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DIRECT TORQUE CONTROL FOR INDUCTION MOTOR USING INTELLIGENT TECHNIQUES

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ABSTRACT

In this paper, we propose two approach intelligent techniques of improvement of Direct Torque Control (DTC) of Induction motor such as fuzzy logic (FL) and artificial neural network (ANN), applied in switching select voltage vector .The comparison with conventional direct torque control (DTC), show that the use of the DTC_FL and DTC_ANN, reduced the torque, stator flux, and current ripples. The validity of the proposed methods is confirmed by the simulative results.

Keywords*: Fuzzy inference system (FIS); Fuzzy logic, direct torque control (DTC), induction motor, artificial neural network (ANN).*

1. INTRODUCTION

Induction motor drives controlled by Field Oriented control (FOC) [1] have been till now employed in high performance industrial applications, has achieved a quick torque response, and has been applied in various industrial applications instead of dc motors [1]-[22].It permit independent control of the torque and flux by decoupling the stator current into two orthogonal components FOC, however, is very sensitive to flux, which is mainly affected by parameter variations. It depends on accurate parameter identification to achieve the expected performance. During the last decade a new control method called DTC (Direct Torque Control) has been developed for electrical machines[1]-[22].TC principles were first introduced by Depenbrock [1] and Takahashi [2]. In this method, Stator voltage vectors is selected according to the differences between the reference and actual torque and stator flux linkage. The DTC method is characterised by its simple implementation and a fast dynamic response. Furthermore, the inverter is directly controlled by the algorithm, i.e. a modulation technique for the inverter is not needed [1]-[7].However if the control is implemented on a digital system (which can be considered as a standard nowadays), the actual values of flux and torque could cross their boundaries too far. The main advantages of DTC are absence of coordinate transformation and current regulator; absence of separate voltage modulation block, Common disadvantages of conventional DTC are high torque ripple and slow transient response to the step changes in torque during start-up[1]-[4]. For that reason the application of Fuzzy logic and artificial neural network attracts the attention of many scientists from all over the world [1]. The reason for this trend is the many advantages which the architectures of ANN have over traditional algorithmic methods [8]-[22]. .

Among the advantages of ANN are the ease of training and generalization, simple architecture, possibility of approximating nonlinear functions, insensitivity to the distortion of the network, and inexact input data [8]-[14] [17].[20].In this paper we present the evaluation of flux and torque using the three stator currents is the voltage of input inverter, and Fuzzy logic and artificial neural network has been devised having as inputs the torque error, the stator flux error and the position of the stator flux in which it lies, and as output the voltage space vector to be generate by the inverter[8]-[13],[17].The ANN then replaces the switching table'. The theoretical Principle, numerical simulation procedures and the results of these methods are discussed and compared with conventional DTC (C_DTC).

2. DIRECT TORQUE CONTROL WITH TWO-LEVEL INVERTER

Fig. 1 shows the schematic of The basic functional blocks used to implement the DTC of induction motor drive. **A** voltage source inverter (VSI) supplies the motor and it is possible to control directly the stator flux and the electromagnetic torque by the selection of optimum inverter switching modes [1]-[4].

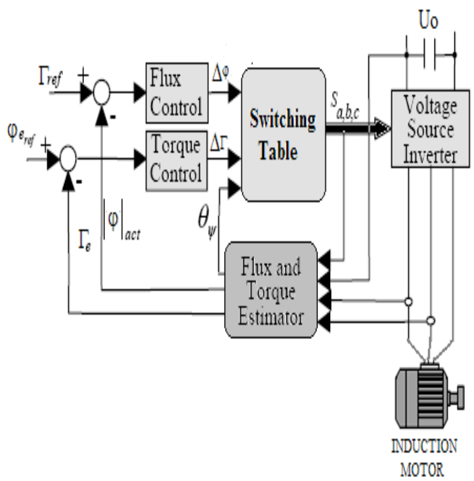

Figure 1. Basic direct torque control scheme for ac motor drives

2.1. Vector Model of Inverter Output Voltage

In the PWM voltage source inverters, considering the combinations of the states of switching functions inverter switching state functions (C_1,C_2,C_3) which can take either 1 or 0, the voltage vector becomes:

$$V_s = \sqrt{\frac{2}{3}} U_0 \left[C_1 + C_2 e^{j\frac{2\pi}{3}} + C_3 e^{j\frac{4\pi}{3}} \right] \quad (1)$$

Eight switching combinations can be taken according to the above relationship: two zero voltage vectors and six non-zero voltage vectors show by Fig.2 [1][2].

