Simulation Studies on Switching Table based DTC and Fuzzy Rule based DTC for Three-Phase Squirrel Cage Induction Motor

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Abstract—**This paper describes a study of Switching Table Direct Torque Control (ST-DTC) and Fuzzy Rule based Direct Torque Control (FR-DTC) in case of a three phase induction motor. The hysteresis band and the switching table used in the ST-DTC scheme have been replaced by a Fuzzy Rule based controller in the FR-DTC. Results show that the FR-DTC method provides better transient performance compared to the ST-DTC method.**

Keywords- ST-DTC; VSI; hysterisis band; three level control signal; fuzzy controller; gaussian; sigmoid; d-sigmoid; membership functions

I. Introduction

Induction motors with conventional control used in common industrial drives are not capable of providing fast and smooth torque variation, due to the inherent characteristics of the induction motor, including complex, non-linear, time varying dynamics and inaccessibility of some states and outputs. Safety concerns regarding DC motors helped induction motors to gain industrial acceptance, especially after the introduction of Field Oriented Control (FOC) in the 1970s. This scheme decouples the stator current into the torque producing and flux producing components. These components are controlled like a separately excited DC motor. The method is complex, due to the reference frame transformation and the dependence on machine parameters. The torque control was simplified with the introduction of the DTC scheme in the 1980s. The DTC method does not require transformation, as the FOC method did, and stator resistance is sufficient to estimate the stator flux and torque. To increase or decrease the output torque, the torque angle is required to be increased or decreased respectively, while stator linked flux is kept intact at desired magnitude [1-9]. The change in the torque angle is performed by acceleration or deceleration of the angular speed of the stator linked flux vector by selecting the optimum voltage vector, which is selected from the switching table based on the flux and torque errors. However, implementing this method using high speed processors with multiple A/D converters is rather costly, especially in case of small scale industries [10, 11]. In such cases, the low cost analog ST-DTC control for single quadrant operation [11, 12] is considered much more cost effective. The speed and torque can also be controlled for forward and reverse motoring operation, as previously reported by the authors [12].

The present simulation study aims to compare the torque response and ripple content of ST-DTC and FR-DTC. The proposed scheme replaces the flux and torque hysteresis bands and the switching table of the ST-DTC scheme with a Fuzzy Rule based controller and, as shown, provides better results. It should be noted that both methods can be implemented using low cost discrete electronic components.

II. Principle of ST-DTC

The three phase motor terminal voltages and line currents are sensed and transformed to d-q stationary frame as shown in Figure 1. Induced emfs are calculated after compensating the resistance drop from line voltage. The stator flux components Ψ_{ds} and Ψ_{qs} are calculated by integrating the induced emfs. The torque is calculated using the flux and current components. The absolute flux and calculated torque are compared with the reference or command signal to generate the flux error and the torque error signals. The instantaneous angular position of the stator flux in space, is determined digitally using a switching table as depicted in Table I. Since the air gap space is divided into six sectors each spreading 60^0, the absolute value of Ψ_{qs}/Ψ_{ds} is compared with $\tan 60^0$. Signal A equals 1 when absolute value of the ratio (Ψ_{qs}/Ψ_{ds}) is greater than or equal to $\tan 60^0$, otherwise it equals 0. Digit '0' denotes the negative sign and digit '1' denotes the positive sign. Thus the sector is determined and the third controlled signal S_θ is generated.

The torque error and flux error signals are compared in terms of their respective hysteresis bands, a three level control signal S_T is obtained for torque and a two logic control signal S_λ is obtained for flux. The three control signals are used as inputs to a look-up table, as shown in Table II, which decides the switching pattern of the Voltage Source Inverter (VSI).

