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# A Multilevel Inverter Fed Electric Traction Drive With Modified Direct Torque Control

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***Abstract – A modified DTC technique with fuzzification using NPC three level inverter fed induction motor for electric traction is presented in this paper. Since railways are considered as the lifeline of Indian economy, this fuzzified DTC can be used to improve the quality of transportation, thus making its operation more smooth and efficient. Compared to the conventional DTC, this three level inverter DTC topology provides better dynamic performance with reduced torque ripple and better stator current. Results were obtained by using a SIMULINK / MATLAB, for demonstrating the effectiveness of the proposed NPC three level Inverter fed Induction motor with Fuzzified Direct Torque Control.***

## INTRODUCTION

Any transportation system needs a source of power to drive its vehicles carrying their passengers or goods from one place to another. From the early invention of steam engines to modern electric locomotives, railway transport systems have had a long history and huge developments to become one of the most popular modes of public transport over the last century.

The demand of railway transportation systems has considerably increased every year by passenger journey and goods delivery in both short and long distance services. To provide power propulsion and the need for higher speed, more luxurious and more reliable services, electrification has been the first choice and widely applied to modernize most of the railway transport systems across the world for several decades. However, not many decades after this modernization, the demand continually grows and nearly reaches the limit of traction power supplies that were previously designed. This significantly results in unstable, unreliable, inefficient, ineffective and uneconomical operations. Thus existing electric railway systems need to be upgraded.

AC drives using induction machines are now finding increasing acceptance in various industrial variable-speed applications because of the development of high-performance control strategies for ac drives. The AC motors serving Indian Railways are three phase induction motor drives. The squirrel cage rotors type of induction motor drive used for traction is controlled by various vector control techniques. One among the various techniques used for controlling the machine's torque and speed are direct torque control. This control strategy proposes to replace motor decoupling and linearization via coordinate transformation, by hysteresis controllers, which corresponds very well to on-off operation of the inverter semiconductor power devices. To increase the power handling capacity of the converter section, multilevel topologies are proposed. The diode clamped multilevel inverter uses clamping diodes and a group of cascaded dc capacitors to achieve multiple levels in the inverter output voltage for the reduction of dv/dt and THD. The diode clamped inverter also features high operating voltage without switching devices in series. The inverter can be configured as a three-, four- or five-level topology. The proposed control consists of an estimation of stator flux vector and electromagnetic torque, a fuzzy controller, and regulation based on the theory of direct torque control DTC. The objective of our work is to implement a switching table by using a fuzzy logic that describe the selection strategies of the inverter state exploiting the simplicity of implementation and robustness offered by artificial intelligent control.

## INDUCTION MOTOR EQUATIONS

A three phase symmetric induction motor is considered with sinusoidally distributed winding and short circuited rotor.

The stator voltage equations are:

$$V_{qs} = I_{qs}R_s + \frac{d}{dt}\psi_{qs} \qquad (2.1)$$

$$V_{ds} = I_{ds}R_s + \frac{d}{dt}\psi_{ds} \qquad (2.2)$$

The rotor voltage equations are:

$$0 = I_{qr}R_r + \frac{d}{dt}\psi_{qr} - \omega_r\psi_{dr} \qquad (2.3)$$

$$0 = I_{dr}R_r + \frac{d}{dt}\psi_{dr} - \omega_r\psi_{qr} \qquad (2.4)$$

where $V_{qs}$ and $V_{ds}$ and are q and d axis stator voltages and $I_{qs}$ and $I_{ds}$ are q and d axis stator currents, $I_{qr}$ and $I_{dr}$ are q and d axis rotor currents, $\psi_{qs}$ and $\psi_{ds}$ and are q and d axis stator flux linkages, $\psi_{qr}$ and $\psi_{dr}$ and are q and d axis rotor flux linkages, and $R_s$ and $R_r$ are stator and rotor resistances and $\omega_r$ is the rotor speed.

The stator flux linkages equations are:

$$\psi_{qs} = L_{ls}I_{qs} + L_m(I_{qs} + I_{qr}) \qquad (2.5)$$

$$\psi_{ds} = L_{ls}I_{ds} + L_m(I_{ds} + I_{dr}) \qquad (2.6)$$

The rotor flux linkages equations are:

$$\psi_{qr} = L_{lr}I_{qr} + L_m(I_{qs} + I_{qr}) \qquad (2.7)$$

$$\psi_{dr} = L_{lr}I_{dr} + L_m(I_{ds} + I_{dr}) \qquad (2.8)$$

where $L_{ls}$ and $L_{lr}$ are stator and rotor leakage inductance and $L_m$ is the magnetizing inductance.