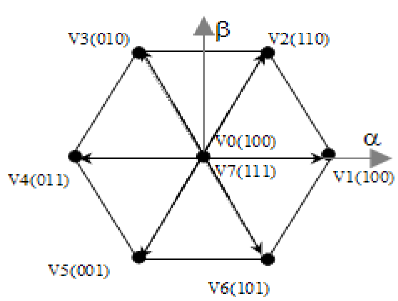

Figure 2. Partition of the αβ plane into 6 angular sectors

2.2. Stator Flux and Torque Estimation

The components of the current (Isα, Isβ), and stator voltage (Vsα, Vsβ) are obtained by the application of the transformation given by (5) and (6), [1] :

$$\begin{cases} I_{S\alpha} = \sqrt{\frac{2}{3}} Isa \\ I_{S\beta} = \frac{1}{\sqrt{2}} (Isb - Isc) \end{cases} \quad (5)$$

$$\begin{cases} V_{S\alpha} = \sqrt{\frac{2}{3}} U_0 \left(C_1 - \frac{1}{2}(C_2 + C_3) \right) \\ V_{S\beta} = \frac{1}{\sqrt{2}} U_0 (C_2 - C_3) \end{cases} \quad (6)$$

The components of the stator flux ($\varphi_{s\alpha}$, $\varphi_{s\beta}$) given by (7).

$$\begin{cases} \overline{\varphi}_{S\alpha} = \int_0^t (\overline{V}_{S\alpha} - R_S \overline{I}_{S\alpha}) dt \\ \overline{\varphi}_{S\beta} = \int_0^t (\overline{V}_{S\beta} - R_S \overline{I}_{S\beta}) dt \end{cases} \quad (7)$$

The stator flux linkage phase is given by (8).

$$\varphi_S = \sqrt{\varphi_{S\alpha}^2 + \varphi_{S\beta}^2} \quad (8)$$

The electromagnetic couple be obtained starting from the estimated sizes of flux ($\varphi_{s\alpha}$,$\varphi_{s\beta}$ and calculated sizes of the current, Isα Isβ)

$$\Gamma_{em} = p\left(\varphi_{s\alpha} I_{s\beta} - \varphi_{s\beta} I_{s\alpha}\right) \quad (9)$$

The stator resistance *Rs* can be assumed constant during a large number of converter switching periods Te. The voltage vector applied to the induction motor remains also constant one period Te. Therefore, resolving first equation of system leads to:

$$\overline{\varphi}_S = \int_0^t (\overline{V}_s - R_s \overline{I}_s) dt \quad (10)$$

$$\overline{\varphi}_S(t) \approx \overline{\varphi}_{S0} + \overline{V}_s T_e \quad (11)$$

In equation (11); φ_{s0} stands for the initial stator flux condition. This equation shows that when the term ***RsIs*** can be neglected, (in high speed operating condition for example), the extremity of stator flux vector V_s. Furthermore, the instantaneous flux speed is only governed by voltage vector amplitude [1][4].

In fact, we have $\frac{d\overline{\varphi}_S}{dt} \approx \overline{V}_s$ the following Fig.3 Established for the case Vs=V3.

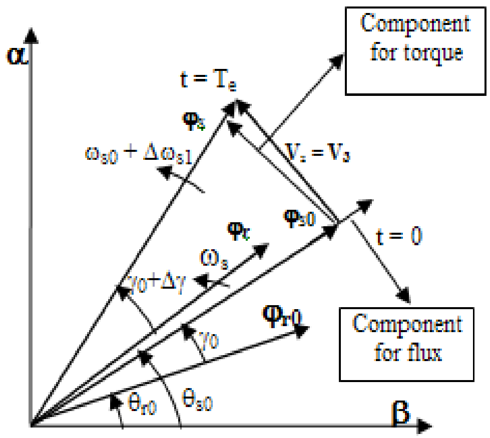

Figure 3. An example for flux deviation

Therefore, by adequate voltage vector selection we can increase or decrease the stator flux amplitude and phase to obtain the required performances. The deviation obtained at the end of the switching period Te can be approached by the first order Taylor Seri as below.

