PERFORMANCE OF INDUCTION MOTOR USING HYSTERESIS BAND PWM CONTROLLER

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ABSTRACT

The aim of the Paper is to design a hysteresis band PWM (HBPWM) current controller for a three level voltage source inverter (VSI) through a fuzzy approach. The fuzzy approach has been selected for the Paper since it has the potential to provide an improved method of deriving non-linear models which is complementary to conventional techniques. A Sugeno type fuzzy inference system is used in the proposed fuzzy controller. To illustrate the validity of this approach, an indirect vector controlled induction motor (IVCIM) drive has been considered as its application. The vector control scheme essentially attempts to decouple the torque and flux controls of an induction motor. In order to carry out this decoupling of torque and flux, the space vector model is implemented and a HBPWM current controlled inverter is used in order to supply variable voltage, variable frequency to the motor. Fuzzy set theory has been applied to the HBPWM controller. The proposed fuzzy controller in which the change of current and rate of change of current have been used as inputs. A set of decision rules expressed in linguistic variables are established to relate input signals to the output (control) signal. A comparison between conventional controller and the proposed fuzzy controller reveals that the effectiveness of fuzzy controller.

KEYWORDS: *Induction Motor, PWM (HBPWM) operation and FHBPWM operation.*

I. INTRODUCTION

Many industrial applications using motors demand variable speed and high starting torque. The dc motors were a preferred choice in such applications for many years, because the dc motors offered an easy method of speed variation and torque control by adjusting the armature voltage and the field current [1]. While the same, is not possible with the ac motors. However, with the advent of thyristors and the continued development in semiconductor devices, induction motors are also now being used for such applications. The induction motor is preferable as they have such features, as being maintenance free in operation, are rugged and reliable machines over their counterparts. A typical present day electric variable speed drive system consists of three basic components: the electric motor, the power converter, and the control system. Electric motor drives can be briefly classified as follows:

- DC drives
- AC drives
- Special drives

This classification is done according to the type of electric motor used. The history [1] of electrical motors goes back as far as 1820, when Hans Christian Oersted discovered the magnetic effect of an electric current. One year later Michel Faraday discovered the electromagnetic rotation and build the first primitive D.C motor. Faraday discovered the electromagnetic induction in 1831, but it was Tesla that invented the AC Asynchronous motor in 1883.In a DC motor, the current through the field winding (stator) creates the magnetic field. This field is always at right angles to the field created by the armature winding. This condition, known as “Field orientation”, is needed to generate maximum torque. Once Field orientation is achieved, the DC motor's torque is easily controlled by varying the armature current by keeping the magnetizing current constant. The advantages of DC drive are that the speed and torque are controlled directly through armature current: i.e., the torque is the inner control loop and the speed is the outer control loop.

This Paper deals only with AC drives employing AC Asynchronous motor. Since its invention AC Asynchronous motor, also named Induction Motor, has become the most widespread electrical motor in use today. This is due to the fact that IMs are most advantageous over the rest of the motors. The main advantage is that IMs do not require any electrical connection between stationary and rotating parts of the motor. Therefore they do not need any mechanical commutator (brushes), leading to the fact that they are maintenance free motors. Further they can work in explosive environments because no sparks are produced. The only effective way of producing an infinitely variable IM speed drive is to supply the IM with three phase voltages of variable frequency and variable amplitude. A variable frequency is required because the rotor speed depends upon the speed of the rotating magnetic field provided by the stator. A variable voltage is required because the motor impedance reduces at low frequencies and constantly the current has to be limited by means of reducing the supply voltages.

Before the days of power electronics, a limited speed control of IM was achieved by switching the three stator windings from delta connection to star connection, allowing the voltage at the motor windings to be reduced. IMs are also available with more than three stator windings to allow a change of the number of pole pairs. However, a motor with several windings is more expensive because more than three connections to the motor are required and only certain discrete speeds are available. Another alternative method of speed control can be realized by means of a wound rotor IM, where the rotor winding ends are brought out to slip rings. However, this method obviously removes most of the advantages of IMs and also introduces additional losses. By connecting resistors or reactance's in series with stator windings of IMs poor performance is achieved.

II. MODELLING AND CONTROL OF 3-Φ IM

In this section we discuss the mathematical modeling of 3-phase IM and principle of vector control.

IMs have now replaced the dc motors not only since the speed control is possible with the help of the semiconductor devices, but also because of control schemes such as the field-oriented or the vector control schemes, which have made it possible to deliver a torque verses speed characteristics similar to that of a dc motor. In the mid-1980s, an advanced scalar control technique, known as direct torque and flux control (DTFC or DTC) was introduced for voltage-fed PWM inverter drives. The scheme, as the name indicates, is the direct control of the torque and stator flux of a drive by inverter voltage space vector selection through a look up table. This technique was claimed to have nearly comparable performance with vector controlled drives

2.1 Modelling of Induction motor.

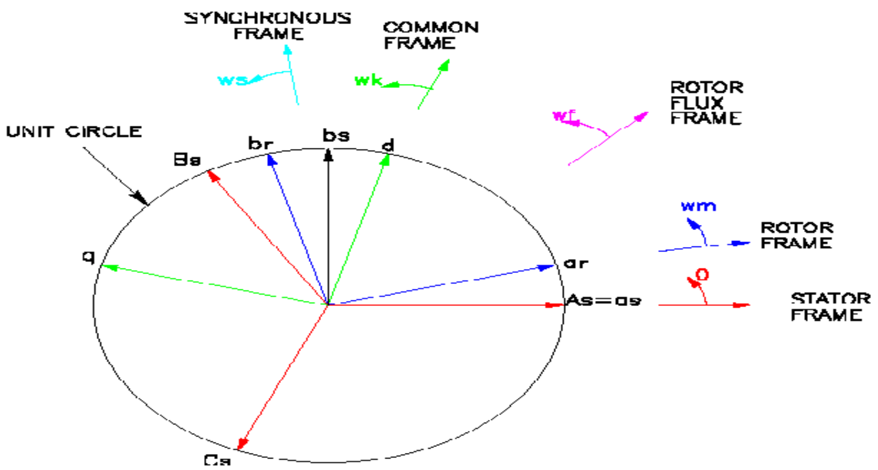

Fig 2.1 Stator and Rotor axes orientation of a 3-phase IM

Consider a symmetrical three-phase induction machine with stationary stator as-bs-cs axes and ar-br-cr axes at 2π/3 apart. With the help of the coupled circuit approach, the voltage equations of the magnetically coupled stator and rotor circuits can be written as