The torque developed in vector form:

$$T_e = \frac{3}{2}\frac{P}{2}\psi_s \times I_s \qquad (2.9)$$

where P is the number of poles.

## MULTILEVEL INVERTER

In recent years the industrial demand increases to high power equipments up to mega watts level. But the power handling capacity of power semiconductor devices are less only up to kilovolts level. The controlled ac drives in that range are connected with medium voltage networks. To increase the power handling capacity, multilevel topologies are proposed. A 3-level inverter generates an output voltage of three values and so on. Increasing the number of levels increases the number of steps in the output. The advantages of multilevel topologies are the voltage across each power semiconductor devices are less, the output voltage harmonic distortion are reduced. However the drawbacks are, the required number of power semiconductor devices is increased and control becomes more complex. They can also used for medium or even low power application with better performance.

The main topologies of multilevel inverters are diode clamped or neutral point clamped multilevel inverter, capacitor clamped or flying capacitor multilevel inverter and cascaded H-bridge multilevel inverter. The three phase 3-level diode clamped multilevel inverter is the most commonly used multilevel inverter.

A three phase 3-level diode clamped multilevel inverter is adopted in this paper. It is obtained from a configuration of twelve switching devices and six clamping diodes as shown in Fig 1.

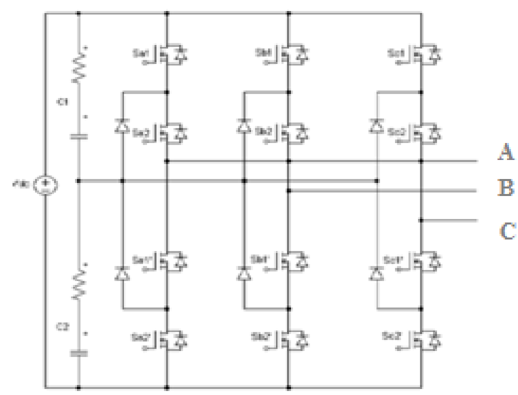


Fig 1: 3 level diode clamped multilevel inverter

Both capacitors are pre-charged to E/2 volts. The voltage of terminal "a" with respect to neutral point O is E/2 volts when the top switches are turned on. When both the bottom switches are turned on, the voltage of terminal "a" with respect to O is –E/2. When the middle two switches in a phase leg are turned on, the terminal "a" is connected to neutral point O through the clamping diodes.

The switch pairs $S_{a1}$, $S_{a1'}$, $S_{a2}$, $S_{a2'}$, $S_{b1}$, $S_{b1'}$, $S_{b2}$, $S_{b2'}$, $S_{c1}$, $S_{c1'}$ and $S_{c2}$, $S_{c2'}$ are complementary. Therefore, $S_{a1'}=1-S_{a1}$, $S_{a2'}=1-S_{a2}$, $S_{b1'}=1-S_{b1}$, $S_{b2'}=1-S_{b2}$, $S_{c1'}=1-S_{c1}$ and $S_{c2'}=1-S_{c2}$.

Using these switching states, 6 large vectors, 6 medium vectors, 12 small vectors and 3 zero vectors can be generated as shown in Fig 2.


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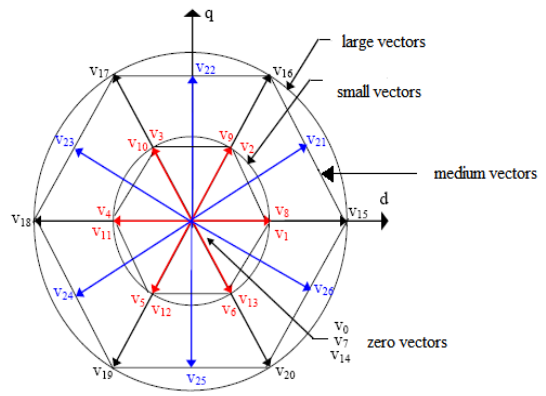


Fig 2: Space vector diagram of 3L inverter

Although in a three-level inverter there are 27 possible states, some of them apply the same voltage vector. There are two possible configurations for each small vector and three for the zero vectors. Therefore, 19 different vectors are available in a three-level inverter. Three-level inverter has more number of voltage vectors, thus different switching tables can be formed. A switching table without using small vectors is proposed in this paper.

## CONTROL STRATEGY

A. Direct Torque Control

The direct torque control method is based on control of torque and flux to desire magnitude by selection of the appropriate voltage vector according to the pre defined vector table.

