Direct Torque Neuro-Fuzzy Control of An Induction Motor

التحكم المباشر في عزم دوران المحرك الحثي باستخدام المنطق الفازي والشبكات العصبية

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الخلاصة: يعتبر التحكم المباشر في عزم المحركات التأثيرية باستخدام المنطق الفازي (FL-DTC) و التحكم المباشر في عزم المحركات التأثيرية باستخدام الشبكات العصبية (ANN-DTC) من الطرق التي أدت إلى تحسين استجابة ما يسمى بالتحكم المباشر في العزم والفيض مقارنة بالطريقة التقليدية(DTC) من هذا المنطلق نشأت محاولة اقتراح لتقديم خطة لدمج كلا من المنطق الفازي والشبكات العصبية (Neuro-Fuzzy) فيما يسمى التحكم المباشر في العزم باستخدام المنطق الفازي والشبكات العصبية (DTNFC) لجمع كلا من مزايا المنطق الفازي والشبكات العصبية . لذلك الغرض ، يهدف البحث للوصول إلى درجة عالية من الدقة والاستجابة في التحكم المباشر في العزم والفيض مقارنة بالطريقة التقليدية(DTC) .

ABSTRACT

In this article a direct torque of the induction motor drive controlled by Neuro-Fuzzy system. The proposed control scheme uses the stator flux amplitude and the electromagnetic torque errors through an adaptive Neuro_fuzzy inference system (ANFIS) to act on both the amplitude and the angle of the desired reference voltage. Simulation results by using ANFIS are compared with those of the conventional direct torque control (DTC). The comparison results of Direct torque Neuro-fuzzy controller (DTNFC), illustrate the reduction in the torque and stator flux ripples. The validity of the proposed method is confirmed by the simulative results.

Keywords: adaptive neuro-fuzzy inference system(ANFIS), direct torque control, induction motor, switching table, three phase inverter.

1.Introduction

Induction motors are today the most widely used ac machines due to the advantageous mix of cost, reliability, and performances. Induction motor characterized by complex, highly non-linear, time varying dynamics, inaccessibility of some states and output for measurements and hence can be considered as a challenging engineering problem[16]. The advent of torque and flux control techniques have partially solved induction motor control problems, because they are sensitive to drive parameters variations and performance may deteriorate if conventional controllers are used. Among many control methods of induction machines, one of the most important method is the Direct Torque Control (DTC)[17]. The DTC technique is intrinsically sensorless[3]. It can provide a very fast, accurate, reliable flux control and torque responses, and it is one of the most important three-phase induction motor control method[17]. The basic concept of direct torque control of induction motors is investigated in order to emphasize the effects produced by a given voltage vector on stator flux and torque variations. In DTC, the torque and stator flux are regulated to their command values by selecting the switching state which gives the proper changes in the torque and flux. There have been some DTC-based strategies, e.g. voltage-vector selection using switching table, direct self-control, and space-vector modulation [1],[2]. The voltage-vector selection strategy using a switching table is widely researched and commercialized, because it is very simple in concept and easy to be implemented. The proper voltage vector selection is based on the error in electromagnetic torque, error in stator flux and the position of the stator flux vector. In the conventional DTC scheme the system makes no difference between a very small and relatively large error of torque and/or flux. The switching states chosen for the large error that occurs during the startup or during a step change in torque command or even flux command are the same that have been chosen for the fine control during normal operation. This may cause a lightly slower response during the start-up and during a step change in electric torque or stator flux. This was the reason of attempting to propose a new approach for direct torque control (DTC) based on "the system response can be improved using different error levels when both the ranges of torque and flux error are considered"[3].

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2. Modeling of Induction motor

The dynamic behavior of an induction motor is complex due to the coupling effect between the stator and rotor phases. Fig .1.outlines the dynamic d-q equivalent circuits of an induction machine[18].

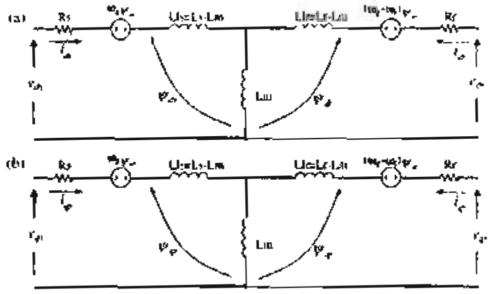

Fig. 1. Dynamic d-q equivalent circuits of an induction machine (a) d-axis circuit, (b) q-axis circuit.