The radial component (component of flux) of the vector of tension acts on the amplitude of the vector flux and its tangential component (component of the torque) on the position of the vector flux. By choosing a suitable sequence of the vectors of tension, one can force the end of the vector flux to follow a desired trajectory. To function with a module of practically constant flux φs, it is enough to choose an almost circular trajectory for the end of the vector flux. That is not possible that if the period of control is very weak for you in front of the period of rotation of flux [1], [3] [10].

2.3. Switching Table

When flux is in zone I, the vectors V_{i+1} or V_{i-1} are selected to increase the amplitude of flux, and V_{i+2} or V_{i-2} to decrease it. What shows that the choice of the vector tension depends on the sign of the error of flux, independently of its amplitude [1]. This explains why the exit of the corrector of flux can be a Boolean variable. One adds a band of hysteresis around zero to avoid useless commutations when the error of flux is very small, [1] [2]. Indeed, with this type of corrector in spite of his simplicity, one can easily control and maintain the end of the vector flux, in a circular ring. The switching table proposed by Takahashi [1], as given by Table1.

Sector		1	2	3	4	5	6
Flux	Torque						
F=1	T=1	V_2	V_3	V_4	V_5	V_6	V_1
	T=0	V_7	V_0	V_7	V_0	V_7	V_0
	T=-1	V_6	V_1	V_2	V_3	V_4	V_5
F=0	T=1	V_3	V_4	V_5	V_6	V_1	V_2
	T=0	V_0	V_7	V_0	V_7	V_0	V_7
	T=-1	V_5	V_6	V_1	V_2	V_3	V_4

Table1. The switching table for DTC basis

3. DTC BASED FUZZY LOGIC

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[8][9], 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.

Flux Linkage Errors

The errors of flux linkage is related value of stator's flux φ_s^* and real value of stator's φ_s^*, they are subject to equation

$$\Delta\varphi = \varphi_s^* - \varphi_s \quad (12)$$

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,[9][10].

Electromagnetic Torque Errors

Error of torque E_{te} is related to desired torque value T^*_e and real torque value T_e, they are subject to equation (13)

$$\Delta\Gamma = T^*_e - T_e \quad (13)$$

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, [9],[10] [14],

Angle of Flux Linkage θ_S

The angle of flux linkage θsis an angle between stator's flux φs and a reference axis is defined by equation (14):

$$\theta s = ar \tan \frac{\varphi_{\beta s}}{\varphi_{\alpha s}} \qquad (14)$$

in equation 3 $\varphi_{s\alpha}$ and $\varphi_{s\beta}$ 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 [9].

3.4. Voltage Vectors U_i

For the voltage vectors U_i(i=0-6), the membership distribution function of U_i is given by Fig.7.

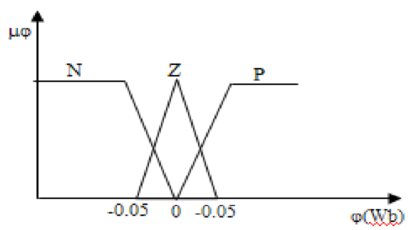

Figure 4. Membership functions for flux error

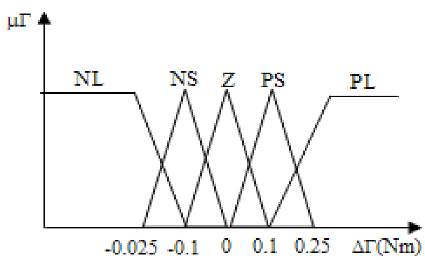

Figure 5. Membership functions for flux error

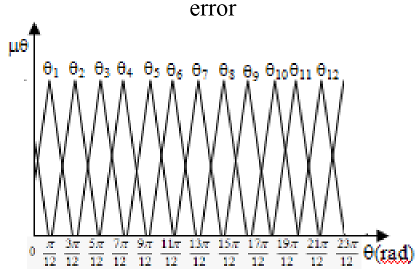

Figure 6. Membership functions for flux error

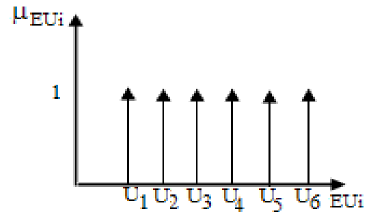

Figure 7. Membership functions for flux error

5.2. The Control Variable

Each control rule can be described using the state variablesΔφ, ΔΓ θs and U. The i^{th} rule R_i can be written as:

Ri : if Δφ, is Ai, ΔΓ is Bi and θs is Ci then n is Ni

The membership functions of variables A, B, C and N are given by μ_A, μ_B, μ_C and μ_N respectively. The weighting factor α_i for i^{th} rule can be written as [9][10][13].

$$\alpha_i = \min(\mu A_i(\Delta\varphi), \mu B_i(\Delta\Gamma), \mu C_i(\Delta\theta_s)) \quad (15)$$

By fuzzy reasoning, Mamdani's minimum procedure [9]
gives :
$\mu'_{Ni}(n) = \min(\alpha_i, (\Delta\Gamma), \mu_{Ni}(n))$ (16)

The membership function μN of the output n is point given by:

$$\mu_N(n) = \max_{i=1}^{180}(\alpha i, \mu'_{Ni}(n)) \qquad (17)$$

$$\mu_{Nout}(n) = \max_{i=1}^{7}(\mu_{Nout}(n)) \qquad (18)$$

According to the all rules and mamdani's organ, and all the variable membership function, a fuzzy control have 180 table can gain, as shown table2 [9], The fuzzy control table be queried in real time, deposited the table into memory of microcomputer.

4. DTC BASED NEURAL NETWORK

Principles of Artificial Neural Networks

Artificial neural networks use a dense interconnection of computing nodes to approximate nonlinear functions [19][20].Each node constitutes a neuron and performs the multiplication of its input signals by constant weights, sums up the results and maps the sum to a nonlinear activation function *g;* the result is then transferred to its output. **A** feed forward **ANN** is organized in layers: an input layer, one or more hidden layers and an output layer. A MLP consists of an input layer, several hidden layers, and an output layer [15]-[22]. Node *i*, also called a neuron, in a MLP network is shown in Fig.8. It includes a summer and a nonlinear activation function *g*.

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

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

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

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

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

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

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

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

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

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

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

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

Table 2. Fuzzy logic rules

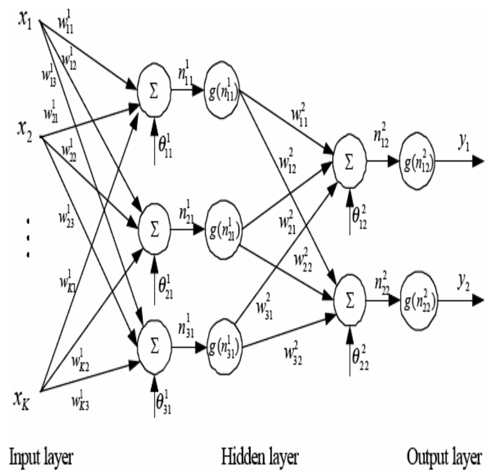

Fig 8. A multilayer perceptron network with one hidden layer.

The inputs x_k, $k = 1...K$ to the neuron are multiplied by weights w_{ki} and summed up together with the constant bias term θ*i*. The resulting *i n* is the input to the activation function *g*. The activation function was originally chosen to be a relay function, but for mathematical convenience a hyberbolic tangent (*tanh*) or a sigmoid function are most commonly used [15] [22].
The mathematical model of a neuron is given by (19):

$$y_i = g_i = g\left(\sum_{i=1}^{N} w_{j_i}.x_j + \theta_i\right) \quad (19)$$

4.2. Simulation Model and Structure of DTC System Based ANN

The **ANN** is trained by a learning algorithm which performs the adaptation of weights of the network iteratively until the error between target vectors and the output of the ANN is less than an error goal. The most popular learning algorithm for multilayer networks is the backpropagation algorithm and its variants [l9]. The latter is implemented by many ANN software packages such as the neural network toolbox from MATLAB [19] [20].

