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DTC Control of Induction Motors Employing Advanced Control Techniques

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Abstract—Conventional Proportional Integral controllers require precise mathematical model of the system and proper tuning of controllers to achieve high performance drive. Induction motor drives controlled by Field Oriented Control are mainly employed in high performance industrial applications, instead of dc motors. Field Oriented Control is very sensitive to flux predominantly affected by variation in parameters. It allows control of both torque and flux by decoupling the stator current into two orthogonal components. The primary limitation of FOC relies on parameter identification to achieve the expected performance. An alternative control method called Direct Torque Control has been developed for electrical machine. The DTC method is characterized by its simple implementation and a fast dynamic response Using this method, Stator voltage vectors can be determined according to the difference between the reference & actual torque and stator flux linkage. With this approach the inverter is directly controlled by the algorithm instead of a modulation technique for the inverter. The key benefit of DTC method is absence of coordinate transformation and also separate voltage modulation is not required. However, high torque ripple and slow transient response to the step changes in torque during start-up also adds to disadvantages of conventional DTC. In order to overcome this issue the soft computing techniques can be employed. The paper proposed the implementation of Induction motor control using Fuzzy logic and Artificial Neural Network methods .

Keywords—Torque control, Fuzzy inference system (FIS); Fuzzy logic, direct torque control (DTC).

Introduction

The growing utilization of Field Oriented Control (FOC) in Induction Motor (IM) drives for commercial applications has significantly impacted ongoing research. Researchers are developing number of different solutions for the control of the IM drives with two major objectives, namely required a fast and accurate control of the motor flux and torque, and secondly reduction of the complexity of the algorithms involved in a FOC. An alternative approach for the control of torque of induction motors was developed as Direct Torque Control (DTC) [1–3], and Direct Self Control (DSC) [4–6]. This technique was characterized by simplicity, good performance and robustness [1–17]. The fundamental framework of DSC includes its the high power range applications and a lower inverter switching frequency justifies higher current distortion.

In contrast to FOC, DTC focuses on fully utilizing the flux and torque-generating capabilities of an Induction Motor (IM) powered by a Voltage Source Inverter (VSI). The DTC scheme does not inlude PI regulators, coordinate transformations, current regulators and PWM signals generators. The presented research work proposes fuzzy logic control of DTC. At the outset the fundamental principles of flux, torque control and the switching table are presented in order to accomplish the DTC concept. Thus independent control of the torque and flux by decoupling the stator current into two orthogonal components can be achieved. Field-Oriented Control (FOC) is highly responsive to changes in flux, particularly those arising from variations in parameters. Distinctive importance has been placed on observing the analytical correlation between the applied voltage and the corresponding torque fluctuations within a cycle period. Subsequently, the Direct Self-Control (DSC) strategy and enhancements to the fundamental Direct Torque Control (DTC) scheme are scrutinized. Lastly, an approach for implementing flux weakening in DTC drive is assessed, and a comparative analysis between DTC and Field-Oriented Control (FOC) is provided.

I. BLOCK DIAGRAM REPRESENTATION OF DTC

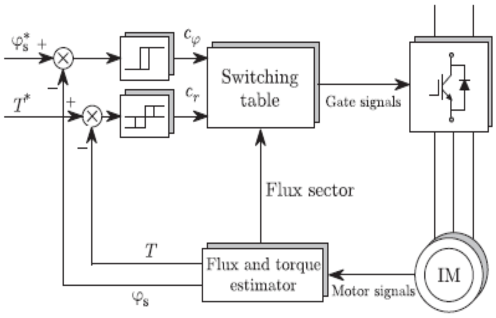

Fig. 1. Basic DTC scheme

A basic DTC scheme for Induction Motor drive is shown in Fig. 1. It shows that the error between the estimated torque *T* and the reference torque *T** is the input of a three level hysteresis comparator, whereas the error between the estimated stator flux magnitude φ_s and the reference stator flux magnitude φ_s^* is the input of a two level hysteresis comparator. The flux and torque are evaluated using the three stator currents to find the voltage of input inverter. Soft computing techniques like Fuzzy logic has been devised having the torque error, the stator flux error and the position of the stator flux as inputs, and voltage space vector to be generate by the inverter as output the [18] [19] [20]. Fig. 1 shows the schematic of the basic functional blocks used to implement the DTC of induction motor drive. **As** voltage source inverter (VSI) supplies the motor, it is possible to control directly the stator flux and the electromagnetic torque by the selection of optimum inverter switching modes.

