fuzzy logic controller is tested with induction motor performance of the controller is observed under different reference speeds.

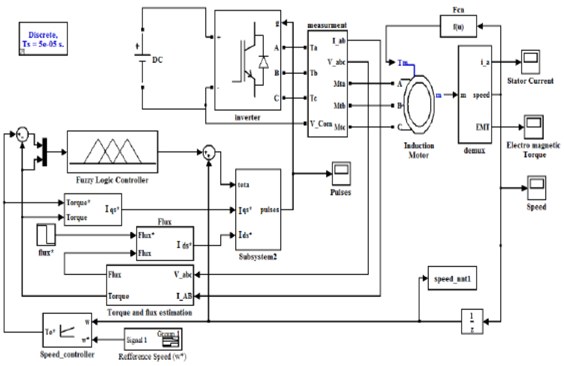

Figure 11. Simulink Model of Fuzzy Logic Speed control System.

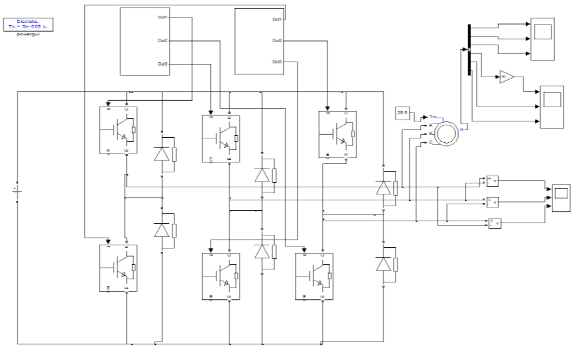

Figure 12. Simulation Circuit for VSI fed Induction Motor

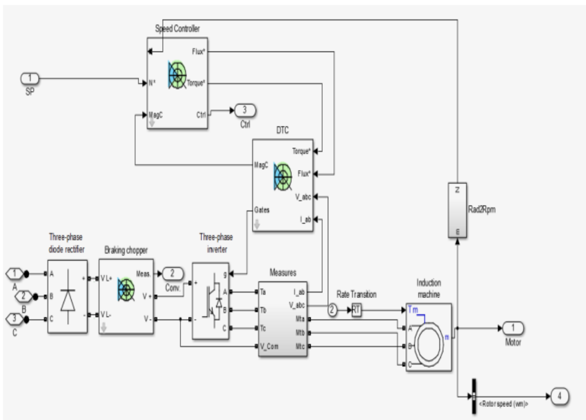

Figure 12. Simulink model of DTC based Induction motor drive

The simulation details of the three phase induction motor were explained. In this, the proposed method SVPWM speed control strategy for induction motor drives is explained. The simulation of speed control of induction motor was done using the software package MATLAB/SIMULINK. For this purpose, the motor's block diagram, space vector modulation blocks are constructed using closed loop models. After running the closed loop model motor speed was analyzed.

When the load is increasing motor speed will start to reduce. The reduction in the motor speed is plotted in Figure 13. Developed torque of the motor is plotted in the Figure 14. The stator current outputs are shown in Figure 15.

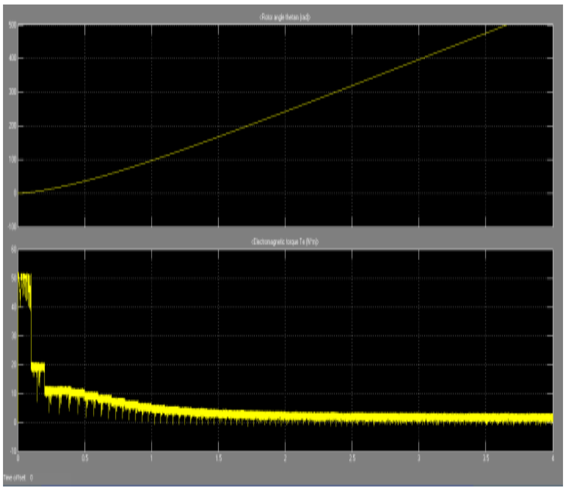

Figure 13. Output torque waveform

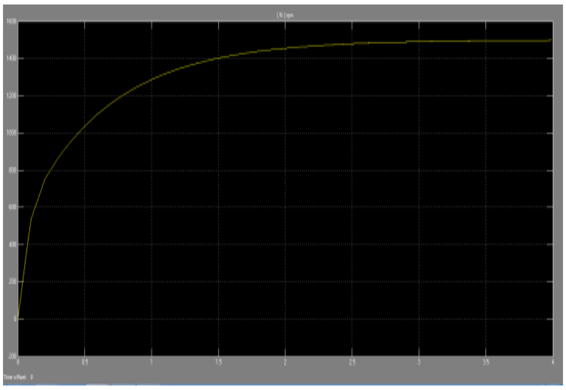

Figure 14. Rotor speed vs Time

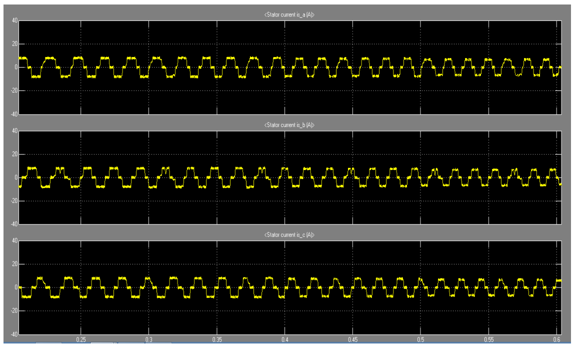

Figure 15. Stator current waveform

combination of the inverter switching which is the basic concept of SVPWM.