In the case presented in this paper the DTC control strategy shown on table I has been implemented. Neural network has been devised having as inputs the torque error, the stator flux error and the position of the stator flux, and as output the voltage space vector to be generate by the inverter [17]. The ANN block then replaces the switching table selector block of Fig.9.

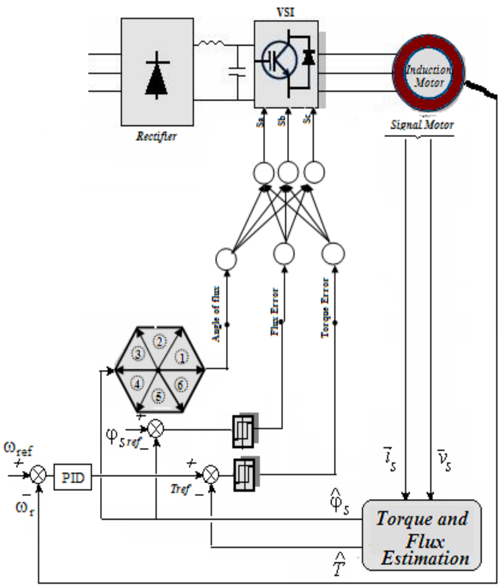

Fig 9. Basic direct torque control scheme based ANN

To create the block ANN switching table we passed by this program Matlab.

```
%P inputs
(E_TORQUE,E_FLUX,E_POSITION)
p=[0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1;0
0 0 0 0 0 1 1 1 1 1 1 0 0 0 0 0 0 1 1 1 1 1 1;1 2 3 4
5 6 1 2 3 4 5 6 1 2 3 4 5 6 1 2 3 4 5 6];
% vector output of state
Sa,Sb,Sc.
t=[0 1 0 1 0 1 0 0 0 1 1 1 1 0 1 0 1 0 1 0 0 0 1 1;0
1 0 1 0 1 1 1 0 0 0 1 1 0 1 0 1 0 1 1 1 0 0 0;0 1 0 1
0 1 0 1 1 1 0 0 1 0 1 0 1 0 0 0 1 1 1 0];
net10 = newff([0 1;0 1;1 6],[10 3],{'tansig'
'purelin'});
net10.trainParam.epochs = 1000;
net10.trainParam.goal=0;
net10 = train(net10,p,t);
Y = sim(net10,p); e=t-Y; plot(p,t,p,Y,'o')
```

The training ANN is given by Fig.10

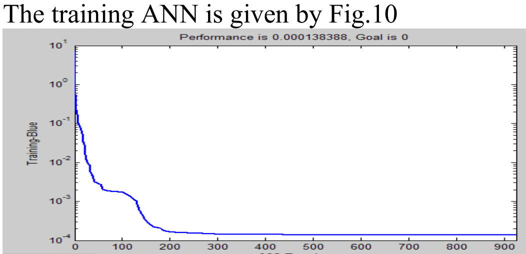

Fig 10. The training ANN

In Matlab command we generate the Simulink block ANN of switching table by **''gensim (net10)''** given this model show Fig11

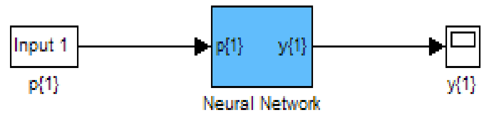

Fig 11. Simulink block for ANN switching table

The block neural network content two layer 1 and 2 show Fig.12

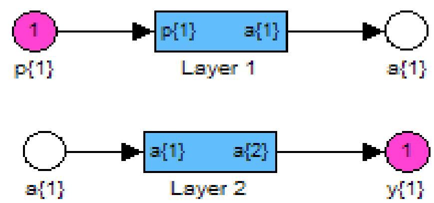

Fig 12. Block neural network

Where the Layer1 and Layer2 given by Fig.13

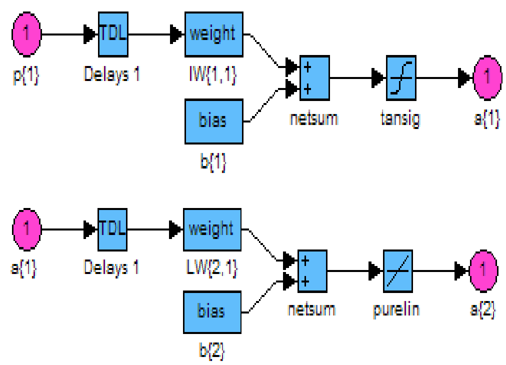

Fig 13. Block Layer1 and Layer2

6. INTERPRETATION RESULTS

To study the performance of the fuzzy logic and neural network 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 following parameters:

P_N = 3KW , Vn = 230V , f_N = 60Hz , Rs = 2.89Ω , Rr = 2.39Ω , P = 2 , $Ls = Lr$ = 0.225H , Lm = 0.214H , J = 0.005kgm2. 3KW.

The Sampling period of the system is 50μs. To compare with C_DTC, FLDTC and ANN_DTC for IM are simulated. In two cases, the dynamic responses of speed, flux, torque and stator current for the starting process with [5→7→3] Nm load torque applied and a constant command flux of 0.6Wbs are shown in Figure from 14to 17 respectively. Figs.14 (a, b and c) show the response of electric torque of the C_DTC, FL_DTC and ANN_DTC respectively. It can be seen that the ripple in torque with FL_DTC and ANN_DTC control is less than 0.3 Nm and with conventional direct torque control the ripple is about 2 Nm at the same operating conditions. Figs.15 (a, b and c) show the response of stator flux magnitude of the C_DTC, FLDTC and ANN_DTC respectively. By FLDTC and ANN_DTC technique shown Fig15 (b and c), the stator flux are 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 shown Fig15a. Fig16 (a, b and c), It can be noticed that stator flux vector describes a trajectory almost circular. Figs .17(b and c) show the steady state current response of the FLDTC and ANN_DTC has negligible ripple in stator current and a nearly sinusoidal wave form while **as** with conventional DTC the stator current has considerably very high ripple.

7. CONCLUSION

In this paper a FLDTC and ANN_DTC of induction machine have been proposed. An improved torque and flux response was achieved with the FLDTC and ANN_DTC than the conventional DTC. The performance has been tested by simulations. Also, a command flux optimization scheme has been proposed to reduce the torque ripple. The optimization was tested using simulation. The results show a reasonable improvement by flux optimization. The main improvements shown are:

• Reduction of torque and current ripples in transient and steady state response.

• No flux droppings caused by sector changes circular trajectory.

• Fast stator flux response in transient state.