The electrical transient model in terms of voltages and currents can be given in matrix form as:

$$\begin{bmatrix} v_{sd} \\ v_{sq} \\ v_{rd} \\ v_{rq} \end{bmatrix} = \begin{bmatrix} R_s+sL_s & 0 & sL_m & 0 \\ 0 & R_s+sL_s & 0 & sL_m \\ sL_m & \omega_r L_m & R_r+sL_r & \omega_r L_r \\ -\omega_r L_m & sL_m & -\omega_r L_r & R_r+sL_r \end{bmatrix} \begin{bmatrix} i_{sd} \\ i_{sq} \\ i_{rd} \\ i_{rq} \end{bmatrix} \quad (1)$$

's' represents the Laplace operator, *d /dt*. The mathematical model of the induction motor can also be rearranged with the stator and rotor currents set as the state variables.

$$\begin{bmatrix} \dot{i}_{sd} \\ \dot{i}_{sq} \\ \dot{i}_{rd} \\ \dot{i}_{rq} \end{bmatrix} = \frac{1}{L_m^2 - L_s L_r} \left(\begin{bmatrix} R_s L_r & -\omega_r L_m^2 & -R_r L_m & -\omega_r L_m L_r \\ \omega_r L_m^2 & R_s L_r & \omega_r L_m L_r & -R_r L_m \\ -R_s L_m & \omega_r L_m L_s & R_r L_s & \omega_r L_r L_s \\ -\omega_r L_m L_s & -R_s L_m & -\omega_r L_r L_s & R_r L_s \end{bmatrix} \begin{bmatrix} i_{sd} \\ i_{sq} \\ i_{rd} \\ i_{rq} \end{bmatrix} + \begin{bmatrix} -L_r & 0 \\ 0 & -L_r \\ L_m & 0 \\ 0 & L_m \end{bmatrix} \begin{bmatrix} V_{sd} \\ V_{sq} \end{bmatrix} \right) \quad (2)$$

The speed *ωr* in the above equations is related to the torque by the following mechanical dynamic equation,

$$T_e = T_{load} + J\frac{d\omega_m}{dt} = T_{load} + J\frac{2}{p}\frac{d\omega_r}{dt} \quad (3)$$

Where *J* = combined rotor and load inertia, and *ωm* = mechanical speed. The torque equation in stationary reference frame can be written as:

$$T_e = \frac{3}{2}\frac{p}{2}\overline{\Psi}_s \times \bar{i}_s \quad (4)$$

In terms of stator and rotor currents, the torque can be written as:

$$T_e = \frac{3}{2}\frac{p}{2}Lm\left(i_{rd}i_{sq} - i_{rq}i_{sd}\right) \quad (5)$$

3. DTC principles

The DTC scheme is given in Fig. 2, the flux error εφ and torque error εT signals are delivered to two hysteresis comparators. The two level hysteresis comparator will produce flux error status, which can be either 1 or 0, when the estimated flux touches the lower band the flux error status is 1, which indicates that the actual flux needs to be increased and the appropriate voltage vector should be selected. The Three-level hysteresis will produce torque error status, which can be either 1 or 0 or -1 ,when the torque increases and reaches the upper band, it is better to decrease the torque as slowly as possible to reduce the inverter(VSI) switching frequency. The corresponding digitized output variables: change of magnetic flux Δφ , of mechanical torque Δ T and the stator flux angle Θ_φ created a digital word, which selects the appropriate voltage vector from the switching table[18]. The switching table generates pulses C1 , C2 , C3 , to control the power switches in the inverter. Three-level torque and two level flux hysteresis controllers are used according to the outputs of the torque controller and the sector information (Sφ) of the stator flux φs , appropriate voltage vectors for both the inverters are selected from a switching table as it is shown in Tab.1 [4]