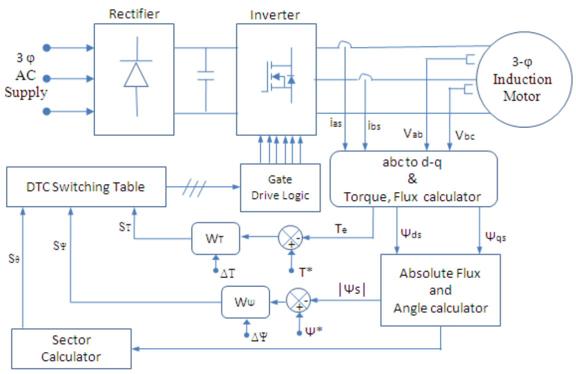

Fig. 1 Block diagram for ST-DTC control of 3 phase IM

TABLE I. SECTOR DETERMINATION

ψ_{ds}	ψ_{qs}	A	S_Θ
0	0	0	<5>
0	0	1	<4>
0	1	0	<6>
0	1	1	<1>
1	0	0	<3>
1	0	1	<4>
1	1	0	<2>
1	1	1	<1>

TABLE II DTC SWITCHING TABLE

S_Ψ	S_T	S_θ					
		<1>	<2>	<3>	<4>	<5>	<6>
1	1	110	100	101	001	011	010
1	0	111	000	111	000	111	000
1	-1	101	001	011	010	110	100
0	1	010	110	100	101	001	011
0	0	000	111	000	111	000	111
0	-1	001	011	010	110	100	101

III. PRINCIPLE OF FR-DTC

In the FR-DTC scheme, the hysteresis bands creating the torque and flux control logic signals are replaced by a Fuzzy Rule based controller as shown in Figure 2. The switching look up table is realized using Fuzzy rules. The fuzzy controller proposed here has been designed so as to use three fuzzy state variables as inputs and three control outputs to achieve the switching pattern for the VSI. The three fuzzy state variables inputs are flux error, torque error and the angular position of the stator flux. The absolute flux is compared with the rated flux of the three-phase induction motor (0.5606 Wb) to obtain the flux error. The six voltage vectors (differential stator flux) for any specific positioned stator flux indicate either increase or decrease of the stator flux for flux control. Thus, flux errors are identified by three state variables chosen as membership functions. The membership function N intends to decrease the flux, P intends to increase it and Z denotes no change in stator flux. The membership functions used are Gaussian, Sigmoid and D-sigmoid functions as shown in Figure 3.