8. SIMULATION RESULTS

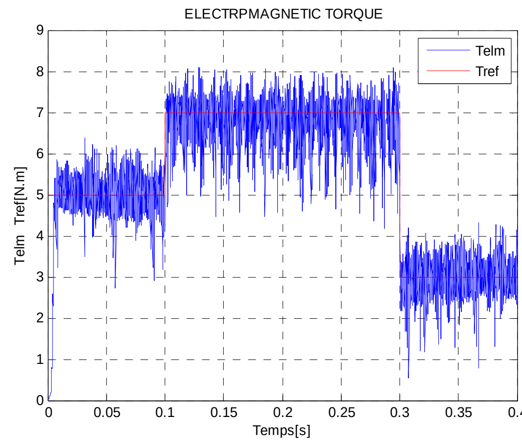

Fig.14a. Electromagnetic torque Response C DTC

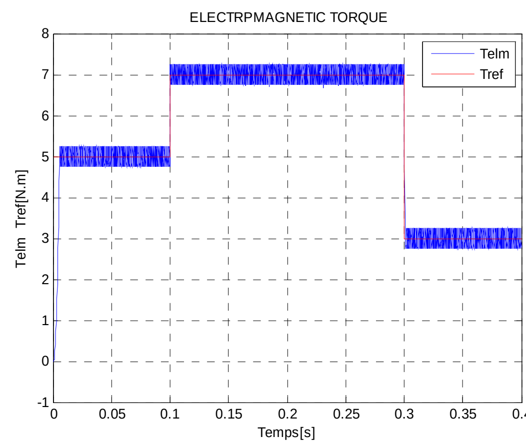

Fig.14b. Electromagnetic torque Response FL DTC

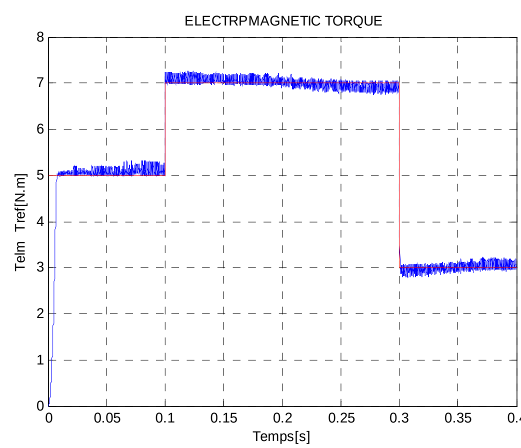

Fig.14c. Electromagnetic torque Response ANN DTC

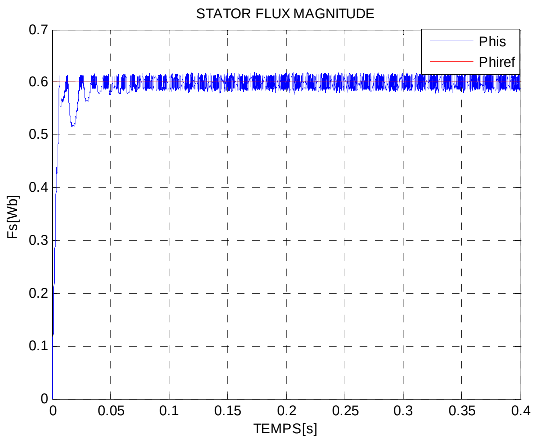

Fig.15a. The stator flux Magnitude C_DTC

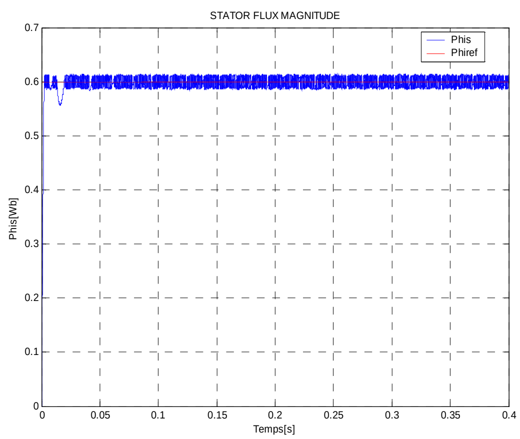

Fig.15b. The stator flux Magnitude FL DTC

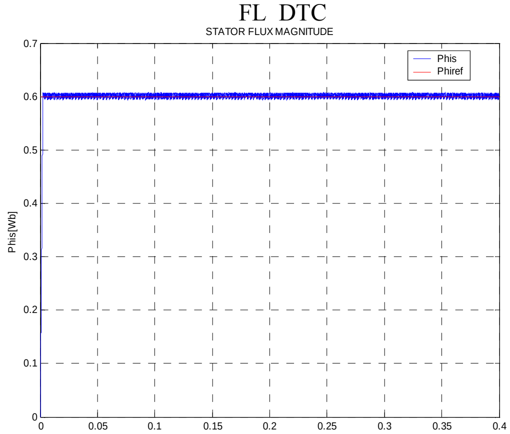

Fig.15c. the stator flux Magnitude ANN DTC