Stator Voltage Equations

$$v_{as} = i_{as} r_s + \frac{d\Psi_{as}}{dt} \quad \text{V} \tag{2.1}$$

$$v_{bs} = i_{bs} r_s + \frac{d\Psi_{bs}}{dt} \quad \text{V} \tag{2.2}$$

$$v_{cs} = i_{cs} r_s + \frac{d\Psi_{cs}}{dt} \quad \text{V} \tag{2.3}$$

Rotor Voltages Equations

$$v_{ar} = i_{ar} r_r + \frac{d\Psi_{ar}}{dt} \quad \text{V} \tag{2.4}$$

$$v_{br} = i_{br} r_r + \frac{d\Psi_{br}}{dt} \quad \text{V} \tag{2.5}$$

$$v_{cr} = i_{cr} r_r + \frac{d\Psi_{cr}}{dt} \quad \text{V} \tag{2.6}$$

Flux Linkage Equations

In matrix notation, the flux linkages of the stator and rotor windings, in terms of the winding inductances and currents, may be written as

$$\begin{bmatrix} \Psi_s^{abc} \\ \Psi_r^{abc} \end{bmatrix} = \begin{bmatrix} L_{ss}^{abc} & L_{sr}^{abc} \\ L_{rs}^{abc} & L_{rr}^{abc} \end{bmatrix} \begin{bmatrix} i_s^{abc} \\ i_r^{abc} \end{bmatrix} \tag{2.7}$$

where

$$\Psi_s^{abc} = \left(\Psi_{as} \quad \Psi_{bs} \quad \Psi_{cs}\right)^t \tag{2.8}$$

$$\Psi_r^{abc} = \left(\Psi_{ar} \quad \Psi_{br} \quad \Psi_{cr}\right)^t \tag{2.9}$$

$$i_s^{abc} = \left(i_{as} \quad i_{bs} \quad i_{cs}\right)^t \tag{2.10}$$

$$i_r^{abc} = \left(i_{ar} \quad i_{br} \quad i_{cr}\right)^t \tag{2.11}$$

And the superscript denotes the transpose of the array. The sub matrices of the stator-to-stator and rotor-to-rotor winding inductances are of the form

$$L_{ss}^{abc} = \begin{bmatrix} L_{ls}+L_{ss} & L_{sm} & L_{sm} \\ L_{sm} & L_{ls}+L_{ss} & L_{sm} \\ L_{sm} & L_{sm} & L_{ls}+L_{ss} \end{bmatrix} \quad \text{H} \tag{2.12}$$

$$L_{rr}^{abc} = \begin{bmatrix} L_{lr}+L_{rr} & L_{rm} & L_{rm} \\ L_{rm} & L_{lr}+L_{rr} & L_{rm} \\ L_{rm} & L_{rm} & L_{lr}+L_{rr} \end{bmatrix} \quad \text{H} \tag{2.13}$$

And those of the stator-to-rotor mutual inductances are dependent on the rotor angle, that is,

$$L_{sr}^{abc} = L_{rs}^{abc} = L_{sr}\begin{bmatrix} \cos\theta_r & \cos(\theta_r + \frac{2\pi}{3}) & \cos(\theta_r - \frac{2\pi}{3}) \\ \cos(\theta_r - \frac{2\pi}{3}) & \cos\theta_r & \cos(\theta_r + \frac{2\pi}{3}) \\ \cos(\theta_r + \frac{2\pi}{3}) & \cos(\theta_r - \frac{2\pi}{3}) & \cos\theta_r \end{bmatrix} \quad 2.14$$

where

L_{ls} = per phase stator winding leakage inductance
L_{lr} = per phase rotor winding leakage inductance
L_{ss} = self-inductance of the stator winding
L_{rr} = self-inductance of the rotor winding
L_{sm} = mutual inductance between stator windings
L_{rm} = mutual inductance between rotor windings
L_{sr} = peak value of the stator-to rotor mutual inductance

From equations (2.1) to (2.6), it can be observed that the idealized IM is described by six first order differential equations, one for each winding. These differential equations are coupled to one another through the mutual inductances between the windings. In particular, the stator-to-rotor coupling terms are functions of rotor position, and thus when the rotor rotates, these coupling terms vary with time.

2.2. HBPWM Current Control

The HBPWM is basically an instantaneous feedback current control method of PWM where the actual current continually tracks the command current within a specified hysteresis band.