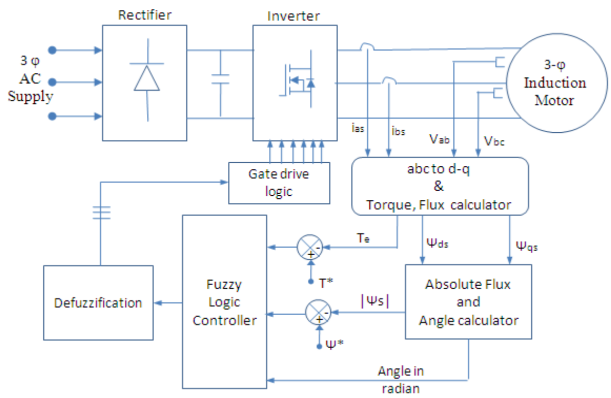

Fig. 2 Fuzzy DTC controlled 3 phase Induction Motor

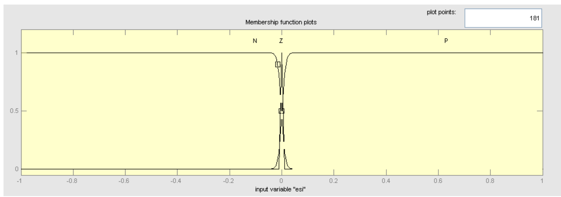

Fig. 3 Membership functions for Flux error

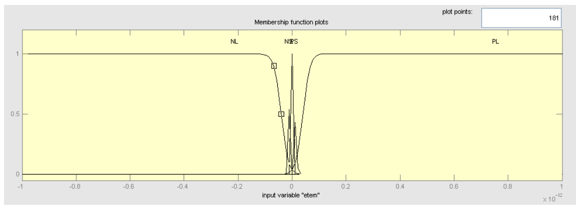

Fig. 4 Membership functions for Torque error

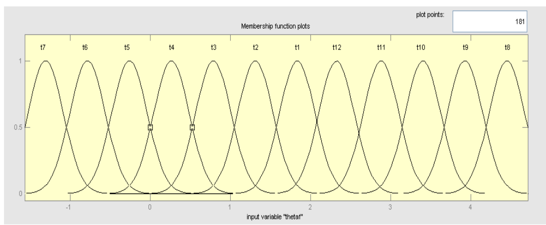

Fig. 5 Membership function for 12 angular dwelling instants of Flux

The torque error is calculated by comparing the calculated electromagnetic torque with the desired command torque. Considering the stator flux to dwell in the first 60^0 in the air gap space and assuming the torque and flux errors to be positive, the demanding voltage phasor will tend to increase the torque. The voltage demand can be satisfied with voltage phasor in sector I or VI. If the flux is in first 30^0 of sector I, then any of the above voltage vectors can meet the purpose.

When it is in the second 30^0, the voltage phasor corresponding to sector VI of sextant provides the advancement of the flux vector. The torque error state-variable is chosen in five states as rapid increase, increase, no action, decrease and rapid decrease. The membership functions are a combination of Gaussian, Sigmoid and D-sigmoid membership functions as shown in Figure 4.

The angular dwelling position of stator flux is defined in twelve zones, spreading for π/6 radian each in the sextant. The angular position θ is defined as $\tan^{-1} \Psi_q / \Psi_d$. The range has been chosen from –π/2 to 3π/2 in twelve equal sub sectors for selecting the membership functions for stator flux position. Each sextant has been divided into two sub sectors to yield accurate judgments regarding the call of appropriate voltage phasor in Direct Torque Control as shown in Figure 5.

The controlled output of the fuzzy controller gives the inverter switching states. In the three phase voltage source inverter eight switching vectors are possible. The controller uses three input state variables and three crisp outputs using a proposed 180 Rule Table. Mamdani method is used for defuzzification.

IV. Simulation Study

The ST-DTC and FR-DTC schemes were simulated using the MATLAB Simulink environment, employing a 3-phase induction motor with the following parameters: 3HP, 220V, 50Hz, R_s=0.435Ω, L_{ls}=2mH, R_r'=0.816Ω, L_{lr}'=2mH, L_m=69.31mH, moment of inertia J=0.00089 kg·m^2, friction constant F=0.0001 and number of poles per phase P=4. In each case the line voltage and line current supplied to the stator are sensed and transformed to d-q components. The emf is calculated after compensating for the resistance drop, then d-q flux is derived which helps to calculate the electromagnetic torque and the stator flux position. The calculated torque and the absolute flux are compared with their respective command values in order to obtain the error.

The simulation has been performed for two quadrant operation. The torque command for the first 0.1 second is 100% of the base value, then it changes to -30% till the 0.15 second, and then returns back to the base value. The errors are processed with respective hysteresis bands in order to obtain two control signals with the third signal being the position of flux, which in ST-DTC are judged by a look up table to decide the switching vectors of VSI. In FR-DTC each of the two errors and the flux position is represented with three input membership functions of a Fuzzy rule based controller. The controller uses 180 newly defined rules. Mamdani method has been used here to obtain the crisp output to be used as a switching vector for the VSI.