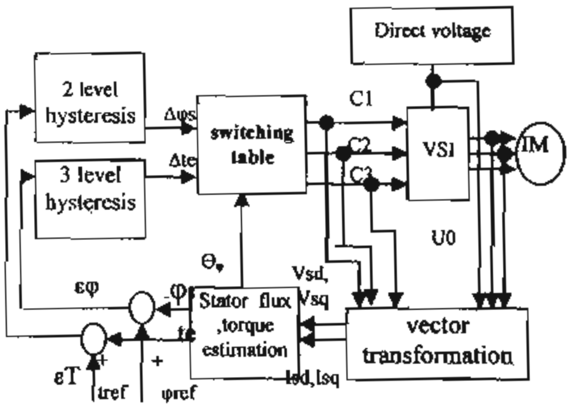

Fig. 2. Block diagram of the induction motor drive system based on DTC scheme

Where Is_{abc}: the three phase stator current.
V_{abc}: the three phase voltage.
V_{sd},V_{sq} : stator voltage components on perpendicular (d,q) axis.
I_{sd},I_{sq}: stator current components on perpendicular (d,q) axis.
U0: Direct voltage

3.1 Three phases voltage inverter

In a voltage fed three phases voltage inverter as shown by fig. 3, the switching commands of each inverter leg are complementary. So for each leg a logic state Ci (i=1,2,3) can be defined. Ci is 1 if the upper switch is commanded to be closed and 0 if the lower one is commanded to be close.

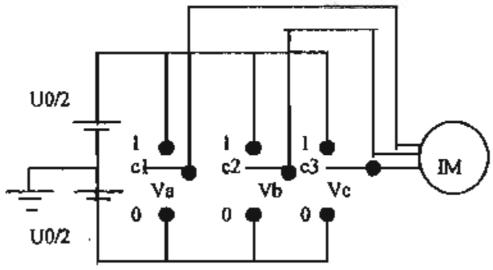

Fig. 3. Three phase voltage inverter

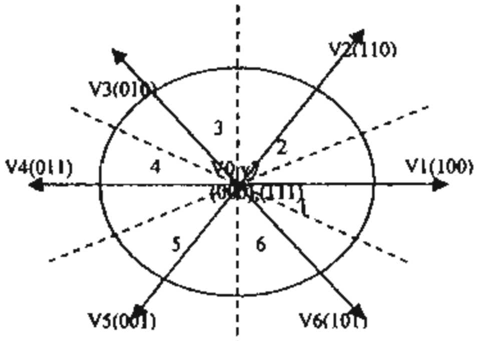

Fig. 4 Partition of the d, q plane into six sectors

Since there are 3 independent legs there will be eight different states, so 8 different voltages.

Applying the vector transformation described as:

$$Vs = \sqrt{\frac{2}{3}}U_0\left[C_1 + C_2 e^{j\frac{2\Pi}{3}} + C_3 e^{j\frac{4\Pi}{3}}\right] \quad (6)$$

As it can be seen in fig 4, there are six nonzero voltage vectors and two zero voltage vectors which correspond to (C1, C2, C3)= (111)/ (000) as shown by Fig.3 [5],[6].

3.2 Stator flux control

Stator voltage components (V_{sd}, V_{sq}) on perpendicular (d,q) axis are determined from measured values (U_0 and I_{sabc}). Boolean switching controls (C_1, C_2, C_3,) by, [7],[5]:

$$V_{sd} = \sqrt{\frac{2}{3}}U_0\left[C_1 - \frac{1}{2}(C_2 + C_3)\right] \quad (7)$$

$$V_{sq} = \frac{1}{\sqrt{2}}U_0(C_2 - C_3) \quad (8)$$

And stator current components (I_{sd}, I_{sq}):

$$I_{sd} = \sqrt{\frac{2}{3}}I_{sa} \quad (9)$$

$$I_{sq} = \frac{1}{\sqrt{2}}(I_{sb} - I_{sc}) \quad (10)$$

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 during one period Te. The stator flux is estimated by integrating the difference between the input voltage and the voltage drop across the stator resistance as given by equation (11):

$$\bar{\phi}s = \int_0^t (\bar{v}s - Rs\bar{I}s)dt \quad (11)$$

To select the voltage vectors for controlling the amplitude of the stator flux linkage, the voltage vector plane is divided into six regions, as shown in Fig.4. In each region, two adjacent voltage vectors, which give the minimum switching frequency, are selected to increase or decrease the amplitude of stator flux, respectively. For instance, the vectors V4 and V3 are selected to increase or decrease the amplitude of stator flux when it is in region number 1, as shown in Fig.4. In this way, amplitude of stator flux can be controlled at the required value by selecting the proper voltage vectors. Voltage vectors are selected for keeping the magnitude stator flux and electromagnetic torque within a hysteresis band [8].

