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Simulation and Analysis of Fuzzy Logic Controlled Induction Motor Drive

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Abstract
This paper presents simulation work of fuzzy controller based Direct Torque Control (DTC) using Matlab / Simulink. The controller is designed to be applied with three-level voltage source inverter (VSI) fed induction motor. The inverter has several advantages over the classical VSI, such as a greater number of levels in the output voltage waveforms, lower dv/dt, less harmonic distortion in voltage and current waveforms and lower switching frequencies. In the new controller, torque and stator flux errors are used together with the stator flux angular frequency to generate a reference voltage vector. The new controller is found to reduce the torque ripple.

Keywords: Direct torque and flux control, induction motor, multilevel inverter, SVM, fuzzy logic controller.

1.INTRODUCTION

The development of high-performance control strategies for induction motor drives needed by industry has evolved rapidly during the last two decades. The two high-performance control strategies for induction motor drives are field-oriented control (FOC) and direct torque control. Both can achieve good transient torque performance, but have some essential disadvantages. In traditional DTC, torque and current ripples are caused by random switching times, and the performance at lower speeds is not satisfactory. However, the complexity of field oriented algorithms led to the development in recent years of many studies to find out different solutions for the induction motor control having the features of precise and quick torque response. The direct torque control technique proposed by I. Takahashi [1] and M. Depenbrock [2] in the mid eighties has been recognized to be a viable solution to achieve these requirements [l]-[3], [7]-[9], [11]-[17]. In the DTC scheme [1], the electromagnetic torque and flux signals are delivered to two hysteresis comparators. The corresponding output variables and the stator flux position sector are used to select the appropriate voltage vector from a switching table, which generates pulses to control the power switches in the inverter.

This scheme presents many disadvantages are variable switching frequency - violence of polarity consistency rules – current and torque distortion caused by sector changes - start and low-speed operation problems - high sampling frequency needed for digital implementation of hysteresis comparators [8], [11], [13-15], [17]. All the schemes cited above use a PI controller for speed control. The use of PI controllers to command a high performance direct torque

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controlled induction motor drive is often characterised by an overshoot during start up. This is mainly caused by the fact that the high value of the PI gains needed for rapid load disturbance rejection generates a positive high torque error. This will let the DTC scheme take control of the motor speed driving it to a value corresponding to the reference stator flux. At start up, the PI controller acts only on the error torque value by driving it to the zero border. When this border is crossed, the PI controller takes control of the motor speed and drives it to the reference value. To overcome this problem, fuzzy logic controller is proposed to replace the classical PI controller in the DTC scheme. This concept is not reported in the literature [1] – [20].

2.THREE LEVEL INVERTER

The standard voltage source inverter (VSI) traditionally used in electrical drive systems is the two-level VSI, which unfortunately has a number of inherent limitations. The maximum voltage that can be supported by the power electronics switching devices in the inverter limits the maximum value of DC bus voltage. Similarly the output voltages and currents from the inverter can contain high harmonic distortion. The output voltage waveforms can also contain large values of dv/dt, which contribute to the degradation of the machine windings insulation and also produce considerable electromagnetic interference during operation. New multilevel VSI topologies however can considerably reduce many of these limitations [16]. The three-level VSI presented in Fig.1, is one of the most commonly applied multilevel topologies [17]. This type of inverter has several advantages over the standard VSI, such as a greater number of levels in the output voltage waveforms, lower dv/dt, less harmonic distortion and lower switching frequencies. The space vector modulation (SVM) technique is used for the proposed fuzzy logic controller of induction motor drive system to control the switching of power devices.