The three phase bridge inverter has eight possible switching states: six active and two zero states. The six switches have a well-defined state ON or OFF in each configuration. At a particular instant, only one switch in each of the three legs is ON. Corresponding to each state of the inverter, there is one voltage space vector. For example for state zero it is V0, for state 1 it is V1 and so on. These switching state vectors have equal magnitude but 60º apart from each other. These vectors can be written in generalized form as follows:

$$V_k = V_{dc} e^{j(\frac{k-1}{3})\pi}$$

k = 1, 2, ……., 6

= 0

k = 0, 7

Where k = inverter state number.

V_{dc} = dc link voltage of the inverter

The space bounded by two inverter space vectors is called a sector. So the plane is divided into six sectors each spanning 60º. In a balanced three phase system the voltage vectors are 120º apart in space and are represented by rotating vectors, whose projections on the fixed three phase axes are, sinusoidal waves. So they can be represented as three sinusoidal references by a voltage reference space vector V_{ref}^* or V_s^* .

$$V_s^* = V_k t_k + V_{k+1} t_{k+1} \quad k = 0, 1, 2……., 7$$

The reference space vector can be synthesized by a combination of eight state vectors and is constant in magnitude at switching instant t_s in case the switching frequency much higher than the output frequency. In a time average sense, the reference vector at that instant can be approximated by two active voltage states of the inverter. For the only certain amount of time, these states are valid.

IV. Speed Regulation Using a Fuzzy Logic Controller

When we need to regulate the speed of the induction motor drive a speed controller is needed. The speed controller takes the error signal between the reference and the actual speed and produces the appropriate reference torque value. That means the drive changes the mode from torque control to speed control. So, now the mechanical load on motor shaft defines the electromagnetic torque of the motor. In torque control mode the mechanical load on motor shaft defines the rotor speed. The speed controller can be a classic PI controller or a fuzzy PI controller. A detailed presentation and comparison of the two controllers is presented and operates with a classic DTC drive is covered in many research papers. In this work the fuzzy controller is used for DTC-SVM.

Fuzzy Logic Controller

One of the reasons for the popularity of Fuzzy Logic Controllers is its logical resemblance to a human operator. It operates on the foundations of a knowledge base which in turn rely upon the various if-then rules, similar to a human operator. Unlike other control strategies, this is simpler as there is no complex mathematical knowledge required. The FLC requires only a qualitative knowledge of the system thereby making the controller not only easy to use but also easy to design.

The fuzzy logic Controllers are basically put to use when:

1. The system is highly non-linear thereby making the mathematical

REFERENCES:

[1] Toliyat, H. A., Lipo, T. A., & White, J. C. (1991). Analysis of a concentrated winding induction machine for adjustable speed drive applications. II. Motor design and performance. *Energy Conversion, IEEE Transactions on*, *6*(4), 684-692.

[2] Takahashi, I., & Noguchi, T. (1986). A new quick-response and high-efficiency control strategy of an induction motor. *Industry Applications, IEEE Transactions on*, (5), 820-827.

[3] Bonnett, A. H., & Yung, C. (2008). Increased efficiency versus increased reliability. *Industry Applications Magazine, IEEE*, *14*(1), 29-36.

[4] Razali, R., Abdalla, A. N., Ghoni, R., & Venkataseshaiah, C. (2012). Improving squirrel cage induction motor efficiency: Technical review.*International Journal of Physical Sciences*, *7*(8), 1129-1140.

[5] Bazzi, A. M. (2010). *Designing better induction motor drive systems from efficiency, reliability, and power electronics perspectives* (Doctoral dissertation, University of Illinois at Urbana-Champaign).

[6] Bonnett, A. H. (1980). Understanding efficiency in squirrel-cage induction motors. *IEEE Transactions on Industry Applications*, *4*(IA-16), 476-483.

[7] Bortoni, E. C., Haddad, J., Santos, A. H. M., De Azevedo, E. M., & Yamachita, R. A. (2007). Analysis of repairs on three-phase squirrel-cage induction motors performance. *IEEE Transactions on Energy Conversion*, *2* (22), 383-388.

[8] Brethauer, D. M., Doughty, R. L., & Puckett, R. J. (1994). The impact of efficiency on the economics of new motor purchase, motor repair, and motor replacement. *IEEE transactions on industry applications*, *30*(6), 1525-1537.

[9] Calzada-Lara, G., Pazos-Flores, F., & Alvarez-Salas, R. (2010, August). A new Direct Torque Control for a better efficiency of the induction motor. In *Power Electronics Congress (CIEP), 2010 12th International* (pp. 78-83). IEEE.

[10] Cao, W., & Bradley, K. J. (2005, May). Assessing the impacts of rewind and repeated rewinds on induction motors: is an opportunity for re-designing the machine being wasted?. In *Electric Machines and Drives, 2005 IEEE International Conference on* (pp. 278-285). IEEE.

* * * * *