V. Results and Discussion

The X-Y plots for d-q flux for both schemes are depicted in Figures 6a and 6b which shows that the circular shape and the magnitude matches the base flux value of the machine. The d-q flux loci plotted against time as depicted in Figures 7a and 7b for ST-DTC and FR-DTC are shown for two quadrant operation. The q-axis flux lags the d-axis flux in forward motoring mode, while its reverse takes place in reverse motoring.

a

b

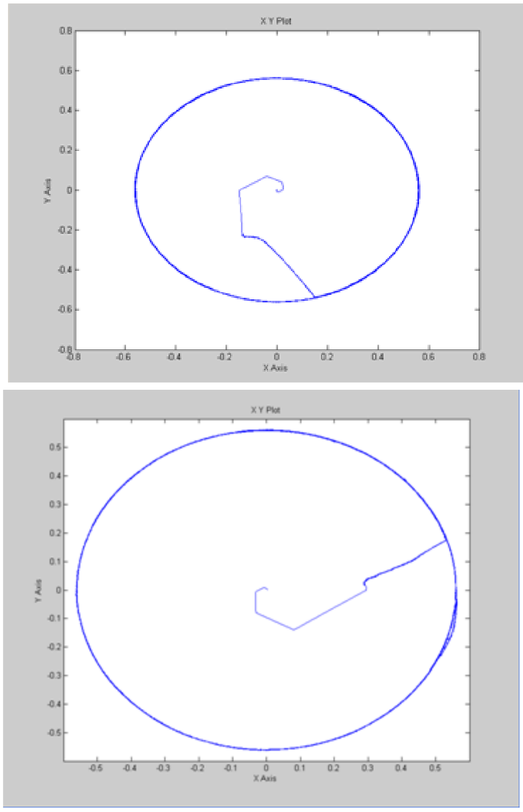

Fig. 6 a. d-q flux in ST-DT b. d-q flux in Fuzzy DTC

a

b

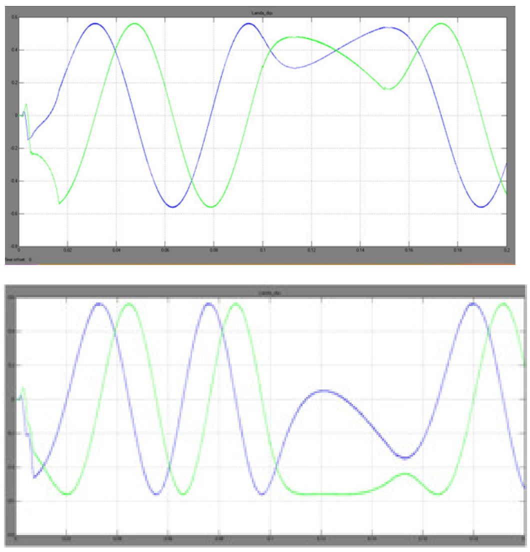

Fig. 7 a. Ψ_q , Ψ_d vs time in ST-DTC b. Ψ_q , Ψ_d vs time in Fuzzy DTC

Absolute flux and angular position of stator flux versus time for both schemes are shown in Figures 8a and 8b. The upper plotting in each figure shows the absolute flux. The flux in both cases attains its steady value (0.56 Wb). In comparison to the ST-DTC scheme the flux reaches its steady value much quicker in the FR-DTC scheme. In the first scheme the time taken is 0.0175 sec, where in the latter it is only 0.004 sec. As observed in the angular position of stator flux shown in Figure 8b, instant rotation of flux is obtained while the motor is commanded from forward motoring to reverse motoring in FR-DTC.

It is further found that FR-DTC responds faster to changes in torque command. Figures 9a and b depict the change in forward motoring to reverse motoring for both schemes. The graph plotted is the superimposed graph of torque command and resulting torque in falling mode. The time taken to respond to the command in the ST-DTC scheme is 0.00004 seconds whereas in the FR-DTC scheme is 0.000025 seconds. The rising mode is depicted in Figures 10a and b. The resulting rising torque attains the command value in 0.00005 seconds for the ST-DTC scheme and in 0.000033 seconds for the FR-DTC scheme.