The magnitude of torque developed torque is:

$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r L_s{}'}|\psi_r||\psi_s|\sin\gamma \qquad (4.1)$$

where $L_s' = L_s L_r - L_m^2$ and $\gamma$ is the angle between the two fluxes. The rotor flux changes very slowly compared with stator flux thus it can be assumed constant. The developed torque can be varied, by varying the stator flux and the angle.

The rate of change of flux is given by:

$$\frac{d}{dt}\overline{\psi_s} = \overline{V_s} - \overline{I_s}\,R_s \qquad (4.2)$$

If the ohmic drop is neglected

$$\frac{d}{dt}\overline{\psi_s} = \overline{V_s} \qquad (4.3)$$

$$\Delta\overline{\psi_s} = \overline{V_s}\Delta t \qquad (4.4)$$

Thus the stator flux can be varied by varying stator voltage vector for time increment as shown in Fig 3.

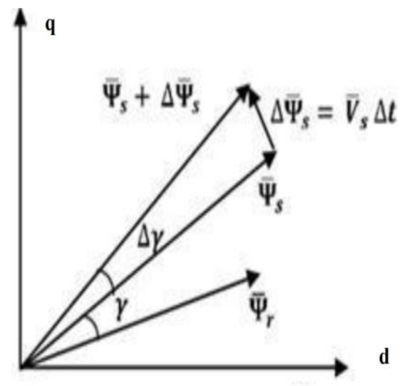


Fig 3: Stator and rotor flux vectors

A. Fuzzified DTC

The proposed fuzzy controller is Mamdani model, using triangular membership for inputs, and constant (*Vi*, *i*=0,..*12* ) for outputs. Using the conventional 6 sector frame complicates the determination of the vectors that need to be applied in a particular sector. But by dividing this sector frame into 12 sectors, each sector will have only 1 vector. Thus the complication of using the 6 sector frame is overcome. The twelve sectors are shown in Fig 4, taking the first sector as -15° to + 15° based on flux angle.

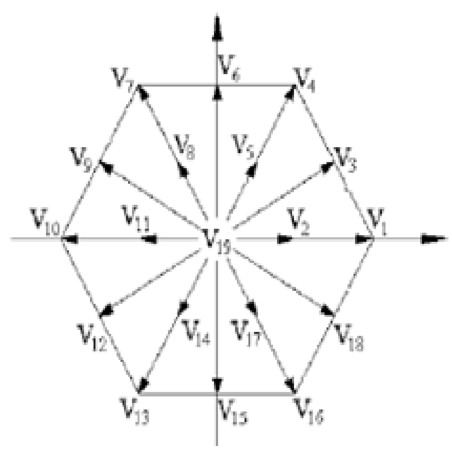


Fig 4: Proposed space vector diagram

The outputs of these controllers are *Si* (i= a, b, c) where their values (-1, 0 or 1) are used to determine the inverter output voltage vector as follows:

$$V_s = \frac{2}{3}V_{dc}\left(S_a + S_b e^{\frac{2\pi}{3}} + S_c e^{\frac{4\pi}{3}}\right) \qquad (4.5)$$


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In this approach, we replaced the two hysteresis controllers (basic DTC) and the switching table by a single fuzzy controller with torque error, flux error and flux sector as inputs as shown in Fig 5. The vector voltage of the inverter will be the control output.

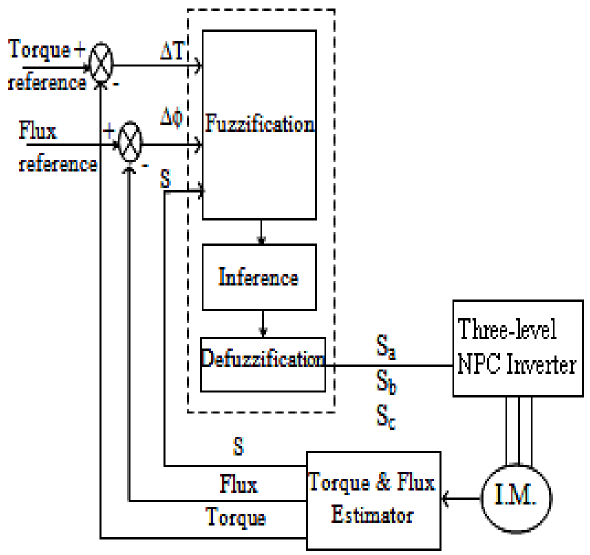


Fig 5: Block diagram of fuzzified DTC with 3 level inverter

The desired (reference) torque Te* and actual toque Te are compared to generate torque error. From the motor speed error the actual torque is estimated. The desired (reference) flux $\psi_s$* and actual flux $\psi_s$ are compared to generate flux error. From the stator voltage and current, the magnitude of actual flux is estimated. The sector in which the flux resides is also found out and all these three are fed as inputs to the fuzzy controller. On the basis of the fuzzy logic implemented, the controller decides which voltage vector should be applied for the desired operation of the motor. The control strategy behind the fuzzy logic is as shown in Table 1.