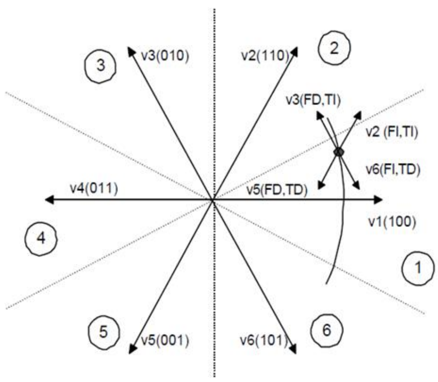

Fig 2: Partition of the αβ plane into 6 angular sectors

FD:flux decrease; FI:flux increase; TD:torque decrease ;TI:torque increase.

In the PWM based voltage source inverters, consider the three switching functions (C1,C2,C3), which can take either 1 or 0.Combinations of the states of inverter switching state functions the voltage vector can be written as:

$$V_S = \sqrt{\frac{2}{3}}U_0[C_1 + C_2 e^{i\frac{2\pi}{3}} + C_3 e^{i\frac{4\pi}{3}}]$$

……….1

There can be eight switching combinations two zero voltage vectors and six non-zero voltage vectors as shown in Fig.2 [21][22]

Switching Table

In Zone I, the selection of vectors Vi+1 or Vi-1 is made to amplify the flux amplitude, while Vi+2 or Vi-2 is chosen to reduce it. This demonstrates that the decision regarding vector selection is contingent upon the sign of the flux error, irrespective of its magnitude [21]. This elucidates that the flux corrector output can be represented as a Boolean variable. a hysteresis band is introduced around zero when the flux error is minimal, [21] [22]. This correction method is very simple and can easily control and maintain the end of the vector flux, in a circular ring.

Table 1:

Sector		1	2	3	4	5	6
Flux	Torque						
F=1	T=1	V2	V3	V4	V5	V6	V1
	T=0	V7	V0	V7	V0	V7	V0
F=0	T=1	V3	V4	V5	V6	V1	V2
	T=0	V0	V7	V0	V7	V0	V7

Stator Flux and Torque Estimation

Using eq (2) and (3),the current components (I_A, I_B), and stator voltage (V_A, V_B) are obtained as follows

$$I_A = \sqrt{\frac{2}{3}}[I_a - \frac{1}{2}(I_b + I_c)]$$

$$I_B = \frac{1}{\sqrt{2}}(I_b - I_c)$$

………………2

$$V_A = \sqrt{\frac{2}{3}}U_0[C_1 - \frac{1}{2}(C_2 + C_3)]$$

$$V_B = \frac{1}{\sqrt{2}} U_0 [C_2 - C_3]$$
…………..3

The components of the stator flux (φ_A, φ_B) given by (4)

$$\phi_A = \int_0^t (V_A - R_s I_A) dt$$

$$\phi_B = \int_0^t (V_B - R_s I_B) dt$$
………………4

The stator flux linkage phase is given by

$$\phi_S = \sqrt{\phi_A^2 + \phi_B^2} \quad \text{………………5}$$

The electromagnetic couple be obtained starting from the estimated sizes of flux and calculated sizes of the current.

$$T = p(\phi_A I_B - \phi_B I_A) \quad \text{……………(6)}$$

Assuming the stator resistance R_s constant during a large number of converter in switching periods T_e,the voltage vector applied to the IM remains also constant one period T_e.

. Therefore, resolving first equation of system leads to:

$$\phi_A = \int_0^t (V_A - R_s I_A) dt \quad \text{………………….(7)}$$

$$\phi_{S(t)} \approx \phi_{S0} + V_s T_e \quad \text{…………………..(8)}$$

In equation (8); ϕs0 stands for the initial stator flux condition. This equation that when the term ***RsIs*** can be neglected, (in high speed operating condition for example), the extremity of stator flux vector Vs. Furthermore, the instantaneous flux speed is only governed by voltage vector amplitude [21][23].