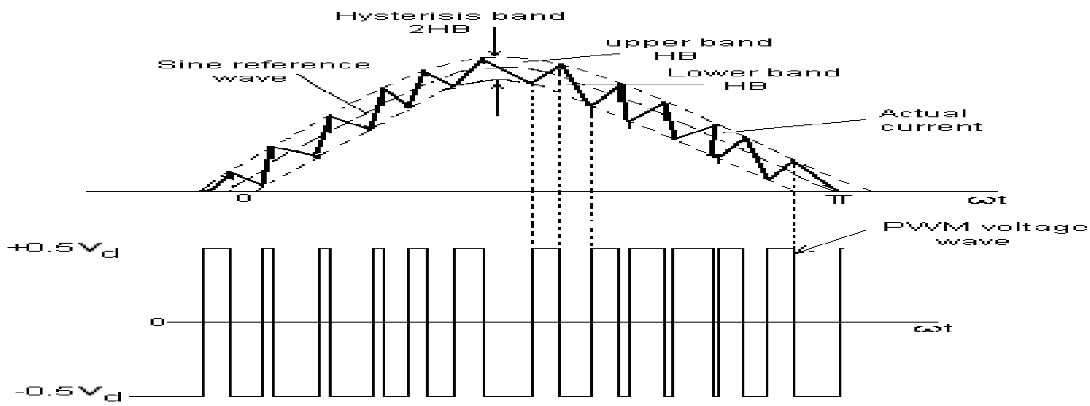

Fig 2.2 Principle of Hysteresis Band current control

The Fig 2.2 explains the operation principle of HBPWM for a half bridge inverter. The control circuit generates the sine reference current wave of desired magnitude and frequency, and it is compared with the actual phase current wave. As the current exceeds a prescribed hysteresis band, the upper switch in the half-bridge is turned off and the lower switch is turned on. As a result the output voltage transitions from $+0.5V_d$ to-$0.5V_d$, and the current starts to decay. As the current crosses the lower band limit, the lower switch is turned off and the upper switch is turned on. The actual current wave is thus forced to track the sine reference wave within the hysteresis band by back- and-forth (or bang-bang) switching of the upper and lower switches. The inverter then essentially becomes a current source with peak to peak current ripple, which is controlled within the hysteresis band irrespective of V_d fluctuation.

The HBPWM inverter control method is shown in the Fig 2.3. The inputs to the HBPWM controller are three phase current errors and the outputs are the switching patterns to the PWM inverter. k in the figure represents the normalization factor and is used for the purpose of scaling the current error input to the HBPWM controller. PS is the pulse separation circuit for the separation of pulses to the IGBTs in the upper and lower leg of the inverter.

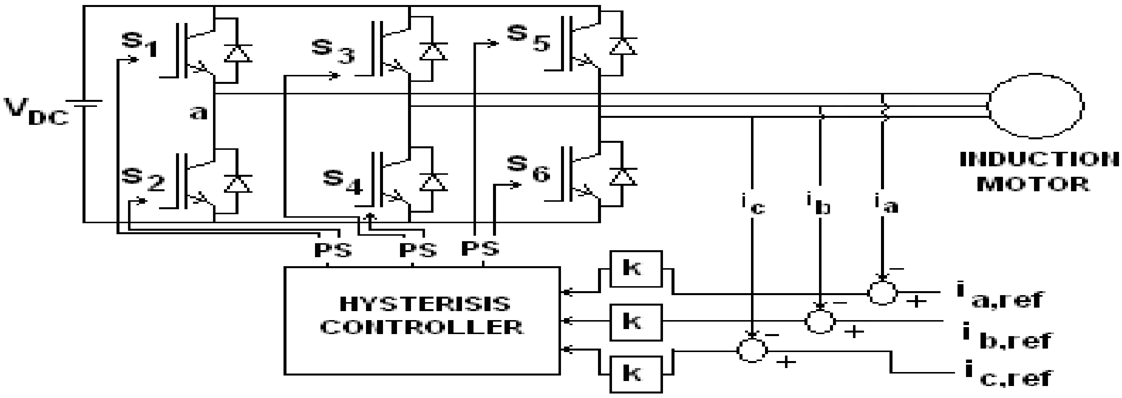

Fig 2.3 Conventional HBPWM Inverter Control method

The hysteresis current controller gives output pulses to the inverter according to this [7]

$|i_{m,ref} - i_m| < \varepsilon$ keeps the output pulse at the same state

$i_{m,ref} - i_m > \varepsilon$ let output pulse =1(high)

$i_{m,ref} - i_m < -\varepsilon$ let output pulse =0(low)

Where m=a, b, c phases and ε is the hysteresis band

The algorithm for this scheme is:

$$i_{m,ref}(t) = I_{m,ref} \sin(wt)$$

Upper band $i_u = i_{m,ref}(t) + \Delta i$

Lower band $i_l = i_{m,ref}(t) - \Delta i$

Where Δi =hysteresis band limit

If $i_m > i_u$, $V_{mo} = -V_{dc}/2$

If $i_m < i_l$, $V_{mo} = V_{dc}/2$

Else, maintain the same state.

Where m=a, b, c phases i is load current and V_{dc} is the dc link voltage of the inverter.

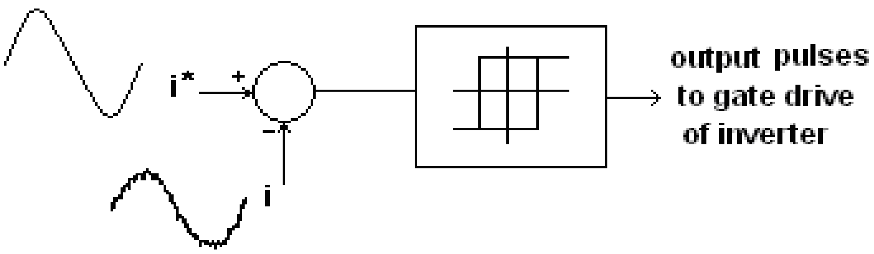

Fig2.4 Control block diagram for HBPWM

The main drawback of this method is that the PWM frequency is not constant (varies within a band) and, as a result non optimum harmonics will result. We have discussed at length in the preceding section the working of HBPWM current controller and the performance of an indirect vector controlled 3-phase IM drive employing HBPWM controller.