TABLE 1: CONTROL STRATEGY

| **Voltage Vector** | **Effect on flux** | **Effect on torque** |
|---|---|---|
| Active forward | Advance forward | Increase |
| Zero | Weakens | Decrease |
| Reverse active | Reverse rotates | Decrease rapidly |

## SIMULATION RESULTS

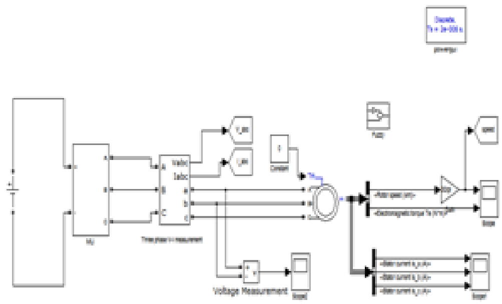

Fig 6: Simulation of Fuzzified DTC for 3 level inverter

Fuzzified Direct Torque Control Modeling of induction motor fed by 3 Level Inverter as shown in Fig 6 was performed in the environment of Matlab-Simulink simulation. Complementary to Matlab, Simulink allows the simulation of dynamic systems from functions for analysis and modeling. The Fuzzified DTC command structure is made in the form of various blocks.

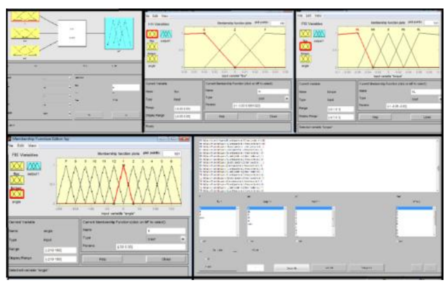

Fig 7: Fuzzy logic implementationFig 7 shows the amalgamation of the 5 toolboxes in which values were set for implementation of the fuzzy logic. The first box shows the first step in creating a fuzzy logic. Here we define the number of inputs for the controller as well as the type of fuzzy to be used. The next three boxes show how the tuning required for the membership function required by the three inputs namely torque error, flux error and sector is done. The last box shows how the various rules of the control strategy are given.

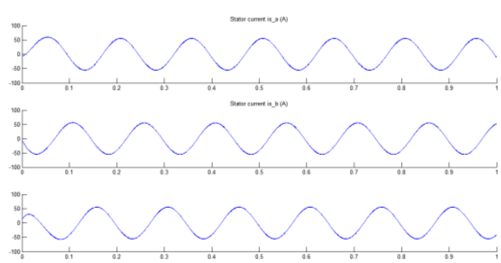

Fig 8: Stator current waveforms



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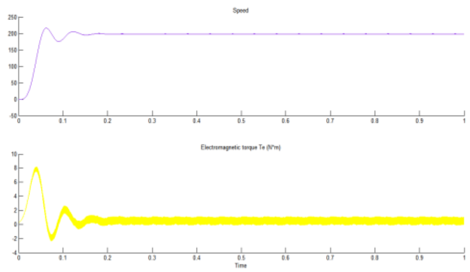


Fig 9: Speed and Torque waveforms

The induction motor used for simulation has a nameplate reading of three phase 2300 V ac, 0.25 HP. Fig.8 shows the stator current of the Fuzzified DTC driven induction motor with 3 level inverter. Fig. 9 shows the rotor speed and electromagnetic torque. The reference speed given was 250 rpm and the motor settles down to a speed of 200 rpm in less than 0.2 sec. Similarly the torque too can be seen to have settled in less than 0.2 sec. This reduction in settling time is the main advantage of using the fuzzy logic.

## CONCLUSION

This work presents a very simple implementation of a fuzzified direct torque control algorithm to be applied to 3-level diode clamped inverters. The proposed algorithm is a natural extension of the classical DTC with a 2 level inverter and does not require any predictive algorithms. Fuzzification of the DTC also helps in reducing the settling time of the torque.

The results of the simulation show that employment of 3 level inverter instead of 2 level one with such control algorithm permits to obtain the same dynamical performance of the drive with far lower torque ripple and flux ripple in the stator currents. These advantages counter balance the increased complexity of the circuitry 3 level converter. On the other hand the reduction of harmonic content permits corresponding cut back of the expenses on the filtering devices. Control algorithms computational burden is practically same as the one of the classical DTC without need of powerful processors when implemented in hardware.

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