II. IMPLEMENTATION OF FUZZIFIED BASED TECHNIQUE

The principal of direct torque control using fuzzy logic (FDTC). The fuzzy controller is designed to have three fuzzy state Variables and one control variable for achieving direct torque Control of the induction machine[24][25], there are three variable input fuzzy logic controllers, the stator flux error, electromagnetic torque error, and angle of flux stator respectively the output it is the voltage space vector. The technique is based on applying switching state to the inverter and the selected active state just enough time to achieve the torque and flux references values. A null state is selected for the remaining switching period, which won't almost change both the torque and the flux. Therefore, the switching state has to be determined based on the values of torque error, flux error and stator flux angle. Exact value of stator flux angle (θ) determines where stator flux lies.

Flux Linkage Errors

The errors of flux linkage is related value of stator's flux φs and real value of stator's φs they are subject to equation

$$\Delta\varphi = \varphi_s^* - \varphi_s \quad \text{…………………………………………9}$$

We use the three following linguistic terms: negative value, zero value and positive value denoted respectively N, Z and P. Three fuzzy sets are then defined by the delta and trapezoidal membership functions as given by Fig.4 [25, 26].

Electromagnetic Torque Errors

Error of torque Ete is related to desired torque value T*e and real torque value Te, they are subject to equation (10)

$$\Delta\Gamma = T^*_e - T_e \quad \text{……………………………………….10}$$

rules may be described by language variable, i, e. Positive Large (LP), Positive Small (PS), Negative Small (NS), and Negative Large (NL), their membership function's distribution is shown as Fig.5, [25],[26] [27]

Angle of Flux Linkage θS

The angle of flux linkage θs is an angle between stator's flux φs and a reference axis is defined by equation (11)

$$\theta_S = ar\tan\frac{\phi_B}{\phi_A} \quad \text{………………………………11}$$

in equation 3 φsα and φsβ are the component of flux linkage φs in the plan (α,β) on the basis of voltage vector shown as Fig.2, fuzzy variable may be described by 12 language value (θ1→θ12),it's the membership function's distribution is shown Fig.6 [25].

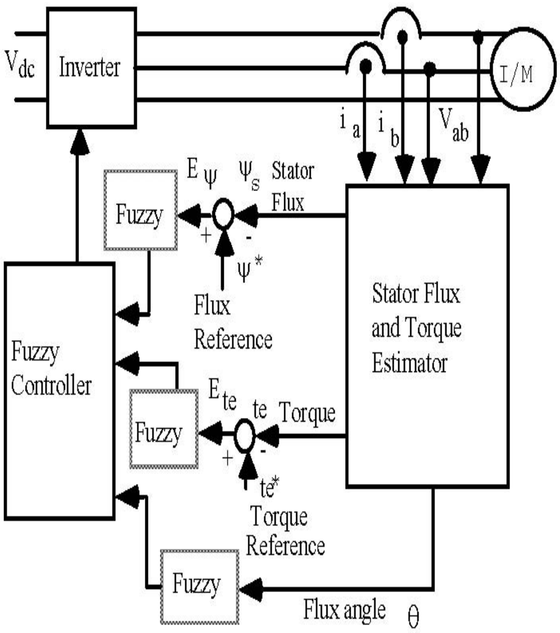

Figure 3: Block Diagram of Fuzzy logic DTC

Voltage Vectors Ui

For the voltage vectors Ui(i=0-6), the membership distribution function of Ui is given by Fig.

