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FLC-Based DTC Scheme for a New Approach of Two-Leg VSI Fed Induction Motor

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ABSTRACT
A new Direct Torque Control (DTC) strategy for Induction Motor (IM) drive fed by a two leg three phase inverter (i.e., Four switches are used in VSI) was proposed in this paper. The proposed methodology is based on the emulation of operation of the conventional Six-switch three phase inverter. The combination of four unbalanced voltage vectors is generated by the two-leg three phase inverter, approaching to the synthesis of the six balanced voltage vectors of the conventional DTC. This approach has been implemented in the design of the vector selection table of the proposed DTC strategy. Further, Fuzzy Logic Controller (FLC) is proposed in the speed controller for the improvement of torque ripples. Convention DTC with Six Switch three phase VSI, two-leg three phase VSI with PI and Fuzzy Controller are implemented using MATLAB/SIMULINK. Simulation results have shown that the proposed DTC strategy, two-leg inverter fed IM drive revealed an improved performance.
***Index Terms*:** Direct torque control (DTC), Two-leg inverter and Six Switch based three phase Inverter, Vector selection, IM, Fuzzy logic Controller (FLC).

I. INTRODUCTION

IN Past decades, DC motors are majorly used for variable speed application due to its advantage like torque and flux could be independently controlled by the armature and field current. But, DC motors have more disadvantages such as high cost, commutator frequent maintenance problem and higher rotor inertia, cannot be operated in explosive environments. Whereas AC motors do not have the disadvantages of DC machines. Among AC drives Induction motors are widely used in industries because of its inherent properties. In normal reference frames, the torque and flux of an IM drive are coupled together and hence independent control becomes difficult. The IM control techniques are mainly classified into two types: Scalar Controls and Vector Controls. Both controls aims to achieve efficient motor torque and flux control regardless load parameter and motor variations. In scalar control, the frequency and magnitude of voltage is controlled, where as in vector control, the instantaneous position as well as the frequency and magnitude of voltage, current and flux linkage space vectors are controlled. For high performance AC Drives mainly have two popular controlling methods. They are (FOC) Field Oriented Control and (DTC) Direct Torque Control. Comparing with the FOC technique, DTC method is preferable because of its less complexity with extremely good dynamic response with simple structure.

The first DTC technique involves a simple control scheme which makes it possible rapid real-time implementation [1]. Later several researches carried out in order to improve the performance of DTC method. The main target focused towards uncontrolled switching frequency of the inverter and torque ripple resulting from the use of hysteresis controllers. At present and from past decades investigations of several DTC controlling strategies have been proposed [2]-[5]. These could be divided into four categories as 1) considering hysteresis band controllers, 2) with space vector modulation (SVM)-DTC,[6]-[7],3) using predictive control, 4) built around intelligent control schemes[8]. In conventional DTC voltage source inverter (VSI) feeding IM is the six-switch three-phase inverter (SSTPI). This said, some applications such as electric and hybrid propulsion systems should be as reliable as possible. In case of switch/leg failure the reconfiguration of the SSTPI into a four-switch three phase inverter (FSTPI), is currently given an increasing attention [9].

A DTC strategy conversion to FSTPI-fed IM drives has been proposed in [10]. Because of its simplicity, this strategy is penalized by the low dynamic and the high ripple of the torque. These drawbacks are mainly due to the application of unbalanced voltage vectors to control flux and torque with a subdivision of the *Clarke* plane limited to four sectors. New design was implemented to discard the previously described disadvantages has been proposed in [11] where a

DTC scheme using a 16-sector vector selection table has been implemented. The drive performance remains relatively low due to the complexity of the involved voltage vector selection table. Therefore, to achieve a constant switching frequency and to decrease the torque ripple, many DTC schemes based on SVM, using the FSTPI as a VSI, dedicated to control induction and permanent-magnet synchronous motors have been implemented. These techniques offer high performance in terms of torque ripple reduction allied to the control of the inverter switching losses. However, these performances are complexity in implementation schemes. This paper proposes a new DTC strategy dedicated to Two-leg fed IM drives. It is based on the reconfiguration of the SSTPI operation of an appropriate vector selection table, which is implemented by hysteresis controllers. Further, this paper proposes a new Fuzzy logic controller (FLC) into DTC strategy with a Four switch three phase inverter fed to an induction motor drive. Fuzzy logic improves the overall performance of DTC controlled system. Using an appropriate vector selection table and emulation of six switch inverter an efficient method is developed. With this approach, the paper proposes a new methodology DTC strategy which belongs to the uncontrolled switching frequency. Based on the two leg inverter topology, the proposed strategy is characterized by low inverter switching losses, leading to reduced torque ripples.