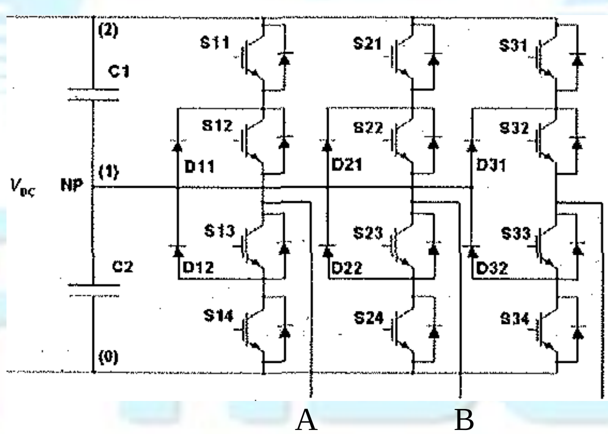

Fig. 1 Three-level Inverter

The VSI states available in a three-level VSI are presented as shown in fig. 2. As it can be seen, there are 4 different kinds of vectors depending on the module, Zero vectors (Vz), Large vectors (Vll, V21, V31, V41, V51, V61), Medium vectors (V1m, V2m, V3m, V4m, V5m, V6m) and Small vectors(V1s, V2s, V3s, V4s, V5s, V6s).

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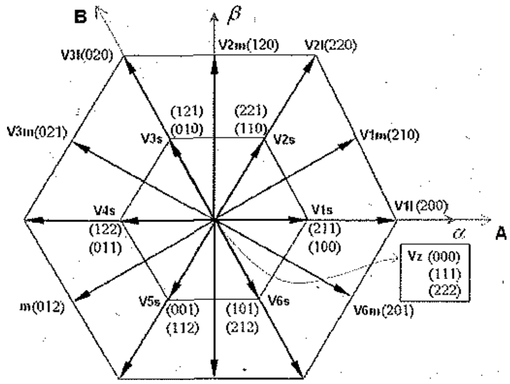

Fig. 2 Voltage vectors for three level inverter

The state of the switches for each leg *(C_A, C_B and C_c)* is shown in brackets (2: phase connected to the positive of the DC-link; 1: phase connected to the middle point of the DC-link (NP); 0: phase connected to the negative of the DC-link). The output voltage vector is defined by the following expression:

$$\vec{v} = \frac{V_{DC}}{9}(3C_A + bC_B + b^* C_c);\ C_A, C_B, C_c \in \{0, 1, 2\} \qquad (1)$$

where $a = e^{j\frac{2\pi}{3}}$ and $b = 2a - a^2 - 1$.

3. DTC PRINCIPLE

In order to understand DTC principle some of the equations of the Induction Motor need to be reviewed. The electromagnetic torque can be expressed as a function of the stator flux and the rotor flux space vectors as follows:

$$\Gamma_e = -\frac{3}{2} P \frac{L_m}{L_s L_r - L_m^2} \vec{\psi}_s \times \vec{\psi}_r \qquad (2)$$

If the modulus of the previous expression is evaluated it is obtained :

$$\Gamma_e = \frac{3}{2} P \frac{L_m}{L_s L_r - L_m^2} \left|\vec{\psi}_r\right| \left|\vec{\psi}_s\right| \sin(\gamma_s - \gamma_r). \qquad (3)$$

Considering the modulus of the rotor and stator fluxes constant, torque can be controlled by changing the relative angle between both flux vectors. Stator flux can be adjusted by the stator voltage according to the stator voltage equation in stator fixed coordinates:

$$\vec{u}_s = R_s \vec{i}_s + \frac{d\vec{\psi}_s}{dt} \quad (4)$$

If the voltage drop in the stator resistance is neglected the variation of the stator flux is directly proportional to the stator voltage applied:

$$\vec{u}_s = \frac{d\vec{\psi}_s}{dt} \qquad \vec{u}_s = \frac{\Delta\vec{\psi}_s}{\Delta t} \quad (5)$$