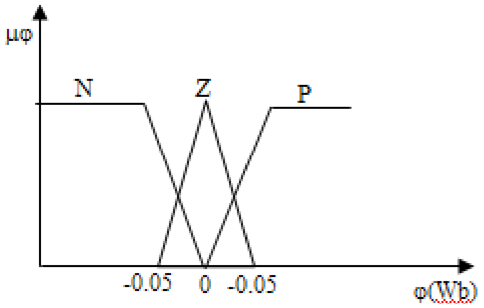

Figure 4: Membership functions for flux error

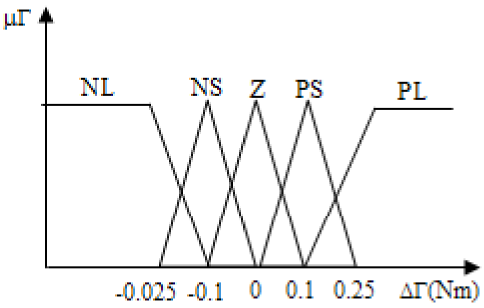

Figure 5: Membership functions for Torque error

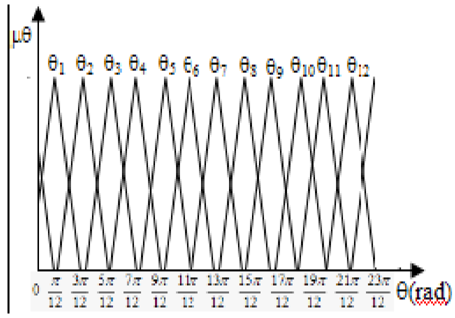

Figure 6: Membership functions for angle of flux linkage

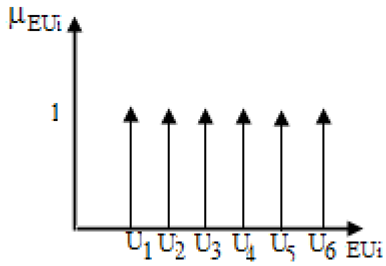

Figure 7: Membership functions for voltage

Fuzzy Control Rules

The rule base monitors the behavior of the fuzzy controller. It stores the expert knowledge on how to control the plant. Fuzzy control rules can be deduced from the diagram of voltage vector in Figure 8. For example, supposing the positional angle θ of stator's flux is located in domain θ2, we can have the following decision rules: if desired control is to make torque decrease slowly and make flux increase rapidly, then desired decision is V1. The control goal is to maintain the stator flux at a level value while keeping the torque's response fast. It is easy to show that we can build up to 180 control rules as shown in Table 1.

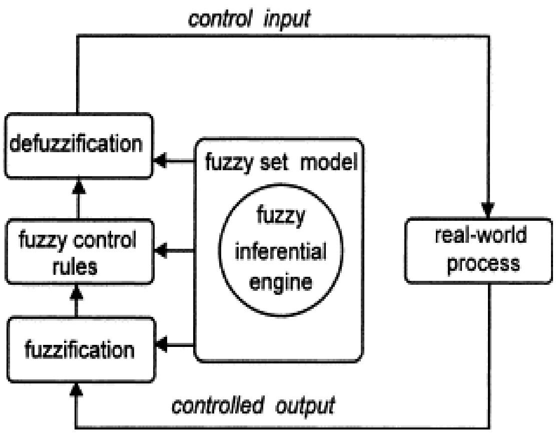

Figure 8: Architecture of fuzzy logic system

The concrete reasoning of fuzzy logic system is shown in the flowchart of Figure 8. For each combination of inputs, usually more than one rule is validated. Each rule generates a significant control action depending on the input values of the variables. Then defuzzification is applied to generate the control output.

III. DTC Based Fuzzy Control

The rule base monitors the behavior of the fuzzy controller. It stores the expert knowledge on how to control the plant. Fuzzy control rules can be deduced from the diagram of voltage vector in Figure 7. For example, supposing the positional angle θ of stator's flux is located in domain θ2, we can have the following decision rules: if desired control is to make torque decrease slowly and make flux increase rapidly, then desired decision is V1. The control goal is to maintain the stator flux at a level value while keeping the torque's response fast. It is easy to show that we can build up to 180 control rules as shown in Table 2.