II. CONVENTIONAL DTC CONTROL

Direct Torque Control (DTC) is an efficient control technique used in Induction Motor drive systems to achieve high performance torque control and flux control. Selection of the appropriate switching state for the inverter makes an improved performance.

2.1 Direct Torque Control:

In 1986 Takahashi and Noguchi proposed the basic concept of the Direct Torque Control (DTC) method. This method is mostly used in controlling the induction motor because it is considered as a simple and robust method. Hysteresis controllers are used in traditional DTC method to control flux and torque directly by the selection of inverter switching vectors. Inverter switching vectors are selected from look up table from the torque and flux errors which are passed through by the hysteresis band limits. In Fig.1, conventional DTC control is shown. Modelling of all blocks is described below.

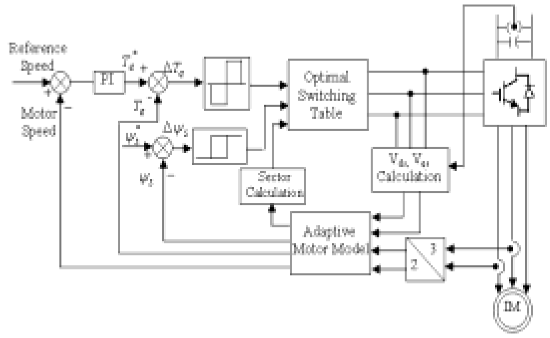


Fig 1: *Conventional DTC Control Scheme for IM*

(i) *Modelling of Induction Motor:*

Firstly three phase IM is converted into dynamic d-q Model to simplify the analysis this transformation is required. From simplified d-q model, currents and voltages are formulated and by using this measurements Stator, Rotor fluxes of IM drive can be calculated. This can be written as in equation (1) & (2)

$$\psi_s = L_s I_s + L_m I_r \quad (1)$$
$$\psi_r = L_r I_r + L_m I_s \quad (2)$$

Where ψ_s *and* ψ_r are stator and rotor flux. L_s, L_r are stator and rotor inductances. I_s *and* I_r are stator and rotor currents.

The Electromagnetic torque developed in IM can be written as

$$T_{em} = \frac{3PL_m}{4}\left(i_{dr}^{;s}\, i_{qs}^{s} - i_{qr}^{'s}\, i_{ds}^{s}\right) \quad (3)$$

(ii) *Modeling of VSI:*

Two level three phase inverter is used in this project. Input of VSI is V_{DC} and output of DTC stator voltage vector. Outputs are V_a, V_b, V_c can be written as

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \frac{V_{DC}}{3}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}\begin{bmatrix} S_A \\ S_B \\ S_C \end{bmatrix}$$

(iii) *Estimation of Torque, Flux and angle:*

From the measured Voltages and currents of Induction motor it is easy to estimate the torque, flux and angle.

$$T_{em} = \frac{3PL_m}{4}\left(\psi_{sq} I_{sq} - \psi_{sq} I_{sd}\right) \quad (4)$$
$$\psi_{sd} = \int (V_{sd} - R_s I_{sd})\, dt$$
$$\psi_{sq} = \int \left(V_{sq} - R_s I_{sq}\right) dt$$
$$\psi_s = \sqrt{\psi_{sd}^2 + \psi_{sq}^2} \quad (5)$$
$$\text{Angle} = \tan^{-1}\left(\frac{\psi_{sq}}{\psi_{sd}}\right) \quad (6)$$

For a 3-ph, two-level, six switch voltage source inverter (VSI), there are six non-zero active voltage space vectors and two zero voltage space vectors.