3.3 Stator flux and torque estimation

The magnitude of stator flux, which can be estimated by (12),(13):

$$\bar{\phi}_{sd} = \int_0^t (\bar{v}_{sd} - Rs\bar{I}_{sd})dt \quad (12)$$

$$\bar{\phi}_{sq} = \int_0^t (\bar{v}_{sq} - Rs\bar{I}_{sq})dt \quad (13)$$

The stator flux linkage phasor is given by:

$$\phi s = \sqrt{\phi_{sd}^{\ 2} + \phi_{sq}^{\ 2}} \quad (14)$$

By comparing the sign of the components stator flux (φ_{sd} φ_{sq}) and the amplitude of stator flux, we can localize the zone where we find the flux. Electromagnetic torque calculation uses flux components (12),(13),

current components (9),(10) and *P*, which is the pair pole number of the induction machine [6][9]:

$$T_{em} = P\left(\phi_{sd} I_{sq} - \phi_{sq} I_{sd}\right) \quad (15)$$

As shown in Fig.4, eight switching combinations can be selected in a voltage source inverter, two of which determine zero voltage vectors and the others generate six equally spaced voltage vectors having the same amplitude. According to the principle of operation of DTC, the selection of a voltage vector is made to maintain the torque and stator flux within the limits of two hysteresis bands. The switching selection table for stator flux vector lying in the first sector of the d-q plane is given in Tab.1[7],[5].

sector		1	2	3	4	5	6
flux	torque						
Δφ=1	ΔT=1	V2	V3	V4	V5	V6	V1
	ΔT=0	V7	V0	V7	V0	V7	V0
	ΔT=-1	V6	V1	V2	V3	V4	V5
Δφ=0	ΔT=1	V3	V4	V5	V6	V1	V2
	ΔT=0	V0	V7	V0	V7	V0	V7
	ΔT=-1	V5	V6	V1	V2	V3	V4

Tab.1 : Optimum switching table

4. Direct torque Neuro-Fuzzy controller

4.1. Principles of ANFIS

Neuro_fuzzy network system combine the advantageous of neural network and fuzzy logic system. Neural network provides connectionist structure and learning abilities to the fuzzy logic systems, and the fuzzy logic systems provide neural networks with a structural framework with high-level fuzzy IF-THEN rule of thinking and reasoning. Neural network-based fuzzy systems, NF have the learning ability of neural networks to realize the fuzzy logic inference system, are gained popularity in the control of nonlinear systems[10]. The adaptive NF inference system (ANFIS) is one of the proposed methods to combine Fuzzy logic and artificial neural networks. Fig.5 shows the adaptive NF inference system structure. It is composed of five functional blocks (rule base, database, a decision making unit, a fuzzyfication interface and a defuzzyfication interface) which are generated using five network layers:

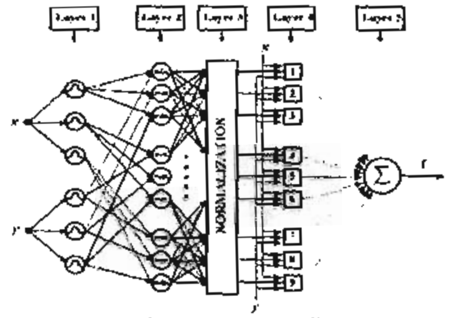

Fig. 5 Two-input NF controller structure.

Layer 1: This layer is composed of a number of computing nodes whose activation functions are fuzzy logic membership functions (triangular functions).

Layer 2: This layer chooses the minimum value of the inputs.

Layer 3: This layer normalizes each input with respect to the others (The *ith* node output is the *ith* input divided by the sum of all the other inputs).

Layer 4: This layer's *ith* node output is a linear function of the third layer's *ith* node output and the ANFIS input signals.

Layer 5: This layer sums all the incoming signals. The ANFIS structure can be tuned automatically by a least-square estimation (for output membership functions) and a back propagation algorithm (for output and input membership functions)[11].

4.2 Structure of DTC System Based ANFIS

The proposed ANFIS logic controllers have three variable input , the stator flux error εφ, electromagnetic torque error εT, and angle of flux stator θφ , the output is the voltage space vector . The block scheme of the proposed self-tuned direct torque neuro-fuzzy controller (DTNFC) for a voltage source inverter fed induction motor is presented in Fig. 6. The internal structure of the NFC is shown in Fig. 7.