Table 2. Fuzzy logic rules

θ1					
ΔΓ / Δφ	PL	PS	Z	NS	NL
P	V6	V1	V0	V2	V2
Z	V6	V6	V0	V0	V3
N	V5	V5	V0	V4	V3

θ2					
ΔΓ / Δφ	PL	PS	Z	NS	NL
P	V6	V6	V0	V1	V2
Z	V5	V5	V0	V0	V2
N	V5	V4	V0	V3	V3

θ3					
ΔΓ / Δφ	PL	PS	Z	NS	NL
P	V5	V6	V0	V1	V1
Z	V5	V5	V0	V0	V2
N	V4	V4	V0	V3	V2

θ4					
ΔΓ / Δφ	PL	PS	Z	NS	NL
P	V5	V5	V0	V6	V1
Z	V4	V4	V0	V0	V1
N	V4	V3	V0	V2	V2

θ5					
ΔΓ / Δφ	PL	PS	Z	NS	NL
P	V4	V5	V0	V6	V6
Z	V4	V4	V0	V0	V1
N	V3	V3	V0	V2	V1

θ6					
ΔΓ / Δφ	PL	PS	Z	NS	NL
P	V4	V4	V0	V5	V6
Z	V3	V3	V0	V6	V2
N	V3	V2	V0	V1	V1

θ7					
ΔΓ / Δφ	PL	PS	Z	NS	NL
P	V3	V4	V0	V5	V5
Z	V3	V3	V0	V0	V6
N	V2	V2	V0	V1	V6

θ8					
ΔΓ / Δφ	PL	PS	Z	NS	NL
P	V3	V3	V0	V4	V5
Z	V2	V2	V0	V0	V5
N	V2	V1	V0	V6	V6

θ9					
ΔΓ / Δφ	PL	PS	Z	NS	NL
P	V2	V3	V0	V4	V4
Z	V2	V2	V0	V0	V5
N	V1	V1	V0	V6	V5

θ10					
ΔΓ / Δφ	PL	PS	Z	NS	NL
P	V2	V2	V0	V3	V4
Z	V1	V1	V0	V0	V4
N	V1	V6	V0	V5	V5

θ11					
ΔΓ / Δφ	PL	PS	Z	NS	NL
P	V1	V2	V0	V3	V3
Z	V1	V1	V0	V0	V4
N	V6	V6	V0	V5	V4

θ12					
ΔΓ / Δφ	PL	PS	Z	NS	NL
P	V1	V1	V0	V2	V3
Z	V6	V6	V0	V0	V3
N	V6	V5	V0	V4	V4

Each control rule from table 1 can be described using the input variables torque error ec, flux error eϕ, flux angle θ and the output variable v Ri : if eϕ is Ai and eT is Bi and θ is Ci then v is Vi. where Ai, Bi and Ci denote the fuzzy set of the variable eϕ, eT and θ respectively. Vi and Ri are the fuzzy singleton and control of rule number i.