2.3 Simulink Model of HBPWM Current Controller

The HBPWM current controller block diagram using SIMULINK/MATLAB is shown below in Fig 2.5 Current errors for the three phases are determined and a hysteresis block is employed for each phase. The outputs of HBPWM controller, which are pulses, are given to inverter feeding the 3-ø IM. The hysteresis block is available in SIMULINK library in discontinuities and fixed point block set.

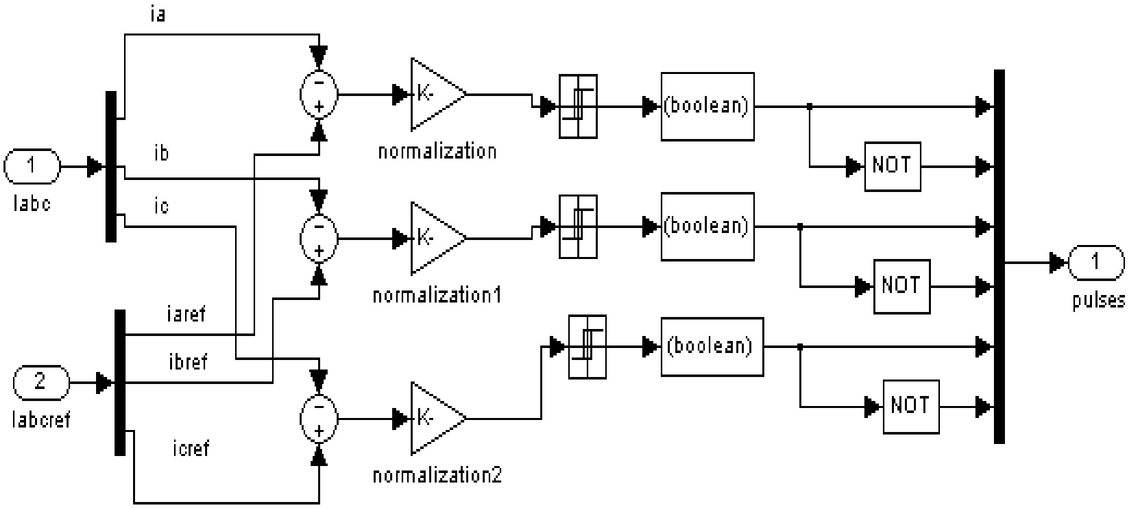

Fig 2.5 Block diagram of HBPWM current controller

III. FUZZY LOGIC CONTROLLERS

3.1Architecture of fuzzy logic controller

As can be seen from the introduction, the fuzzy logic approach is an artificial method in decision-making. This idea is used in developing the fuzzy controller, which is an artificial decision-maker that operates in a closed loop system in real time. From the block diagram (Fig 3.1), it can be seen that, the main components of FLC are:

1. Knowledge base
2. Fuzzification interface
3. Decision-making logic
4. Defuzzification interface

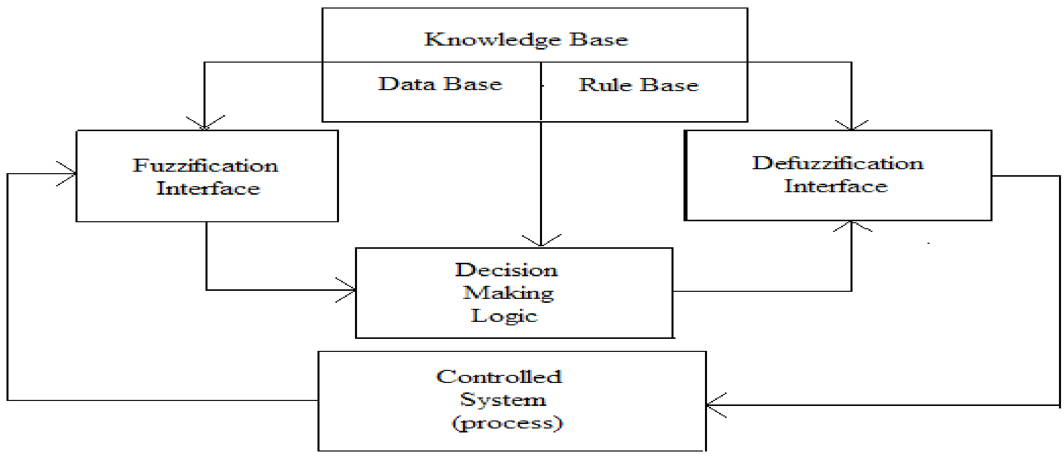

Fig 3.1 Block Diagram of Fuzzy Logic Controller

Knowledge Base

It comprises knowledge of the application domain and the attendant control goals. It consists of a “database” and “rule-base”. Fuzzification is related to the vagueness and imprecision in a natural language. It is a subjective valuation, which transforms a measurement into a valuation of a subjective value. Hence it could be defined as a mapping from an observed input space to fuzzy sets in certain input universes of discourse. Fuzzification plays an important role in dealing with uncertain information, which might be objective or subjective in nature.