Because the rotor time constant is larger than the stator one, the rotor flux changes slowly compared to the stator flux. Thus torque can be controlled by quickly varying the stator flux position by means of the stator voltage applied to the motor. The desired decoupled control of the stator flux modulus and torque is achieved by acting on the radial *(x)* and tangential (y) components respectively of the stator flux vector. According to (5) these two components will depend on the components of the stator voltage vector applied in the same directions. The tangential component of the stator voltage will affect the relative angle between the rotor and the stator flux vectors and in turns will control the torque variation according to (3). The radial component will affect the amplitude of the stator flux vector. There are two different loops corresponding to the magnitudes of the stator flux modulus and torque. The reference values for the stator flux modulus and the torque are compared with the estimated values, the resulting error values are fed into a standard VSI and a three-level hysteresis block respectively. The outputs of the stator flux error and torque error hysteresis blocks, together with the position of the stator flux are used as inputs to the switching table (Table 1). The position of the stator flux is divided into six different sectors. The output of the look-up table is the VSI state that will be applied during a sampling period. The stator flux modulus and torque errors tend to be restricted within its respective hysteresis bands. The principle of DTC operation can also be explained by analyzing the Induction Motor stator voltage equation in the stator flux reference frame.

$$\vec{u}_s = R_s \vec{i}_s + \frac{d\vec{\psi}_s}{dt} + j\omega_s \vec{\psi}_s \quad (6)$$

If this expression is separated into de direct *(x)* and the quadrature component (y) of the stator voltage, the following expressions are can be obtained:

$$u_{sx} = R_s i_{sx} + \frac{d\psi_{sx}}{dt} \quad (7)$$

$$u_{sy} = R_s i_{sy} + \omega_s \psi_{sx} \quad (8)$$

In the same reference frame fixed to the stator flux vector the electromagnetic torque can be expressed as:

$$\Gamma_e = \frac{3}{2} P \, \vec{\psi}_s \times \vec{i}_s \qquad (9)$$

$$\Gamma_e = \frac{3}{2} P \, (\vec{\psi}_{sx} \, i_{sy} - \psi_{sy} i_{sx}) = \frac{3}{2} P \psi_{sx} \, i_{sy} \qquad (10)$$

Combining expression (8) with (10) the following torque expression is obtained:

$$\Gamma_e = \frac{3}{2} P \frac{\psi_{sx}(u_{sy} - \omega_s \, \psi_{sx})}{R_s} \qquad (11)$$

From expression (7) it can be concluded that stator flux amplitude can be controlled by means of the direct component of the stator voltage. It is also evident from equation (11) that the electromagnetic torque can be controlled by means of the quadrature component of the stator voltage, under adequate decoupling of the stator flux. From equation (11) some other considerations can be made as torque depends on the stator flux amplitude as well and it also depends on the stator flux angular speed, which depends on the operating point of the machine. DTC requires the estimation of stator flux and torque, which can be performed by means of two different phase currents, the state of the VSI and the voltage level in the DC-link. This estimation is based in the stator voltage equation [3].

$$\vec{\psi}_s = \int (\vec{u}_s - R_s \vec{i}_s) \, dt \qquad (12)$$

Table.1

K(γs)		**1**	**2**	**3**	**4**	**5**	**6**
$d_\psi = 1$	$d_\Gamma = 1$	V2	V3	V4	V5	V6	V1
	$d_\Gamma = Q$	V7	V0	V7	V0	V7	V0
	$d_\Gamma = -1$	V6	V1	V2	V3	V4	V5
$d_\psi = -1$	$d_\Gamma = 1$	V3	V4	V5	V6	V1	V2
	$d_\Gamma = 0$	V0	V7	V0	V7	V0	V7
	$d_\Gamma = -1$	V5	V6	V1	V2	V3	V4

In order to show the effect of fuzzy logic controller on DTC motor drive performances, simulation have been performed using the DTC induction motor drive structure illustrated by Fig.3, where the controller block is first replaced by a classical PI controller and then by a fuzzy logic controller. The parameters of the motor used in the simulation are given in Table 2. The reference speed used is Ω_{ref} = 1420 rpm