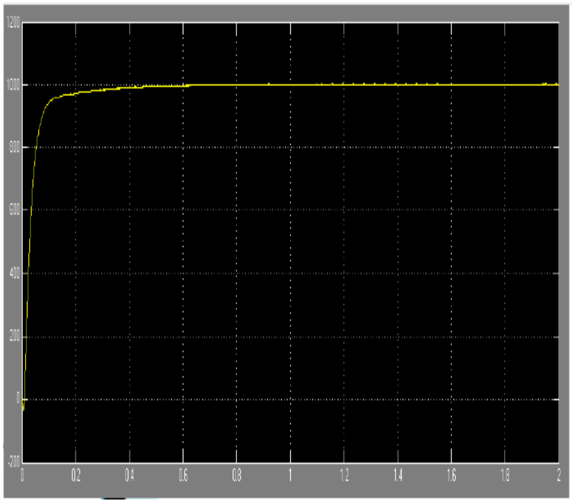

Figure 9: Scope for Speed of basic DTC model

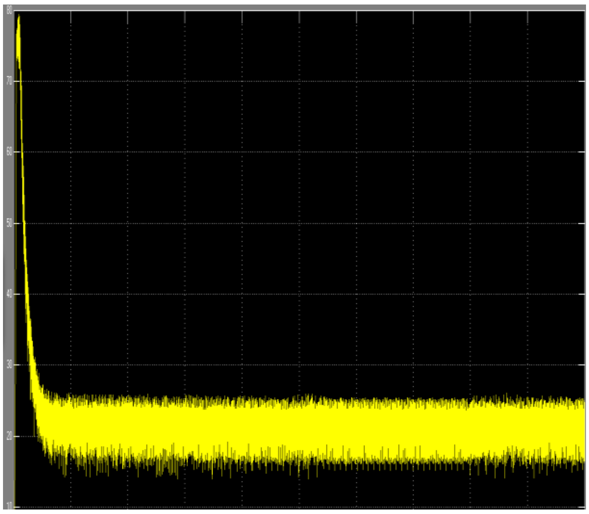

Figure 10: Scope for TORQUE of Basic DTC Scheme

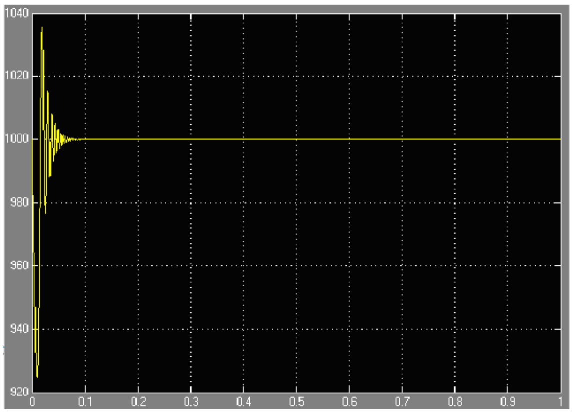

Fig11:Scope for speed of fuzzified DTC model

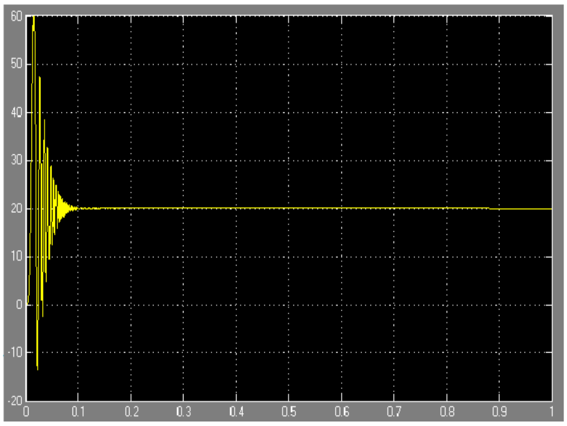

Fig11:Scope for Torque of fuzzified DTC model

To study the performance of the fuzzy logic switching table with direct torque control strategy, the simulation of the system was conducted using SIMULINK and Fuzzy Logic Toolbox. Simulation results for a DTC system when controlling the induction machine is represented in figure 9 and figure 10 respectively. The Sampling period of the system is 50µs. To compare with C_DTC, FLDTC for IM are simulated. In two cases, the dynamic responses of speed, flux, torque for the starting process with [5→7→3] Nm load torque applied Figure 10 show the response of electric torque of the

C_DTC, FL_DTC. It can be seen that the ripple in torque with FL_DTC is less with conventional direct torque control the ripple at the same operating conditions. Fig.9 show the response of speed of Rotor of the FLDTC. Stator flux is the fast response in transient state and the ripple in steady state is reduced remarkably compared with conventional DTC, the flux changes through big oscillation and the torque ripple is bigger in C_DTC It can be noticed that stator flux vector describes a trajectory almost circular.

IV. Conclusion & Future Work

In this paper, an improvement for direct torque control algorithm of induction machine is proposed using intelligent approaches which consists of replacing the switching table selector block and the two hysteresis controllers. Simulations have shown that the two proposed strategies have better performances than the CDTC. In fact, they allow a significant reduced torque and stator flux ripples and a good starting behavior. Using the intelligent techniques, the selection of the voltage vector becomes much convenient and the switching state can be obtained when the error of the torque and stator flux is attained. The validity of the proposed control is confirmed by the simulative results. None of the known advantages of the CDTC are impacted by the proposed methods. It has been found that the direct torque fuzzy control strategy allows a higher dynamic behavior than the conventional DTC. In the future research, the simulative results will be brought into the experimental system to prove the proposed neural network and fuzzy logic control. A digital implementation of these intelligent controls may be performed using different devices such as custom design, programmable logic, etc. In a Field Programmable Gate Array (FPGA), which is a family of programmable devices, multiple operations can be executed in parallel so that algorithms can run faster, which is required for control systems.

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