Decision-Making logic

The decision-making logic is the kernel of an FLC. It has the capability of simulating human decision-making based on fuzzy concepts and of inferring fuzzy control actions employing fuzzy implication and the rules of inference in fuzzy logic. The concepts related to the decision-making logic of an FLC are:

1. Fuzzy implication functions
2. Interpretation of sentence connectives “and, also”
3. Compositional operators
4. Inference Mechanism

Defuzzification Interface

The defuzzification interface performs the following functions:

1. Scale mapping, which converts the range of values of output variables into corresponding universe of discourse
2. Defuzzification, which yields a non-fuzzy control action from an inferred control action. For this purpose, the some strategies of which three commonly used ones are
1. The Mean of Max. Method (MOM)
2. The Centroid or Center of Area Method (COA)

Table 3.1 Fuzzy decision table

	Change in current (Δi)					
		NB	**NS**	**Z**	**PS**	**PM**
Rate of Change in current	**NB**	Z	Z	Z	P	P
	NS	Z	Z	Z	P	P
	Z	Z	Z	Z	P	P
	PS	Z	Z	Z	P	P
	PM	Z	Z	Z	P	P

At the end of fuzzy inference, the result for the output is given as the value of a linguistic variable. As the control action must be a crisp value, the output of the FLU is converted by the center of gravity (COG) method. The FHBPWM inverter control method is shown in the Fig 3.2 the inputs to the FHBPWM controller are three phase current errors and the outputs are the switching patterns to the PWM inverter as in the case of conventional HBPWM controller. k in the figure represents the normalization factor and is used for the purpose of scaling the current error input to the FHBPWM controller.

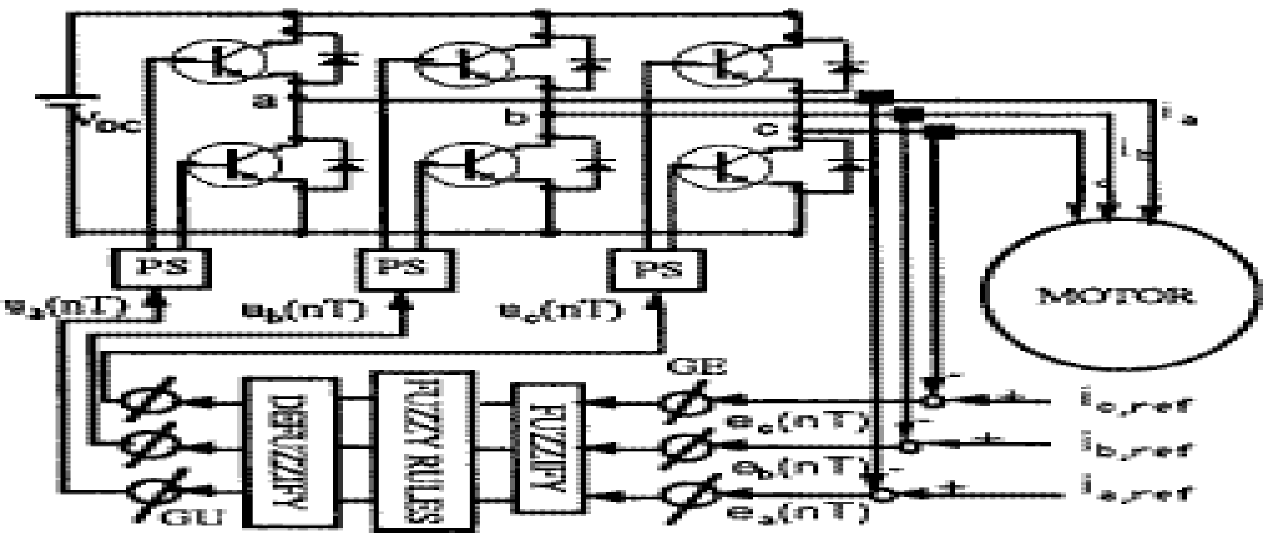

Fig3.2 FHBPWM Inverter Control method

The training is the same as the principle of operation of HBPWM current.

IV. SIMULATION RESULTS AND DISCUSSIONS

The simulation results of the IVCIM drive employing HBPWM controller shown in the Fig 3.2 are presented in this section. An inverter and an IM with the following specifications are considered.

Inverter: DC link voltage (V_{dc}) = 564.31961V

The dc link voltage V_{dc} should be around 1.2825V_L where V_L is R.M.S value of line voltage.

Therefore,

$V_{dc}/2 = 1.2825\times 220 = 282.1598$V

V_{dc} = 564.31961

Sampling time (T_s): 2µs

Hysteresis Band width of HBPWM current controller is 0.02

Induction motor: 3 phase, 60 hp, 220 V, 4-pole

Frequency:	50 Hz
Stator resistance (r_s):	0.087 ohm
Rotor resistance (r_r'):	0.228 ohm
Stator Leakage inductance (L_{ls}):	0.8 mH
Rotor Leakage inductance (L_{lr}'):	0.8 mH
Magnetizing inductance (L_m):	34.7 mH