As shown in fig 2, the six active voltage space vectors can be represented as

$$\bar{V}_k = \frac{2}{3} V_{dc} \, exp\left[j(k-1)\frac{\pi}{3}\right] \qquad k=1,2\ldots6 \qquad (7)$$

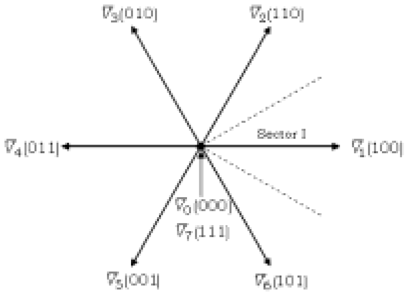


Fig2: *Representation of six active voltage vectors and zero vectors*

Depending on the position of stator flux linkage space vector, it is possible to switch the appropriate voltage vectors to control both stator flux and torque. Fig3 shows an example for sector1 and table 1 shows the switching states of all six sectors.

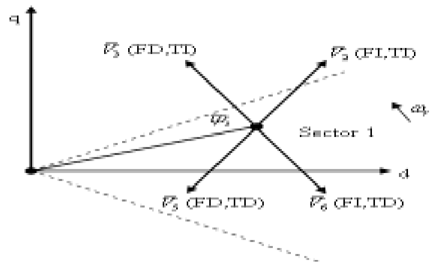


Fig3: *Reference Stator flux representation in sector-I*

		Sector					
Flux	$Torque$	1	2	3	4	5	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
-1	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_7
	-1	V_5	V_6	V_1	V_2	V_3	V_4

Table 1: *Optimal Vector Selection table for two level inverter.*

III. PROPOSED DTC CONTROL TECHNIQUE

Two-leg Inverter Fed IM:

The implementation of the Four switch inverter fed DTC strategy of an IM as shown in fig4, has the same layout as of the basic DTC strategy except that the Six switches in inverter is reconfigured to a four switch by replacing one leg of the 3 leg inverter with a dc voltage.

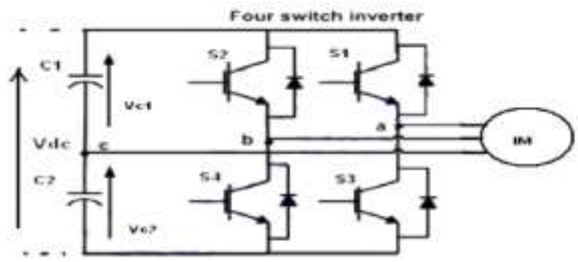


Fig 4: *Two-leg three phase inverter fed IM*

3.1 Voltage Vectors of Two-Leg inverter:

The three phase IM is connected as: two phases of the motor terminal is connected with the two leg of the inverter and the remaining phase is connected to the dc bus voltage midpoint. Compared to Six switch inverter the voltage vectors of the Four switch inverter has unbalanced amplitudes and phase shifted by an angle of $\frac{\pi}{2}$. But, voltage vectors V_1 and V_3 have the equal amplitude with magnitude of $\frac{V_{DC}}{\sqrt{6}}$.The vectors V_2 and V_4 have the amplitude with a magnitude of $\frac{V_{DC}}{\sqrt{2}}$. The voltage vectors and switching states accordingly are illustrated in Fig. 5