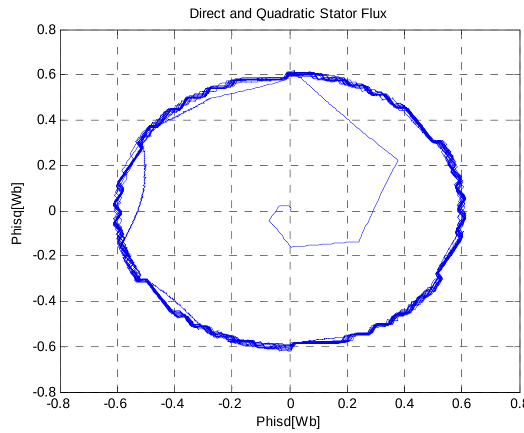

Fig.16a. Direct and quadratic stator flux C_DTC

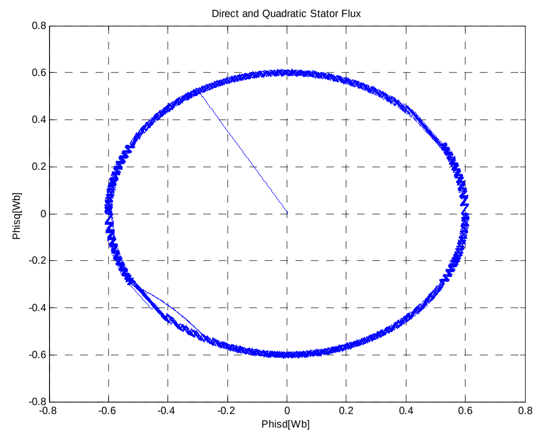

Fig.16b. Direct and quadratic stator flux FL DTC

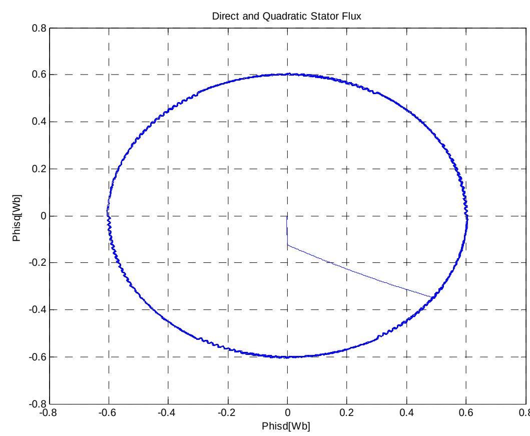

Fig.16c. Direct and quadratic stator flux ANN DTC

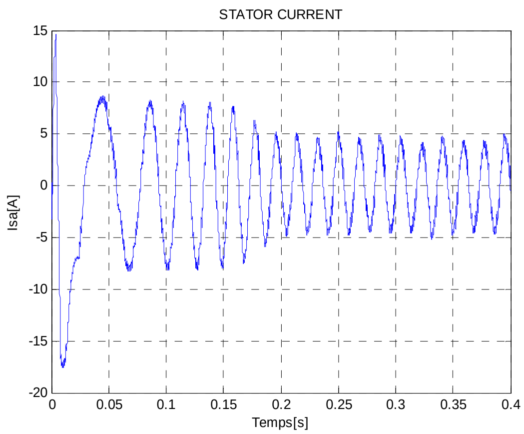

Fig.17a. the stator current C_DTC

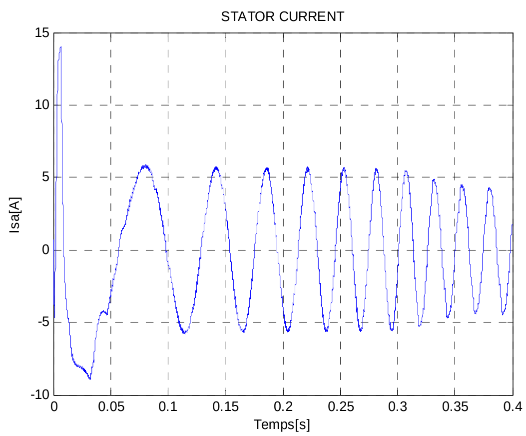

Fig.17b. the stator current FL_DTC

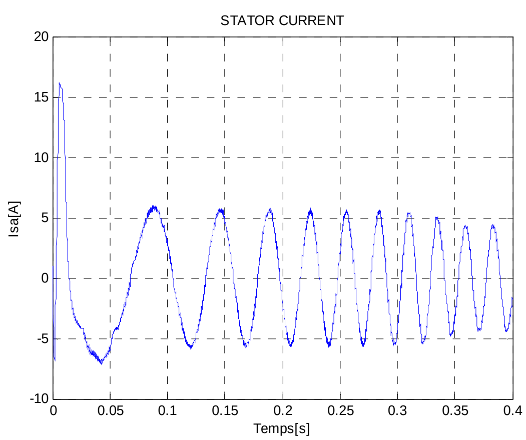

Fig.17c. the stator current ANN DTC

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