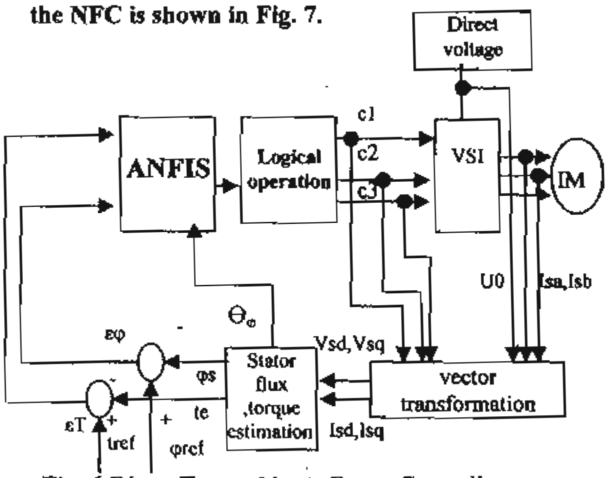

Fig. 6 Direct Torque Neuro Fuzzy Controller scheme.

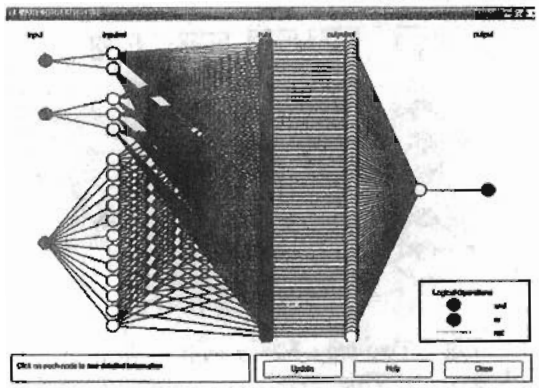

Fig. 7 Proposed Neuro Fuzzy Controller Structure.

In the first layer of the NF structure, sampled flux error εφ ,torque error εT and flux angle Θ_φ, multiplied by respective weights , are each mapped through three fuzzy logic membership functions. These functions are chosen to be triangular shaped for all the inputs flux error εφ ,torque error εT and flux angle Θ_φ where it is given a good outputs compared the others membership functions as shown in Fig. 8(a,b,c). For more accuracy, the universe of discourse of the stator flux vector position (Θs) is divided into twelve fuzzy sets denoted ($\Theta 1$) to ($\Theta 12$), as shown in fig 8(c).

The second layer calculates the minimum error value of three input weights by determines the firing strengths of the rules and given as:

$$\mu_i = \min(\mu^{j}_{A1}(\varepsilon\varphi), \mu^{j}_{A2}(\varepsilon T), \mu^{j}_{A3}(\theta\varphi)) \qquad (16)$$

The third layer calculates the weight which is normalized. Normalized value of the firing strengths is defined as the ratio of firing strength of the k_{th} rule to the sum of the firing strengths.

$$\overline{\mu_i} = \frac{\mu_i}{\sum \mu i} \qquad (17)$$

The fourth layer containing adaptive nodes is the defuzzyfication layer. The output from this layer is: $\overline{\mu_k}\,(p_i x + q_i y + m_i z + r_i)$, where p_i, q_i, m_i and r_i are the consequent parameters of the node. The inputs($x = \varepsilon\varphi$, $y = \varepsilon T$, $z = \Theta_\varphi$) and output$O_{4,i}$ relationship in this layer can be defined as:

$$O_4 = \overline{\mu_i} f_i = \overline{\mu_i}(p_i x + q_i y + m_i z + r_i) \qquad (18)$$

where i is the 4th layer output.