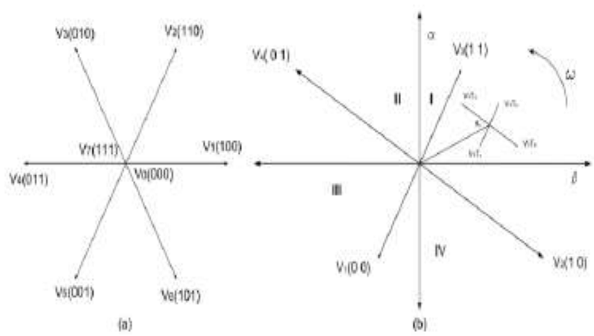


Fig 5: *Representation of voltage vectors for four switch inverter.*

***3.2 Generation of Balanced Voltage Vectors from two-leg inverter Voltage Vectors*:**

The four voltage vectors for FSTPI are generated from the Six switch inverter voltage vectors itself. The six balanced voltage vectors of the Six switch inverter are generated using four unbalanced voltage vectors of the Four switch inverter. This generated voltage vectors will have the equal amplitude and angular shift of Six switch inverter. The active voltage vectors $V_k = \sqrt{\frac{2}{3}} V_{dc}$. A dual application of the voltage vector V_1,V_3 of the two-leg, leads to generation of the voltage vector V_{11}(respectively, V_{33}) as shown in fig5. V_{11} and V_{33} are same as two vectors among the six generated voltage vectors. Consider V_{xy} is the resulting voltage vector from the sums of successive voltage vectors V_x and V_y with $1 \leq x \leq 4$ and $1 \leq y \leq 4$. The angular shift between two successive voltage vectors is equal to $\frac{\pi}{2}$, amplitude of vectors can be written as

$$V_{xy} = \sqrt{V_x^2 + V_y^2} = \sqrt{\left(\frac{1}{6} + \frac{1}{2}\right)} V_{dc} = \sqrt{\frac{2}{3}} V_{dc} = V_k \qquad (8)$$

Therefore, V_{xy} have the same amplitude as the voltages generated by the six switch inverter. The fig5 illustrated that six symmetrical sectors subdivided same as previous method.

3.3 Vector Selection Table:

In order to reduce the torque ripple content in the DTC a proposed vector selection table is implemented. In the conventional system has a three level torque controller, it is replaced by a two level torque controller. To obtain each voltage vector of the six switch inverter appropriate combination of the unbalanced voltage vectors of the four switch inverter is applied. Each control combination (error flux and error torque) should be maintained during two sampling periods (2Ts). Both the compounded and intrinsic voltage vectors are involved in sectors I, III, IV, and VI, while the sectors II and V, only the compounded voltage vectors are applied.). Implemented voltage vector selection table is shown in Table III. The application of V_1 (followed, V3) during two successive sampling periods $2Ts$ allows the generation of V_{11} (followed, V_{33}), The equivalent voltage vector per sampling period T_s can be written as

$$V_{11H} = \frac{1}{2} V_{11} = V_1 \qquad (9)$$

$$V_{33H} = \frac{1}{2} V_{33} = V_3$$

Where H represents the half of the corresponding voltage vector

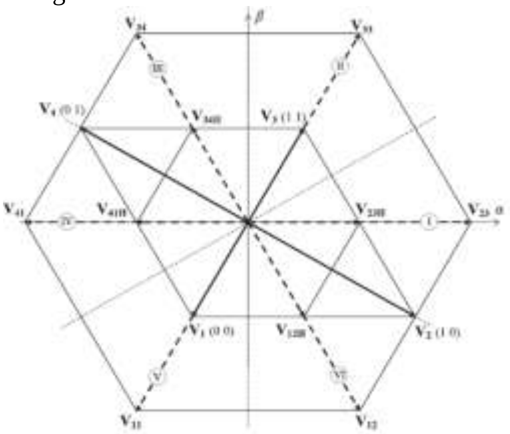


Fig6: *Generation of six active voltage vectors using four unbalanced voltage of Two-leg inverter*

Table II: Desired Vector Selection

		SECTOR					
Flux error	Torque error	1	2	3	4	5	6
1	+1	V_3	V_{34H}	V_{41H}	V_1	V_{12H}	V_{23H}
1	-1	V_{12H}	V_{23H}	V_3	V_{34H}	V_{41H}	V_1
-1	+1	V_{34H}	V_{41H}	V_1	V_{12H}	V_{23H}	V_3
-1	-1	V_1	V_{12H}	V_{23H}	V_3	V_{34H}	V_{41H}

Table III: Implemented Voltage Vector Selection

			SECTOR					
Flux	Torque	Period T_s	1	2	3	4	5	6
+1	+1	I^{st}	V_3	V_3	V_4	V_1	V_1	V_2
		II^{nd}		V_4	V_1		V_2	V_3
+1	-1	I^{st}	V_1	V_2	V_3	V_3	V_4	V_1
		II^{nd}	V_2	V_3		V_4	V_1	
-1	+1	I^{st}	V_3	V_4	V_1	V_1	V_2	V_3
		II^{nd}	V_4	V_1		V_2	V_3	V_4
-1	-1	I^{st}	V_1	V_1	V_2	V_3	V_3	V_1
		II^{nd}		V_2	V_3		V_4	

IV. FUZZY LOGIC CONTROLLER:

Fuzzy logic controller is majorly used in nonlinear systems for control applications. Fuzzy logic controller has adaptive characteristics. The adaptive characteristics can achieve robust performance to system with uncertainty parameters variation and load disturbances. In 1960's Lotfi A Zadeh introduced the fuzzy controllers. In this project the fuzzy logic controller inputs are torque error and change in error are taken and Mamdani type is consider 'min' type fuzzy is used for implication and for defuzzification centroid method is used.