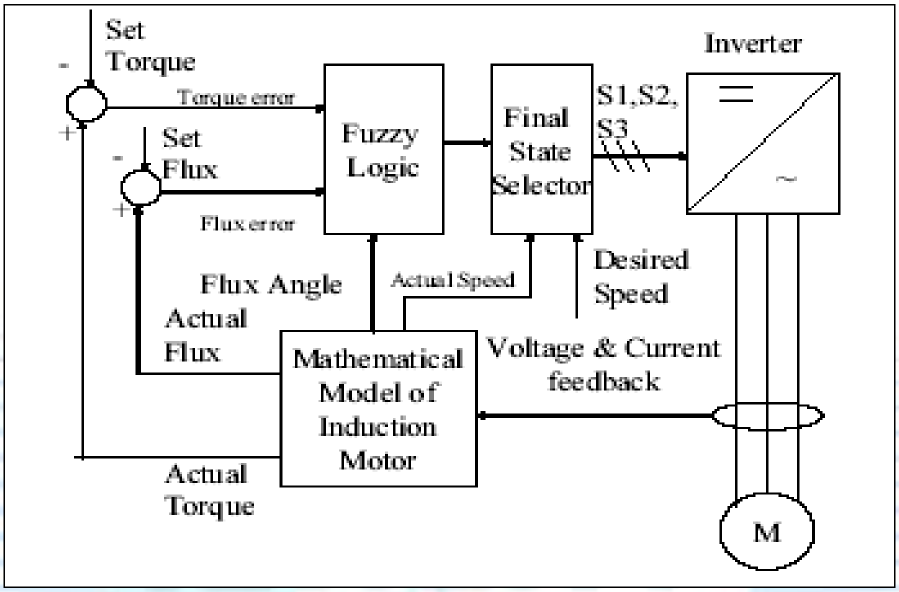

Fig. 3 Block diagram of fuzzy logic controlled drive

Table 2. Induction machine Parameters

No of poles .4, 50 HZ	2HP, 400V, 1420rpm
Rs = 4.85ohm, Ls=274 mH	Rr= 3.805ohm, Lr=274 mH
Lm=258 mH	J=0.031 kg sq.m

4. FUZZY LOGIC CONTROLLER

During the past several years, fuzzy logic control technology has been widely and successfully utilized in numerous industrial applications and consumer products. Since fuzzy logic with human like but systematic property can convert the linguistic control rules based on expert knowledge into automatic control strategy, it can be well applied to control the systems with un-modeled dynamics [7, 8]. On the basis of these properties of fuzzy logic, this paper proposes an adaptive fuzzy logic concept to improve the performances of existing DTC drive systems. The main advantage of using fuzzy logic control structure is that one does not have to

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redesign the existed control system but also acquire the satisfactory response when disturbances and noises enter.

V. SIMULATION RESULTS

The simulation results of the adaptive fuzzy logic controller and classical PI controller based three level VSI fed DTC scheme for induction motor drive are presented and compared. The inverter voltage and stator current waveforms of classical PI controller are shown in Figs. 4 & 5. The speed & torque curves are shown in Fig. 6. The inverter voltage and stator current waveforms of the adaptive fuzzy controller are shown in Figs. 7 & 8. The speed & torque performance are shown in Fig. 9.