VI. Conclusion

A simulation study was performed for ST-DTC scheme and the proposed FR-DTC scheme. The basic objective of the DTC scheme is to obtain fast response to changes in torque command. It is shown that the FR-DTC scheme offers faster transient response to torque changes. The ripple content in the resulting torque in the FR-DTC can be minimized by further refining the tuning of the input membership functions.

a

b

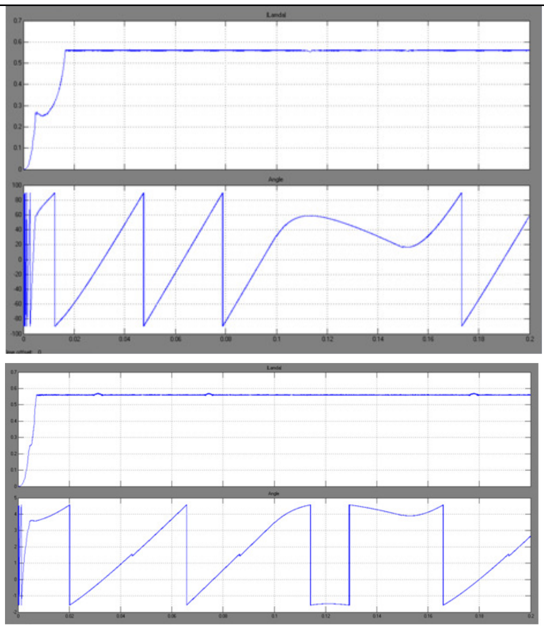

Fig. 8 a. |Ψ| and Stator flux position vs time in ST-DTC b. |Ψ| and Stator flux position vs time in FR-DTC

a

b

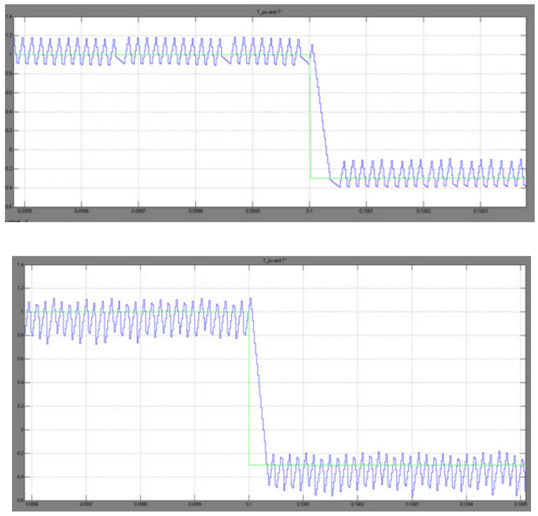

Fig. 9 a. Falling mode T* and T_e superimposed in ST-DTC b. Falling mode T* and T_e superimposed in FR-DTC

a

b

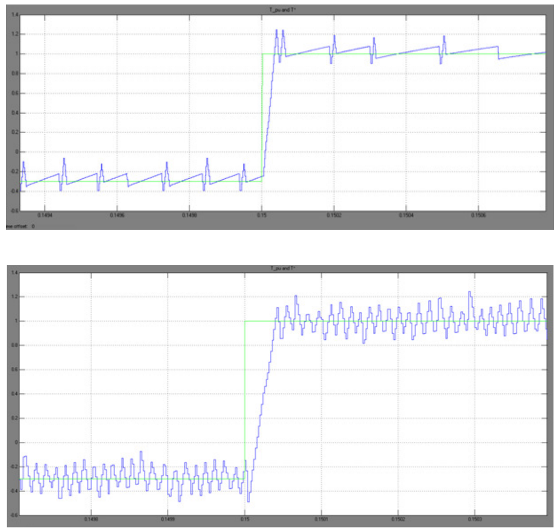

Fig. 10 a. Rising mode T* and T_e superimposed in ST-DTC b. Rising mode T* and T_e superimposed in Fuzzy-DTC

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