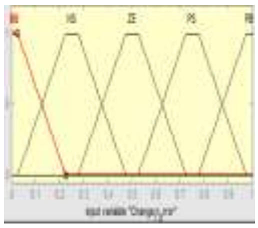
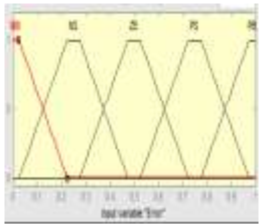
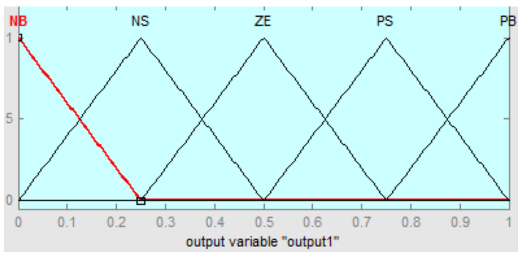


Fig (a)



Fig(b)



(c)

Fig7: *a)& b) Trapezoidal membership of torque error and change in error of input respectively and (c) triangle membership for output*

For the fuzzy logic speed control system, where the input signals are consider as speed error (E) and change in speed error (ΔE) and the output is torque reference .They are fuzzified by assigning corresponding membership functions to each signal. The universe of discourse of all the variables expressed in per unit values of between 0 and 1. Rule base consist of "If Then fuzzy rule" .It stores the data which defines the input and the output fuzzy sets. There are three membership functions for E and ΔE whereas three membership functions for the output. Hence there may be 5*5=25 possible rules in the matrix. Table IV shows the rule table for the speed controlled. Defuzzification does the transformation of fuzzy sets to crisp values to continue the system process.

TABLE IV: *FUZZY RULE BASE*

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

V. SIMULATION MODELS & RESULTS:

5.1 Simulation Models:

***a) Induction Motor Model**:*

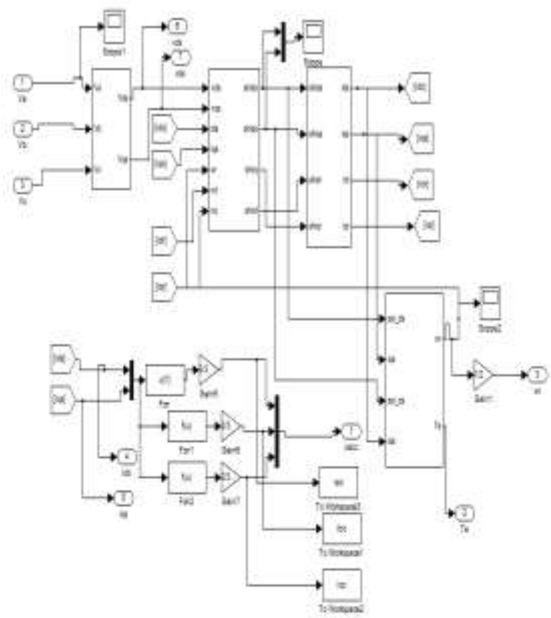
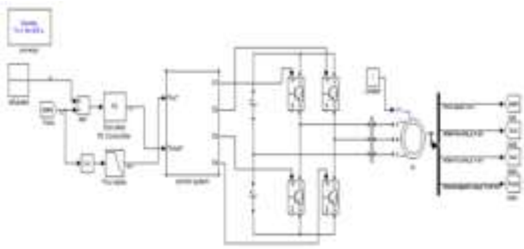
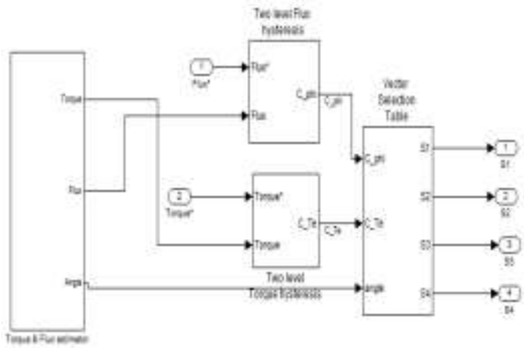