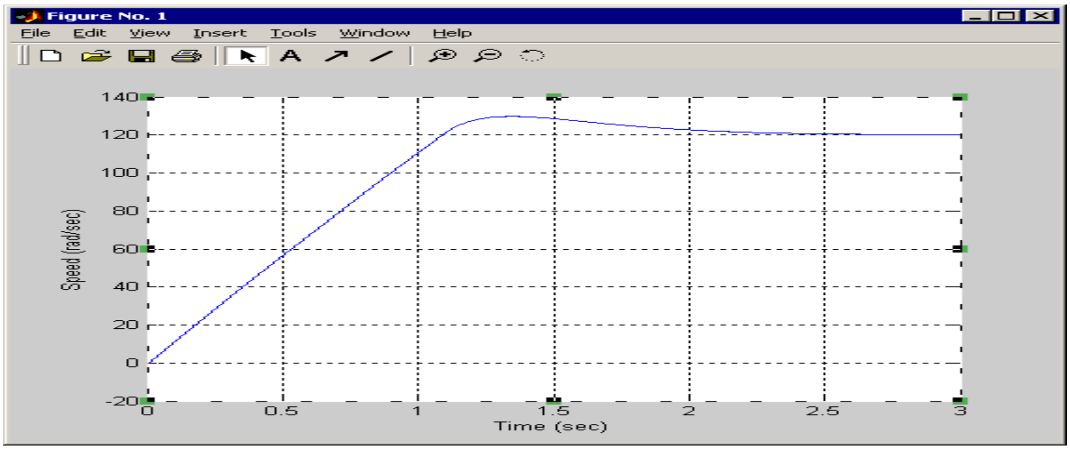

Fig 4.1 Speed response of IVCIM using FHBPWM controller without any disturbance

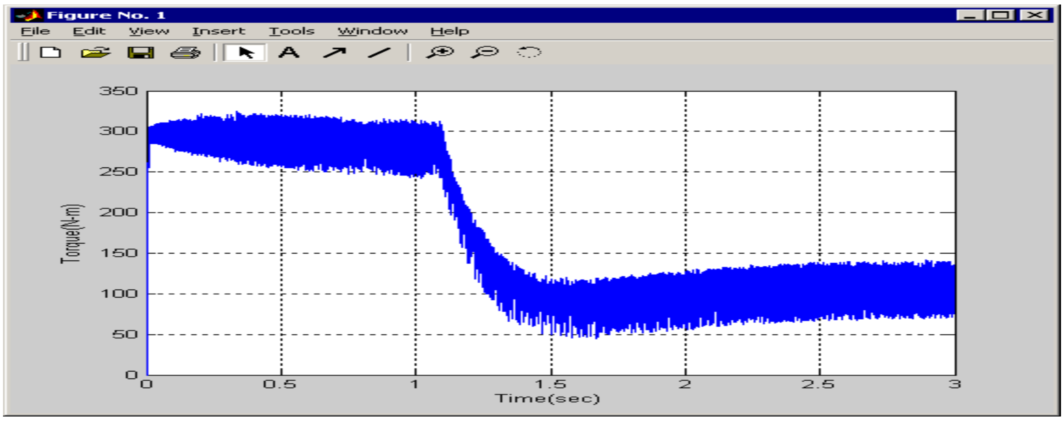

Fig 4.2 Torque response of IVCIM using FHBPWM controller without any disturbance

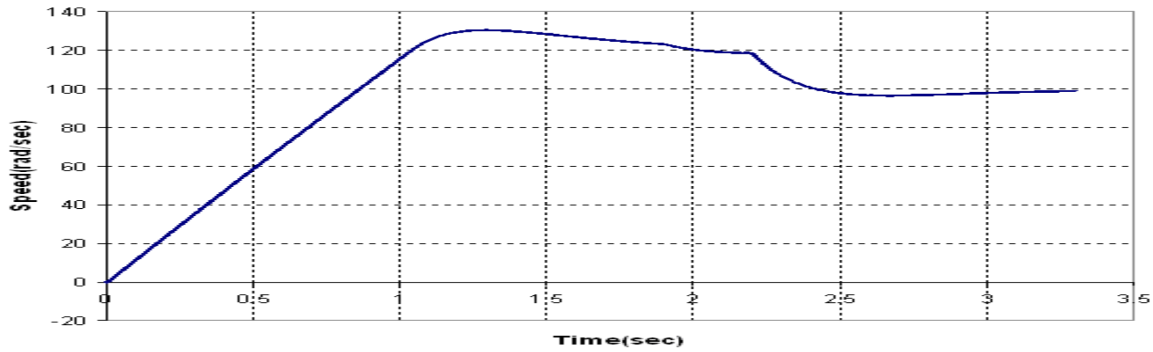

Fig 4.3 Speed response of IVCIM using FHBPWM controller with step disturbance

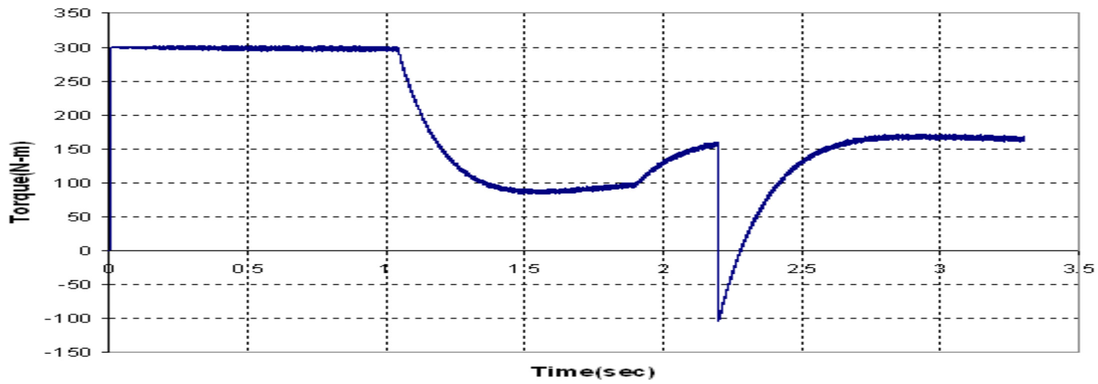

Fig 4.4 Torque response of IVCIM using FHBPWM controller with step disturbance

From the speed and torque responses of the IVCIM shown in Figs 4.1, 4.2, 4.3 and 4.4 it is concluded that the performance of both the HBPWM and FHBPWM controllers is the same.