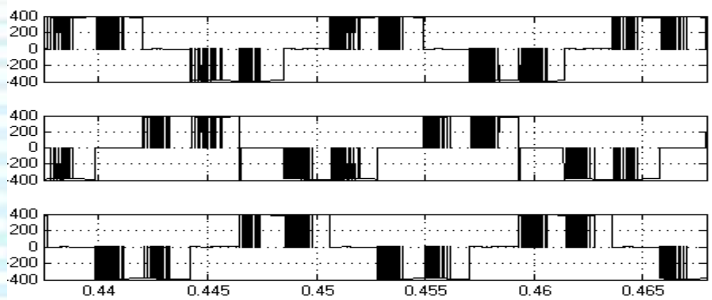

Fig. 4 Inverter voltage waveform

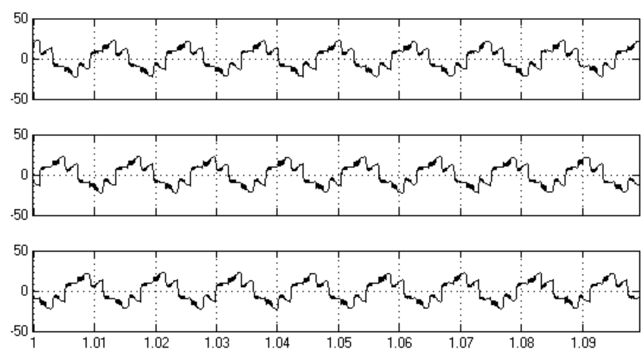

Fig. 5 Stator current waveform

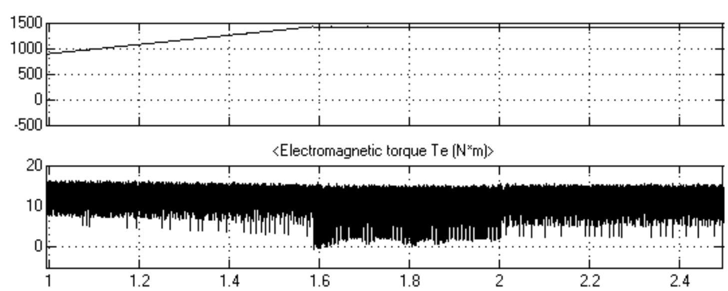

Fig. 6 Motor speed and torque waveform

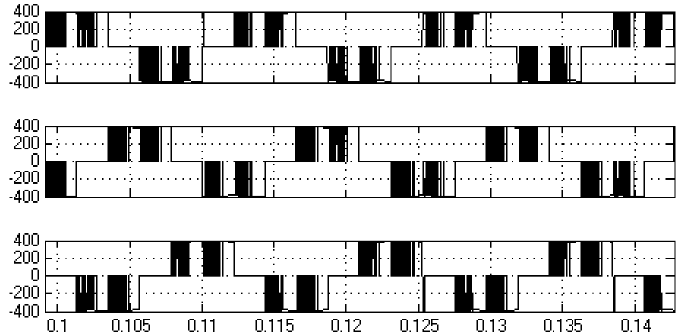

Fig. 7 Inverter voltage waveform

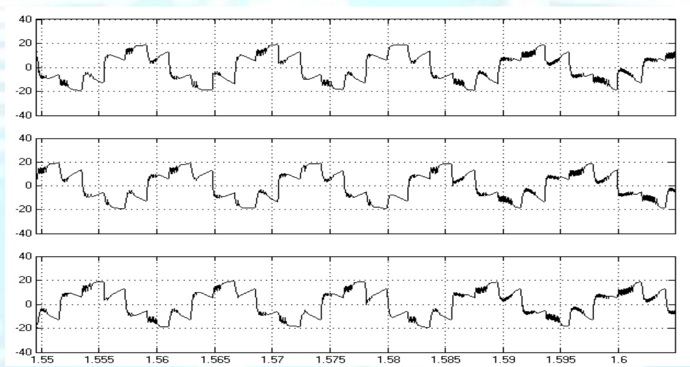

Fig. 8 Stator current waveform

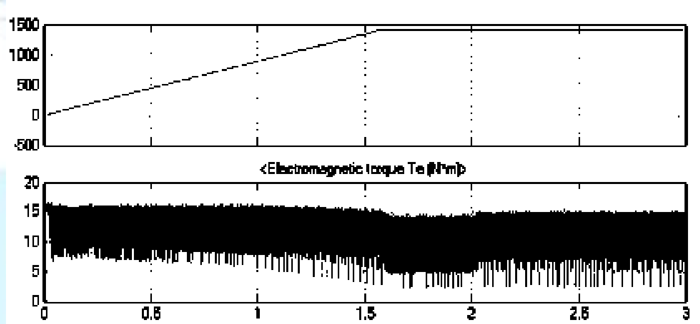

Fig. 9 Motor speed and torque waveform

VI. CONCLUSION

The fuzzy logic controller and classical PI controller based three level VSI fed DTC scheme for induction motor drives are simulated and the simulation results are presented. The performance with the fuzzy logic controller is better than that of PI controller based DTC scheme. The torque ripple is reduced in the fuzzy controller based system. There is a considerable reduction of harmonic distortion in stator current by using three level inverter.

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