Fig 8: *Induction Motor Simulation Model*

b) Simulation Model for Proposed Two-leg Inverter fed IM drive with PI controller:



The subsystem of control block is designed as follows which involues torque and flux estimator, Hysteresis controller and voltage vector selection procedure.



c) Proposed Two-leg Inverter Fed IM Drive with FLC:

The below Fig9 shows the schematic diagram of Four switch inverter fed to an induction motor using a fuzzy logic controller system. In the conventional DTC PI controllers are used for speed control. Here, it is replaced by a fuzzy logic controller as shown in Fig10 whose output is torque reference from the speed error values to maintain speed of the motor to be constant whenever the load varies.

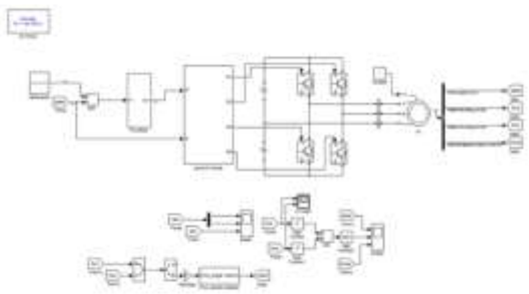


Fig 9: *Proposed DTC method Two-leg three phase inverter fed IM*

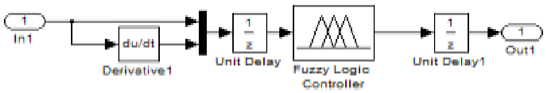


Fig10: *fuzzy logic controller block*

RESULTS:

(I)DTC of Two-leg VSI fed IM using PI Controller:

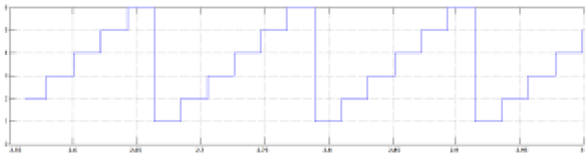
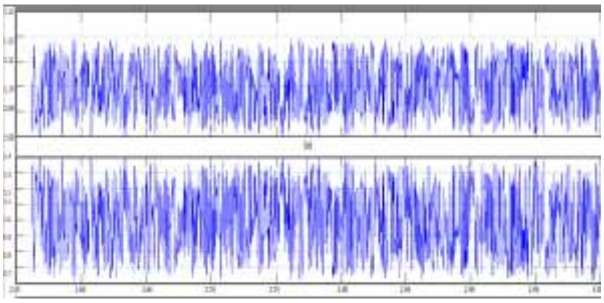
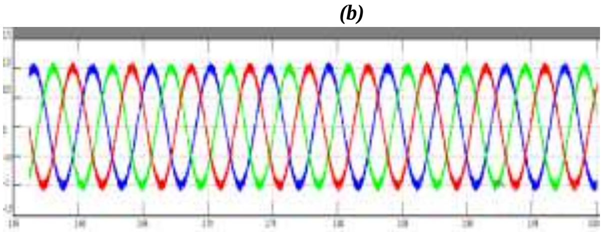


Fig11: Sector succession with PI



(b)



(c)

Fig12: At steady-state condition with PI Controller (a)Stator Flux and (b)Torque wavefrom (c) Stator current waveform

(II)DTC of Two-leg VSI fed IM using Fuzzy Logic Controller:

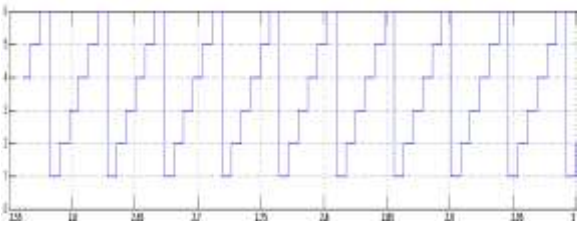
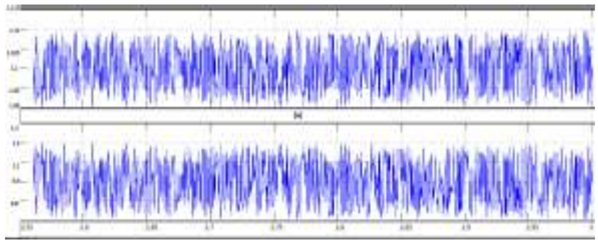
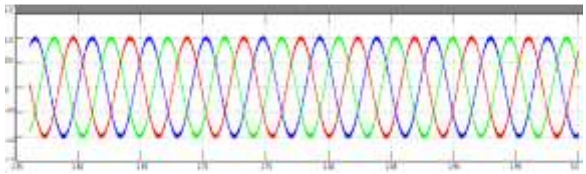


Fig13: Sector succession with FLC



(b)



(c)

Fig14: At steady-state condition with FLC(a)Stator Flux and (b)Torque wavefrom c) Stator current waveform

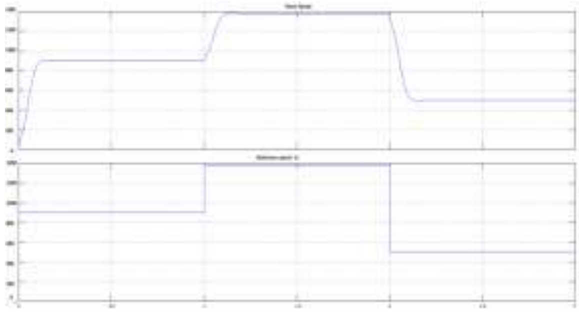


Fig15: Upper fig: Actual Rotor Speed & Lower fig: Reference Speed Using PI Controller

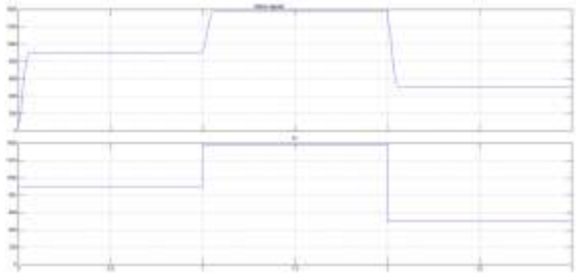


Fig16: Upper fig: Actual Rotor Speed & Lower fig: Reference Speed Using FLC

TABLE V

Induction Machine Parameters & Ratings

Power	0.37kW
Frequency	50Hz
Speed	1380rpm
Rs	24.6Ω
Rr	17.9 Ω
Ls	984mH
Lr	984mH
Lm	914mH

It can be noticed that the stator phase currents are almost balanced. The analysis of fig14(a)&12(a) w.r.t fig11&13 clearly reveals that a demagnetization appears at the beginning of each sector. From the vector selection table it is found that It is noted that both intrinsic and compounded voltage vectors are involved in sectors I,III,IV and VI while in sectors II & V only compounded voltage vectors are applied. Thus an increase of the switching frequency in sectors II & V compared to remaining sectors. Simulation results Fig 12&Fig13 show an improvement in the flux and torque responses. The ripples are reduced with the use of FLC when compared to PI controller.

Comparison Table:

Controller	**Torque Ripple(Nm)**	**Flux Ripple(wb)**
PI	1.4	0.03
Fuzzy Logic	1.2	0.015

CONCLUSION

This paper mainly focused on a new DTC strategy of Two-Leg VSI fed IM drives. The proposed DTC method is based on the emulation of the operation of the conventional six-switch inverter. This has been achieved by suitable combinations of the four unbalanced voltage vectors generated by the two-leg inverter which is identical as six-switch VSI. This approach has been implemented in the design of the vector selection table which is processed by hysteresis controllers, considering a subdivision of the Clarke plane into six sectors. Simulation results of the proposed DTC method at steady state features have revealed that high performance of the introduced DTC method. Further torque and flux ripples are reduced and better improvement was achieved by using the proposed Two-leg inverter fed IM drive based DTC with Fuzzy Logic Controller.

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