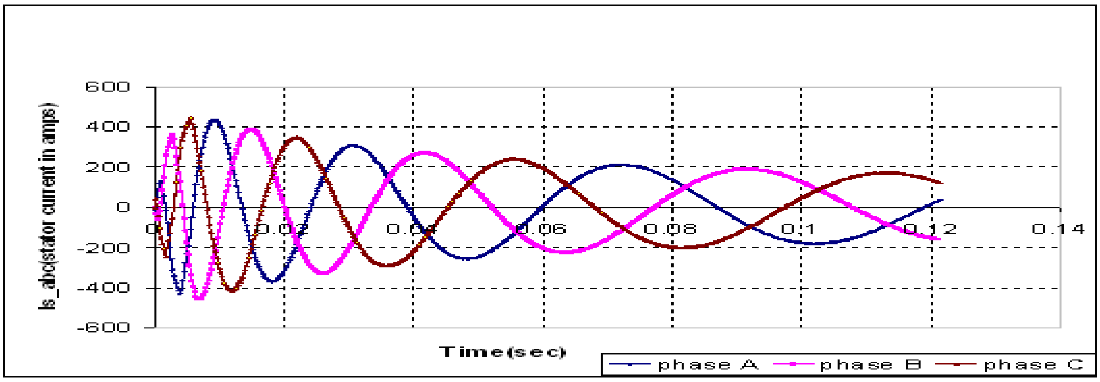

Fig 4.5(a) Stator current of IVCIM using FHBPWM controller with k=1

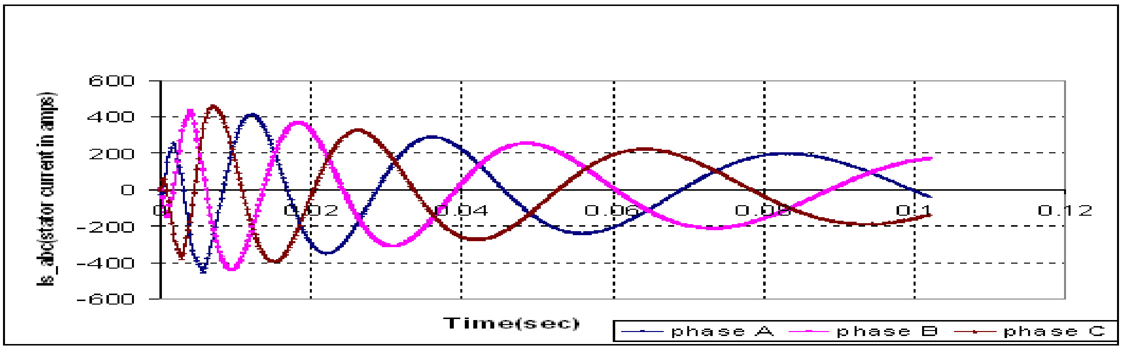

Fig 4.5(b) Stator current of IVCIM using HBPWM controller with k=1

From the Figs 4.5(a) and 4.5(b) it is observed that the stator currents of the motor using FHBPWM and HBPWM controllers respectively, with normalization factor k=1, are smooth and identical.

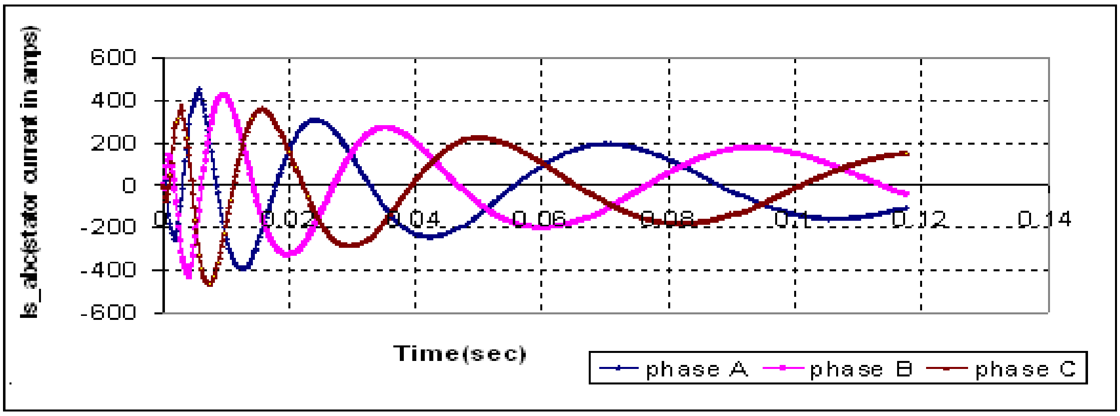

Fig 4.6(a) Stator current of IVCIM using FHBPWM controller with k=0.003

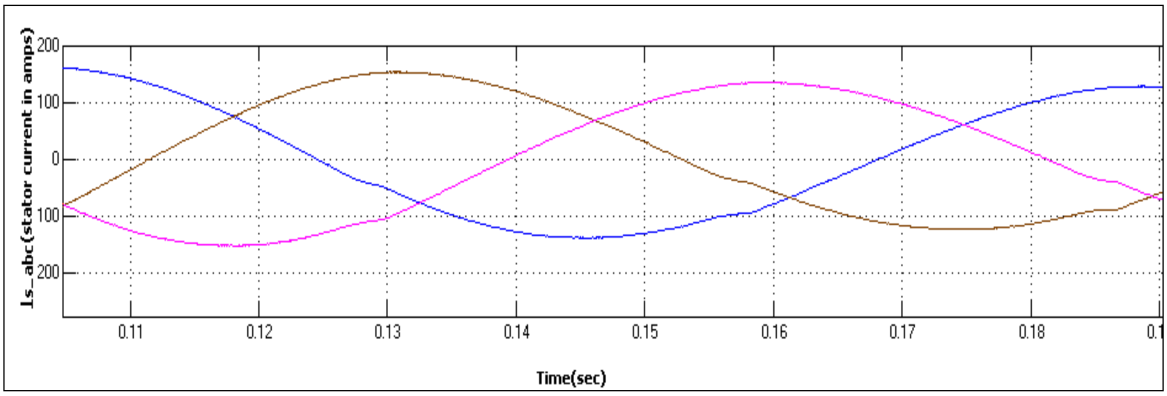

Fig 4.6(b) Zoomed portion of Stator current of IVCIM using FHBPWM controller with k=0.003

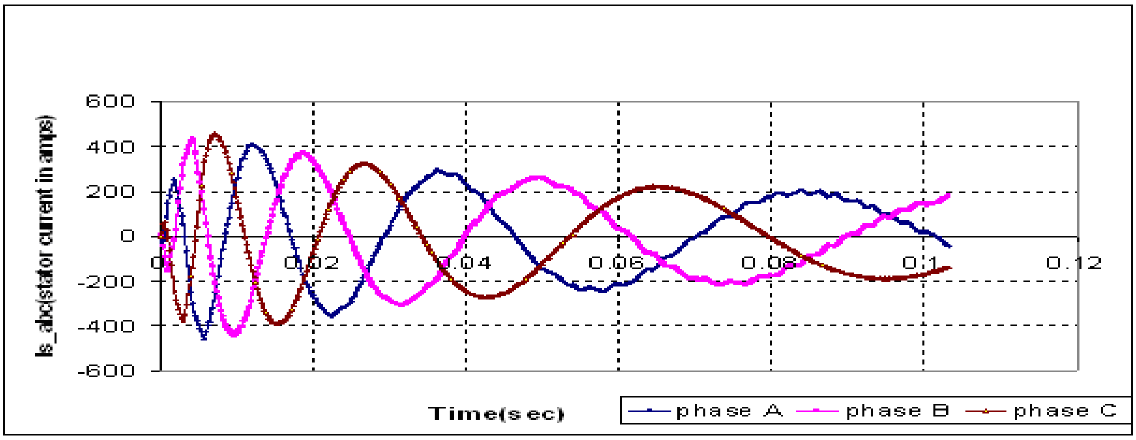

Fig 4.6(c) Stator current of IVCIM using HBPWM controller with k=0.003

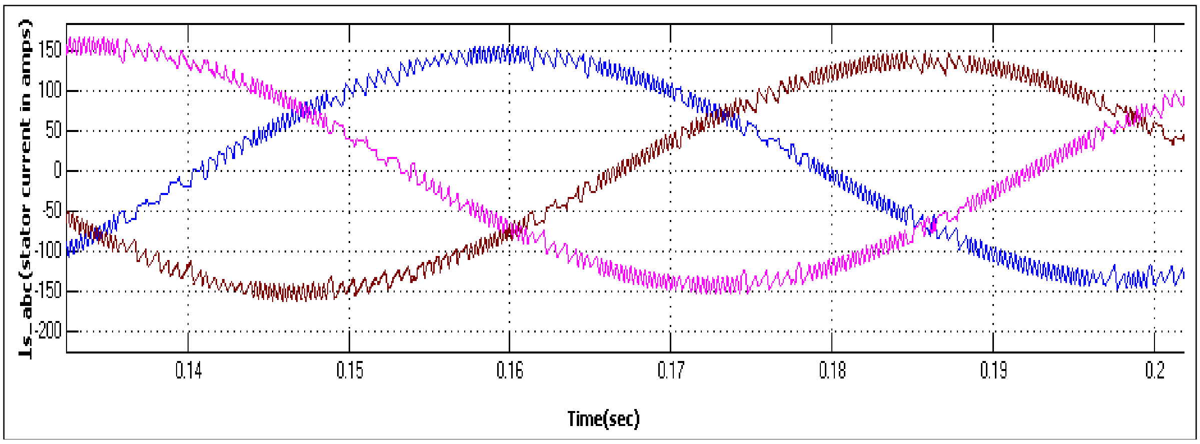

Fig 4.6(d) Zoomed portion of stator current of IVCIM using HBPWM controller with k=0.003

From the Figs 4.6(a) and 4.6(c) it is observed that if the input to the current controller is normalized by a normalization factor of 0.003, the input current to the motor using FHBPWM controller is smooth but the input current to the motor using HBPWM controller is distorted. The Figs 4.6(b) and 4.6(d) show the zoomed portions of the stator currents in the Figs 4.6(a) and 4.6(c) respectively. Also the torque pulsations for the motor developed torque are smaller for the drive employing FHBPWM controller.

4.1 Total Harmonic Distortion

The % total harmonic distortion (%THD) of the input current to the stator of the IVCIM using HBPWM controller and FHBPWM controller respectively for hysteresis band widths of 0.02 and 0.5 are shown in the Table 4.1

Table 4.1: Comparison of %THD

Hysteresis Band Width	%THD of stator current (phase-A) of IVCIM using	
	HBPWM controller	FHBPWM controller
0.02	3.679	3.648
0.5	4.210	3.0467

It can be inferred from the data given in the Table4.1 that the use of a FHBPWM controller reduces the THD of the stator current of the IVCIM. For a hysteresis band width of 0.02 there is no appreciable decrease in the THD but for a hysteresis band width of 0.5 the THD is decreased by 1.1725%.

V. Conclusions and Discussions

This paper consists of the development and implementation of fuzzy logic based HBPWM controller for the control of VSI. A sugeno type fuzzy inference system is taken. The validity of this approach is confirmed by simulation results. This approach is more effective because of the advantages offered. We briefly discussed the architecture of fuzzy logic controller, advantages and disadvantages of fuzzy logic system, algorithm for FHPWM current controller design. The basic idea behind this fuzzy approach is to incorporate the experience of an operator in the design of control strategy. From a set of linguistic rules, which describe the operator's control strategy a control algorithm is constructed where the words are defined as fuzzy sets. The control strategies employed by an operator are formulated as set of rules that are simple to carry out manually but difficult to implement by using conventional algorithms. This difficulty is because human beings use qualitative rather than quantitative terms when describing various decisions to be taken as a function of different states of the process. The proposed fuzzy controller in which two dominant factors of the system are used as inputs to the controller and generates a control signal.Simulation models of IVCIM drives using conventional HBPWM and, FHBPWM current controllers are developed and simulated using SIMULINK.

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