For a zero-order Sugeno model, the output level O is a constant ($p=q=m=0$)so the relationship between inputs and output is:

$$O_4 = \overline{\mu_i} f_i = \overline{\mu_i}(r_i) \qquad (19)$$

The fifth layer consists of a single fixed node, it is the summation of the weighted output of the consequent parameters in layer 4. The output layer is given by[15]:

$$O_{5,i} = \sum_i \overline{\mu_i} f_i = \frac{\sum_i \mu_i f_i}{\sum_i \mu_i} \qquad (20)$$

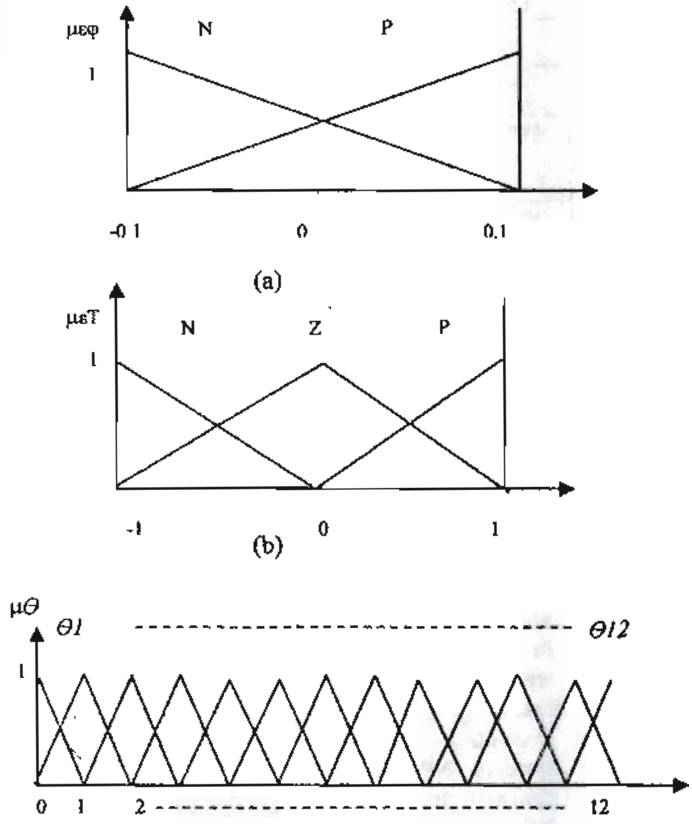

Fig. 8 (a) Membership functions for flux error signal.
(b) Membership functions for torque error signal.
(c) Membership function for stator flux angle.

According to zero-order Sugeno method and all the variable membership function, a neuro- fuzzy controller have72 rules, where these rules used to give appropriate output. The output of the ANFIS are crisp value

varies from V0 toV7, to generate three digital logic signals, that select the proper switching states of the inverter by using logical operation depending on Tab. 2 The switching state is the input to the inverter, where '1' represents the upper limb switches and '0' represents the lower limb switches of the inverter. Switching states of the inverter varies from V0 to V7.

states	S1	S2	S3
V0	0	0	0
V1	1	0	0
V2	1	1	0
V3	0	1	0
V4	0	1	1
V5	0	0	1
V6	1	0	1
V7	1	1	1

Tab.2: Switching States of Voltage Vectors.

5.Simulation Results of Direct torque Neuro-Fuzzy controller

The Induction motor can be modeled with stator flux and rotor flux as given in [12]-[13]. 149.2e3VA induction motor was used for simulation. The parameters of the motor were determined experimentally and are given in the Appendix. For the simulation of the viable torque control schemes, Voltage source inverter (VSI) was employed. The simulations were carried out using MATLAB2008 / SIMULINK technical. In MATLAB2008, the ANFIS editor graphics user interface is available in Fuzzy Logic Toolbox [14]. Using a given input/output data set, the toolbox constructs a fuzzy inference system (FIS) whose membership function parameters are adjusted using either a backpropagation algorithm alone, or in a combination with a least squares type of method. We used A hybrid method which employs for updating membership function parameters which consisting of backpropagation for the parameters associated with the input membership functions, and least squares estimation for the parameters associated with the output membership functions[15]. This allows the fuzzy systems to learn from the data they are modeling[14]. As shown in Fig.10 and fig.12 Using ANFIS control provides the system with minimum ripple for both torque and flux, where the torque ripple percentage is 3.5% and the flux ripple percentage is 2.1%. While the conventional DTC have a relatively large ripple as shown in fig.9 and fig.11 , where the torque ripple percentage was 13.3% and the flux ripple percentage was 3.75%.Finally, the simulation results show an improvement with ANFIS controller over the conventional DTC in both flux and torque responses. Tab. 3 represents the comparison results in both flux and torque error percentage For DTC and DTNFC. The steady state response for both controllers was found to be relatively the same.

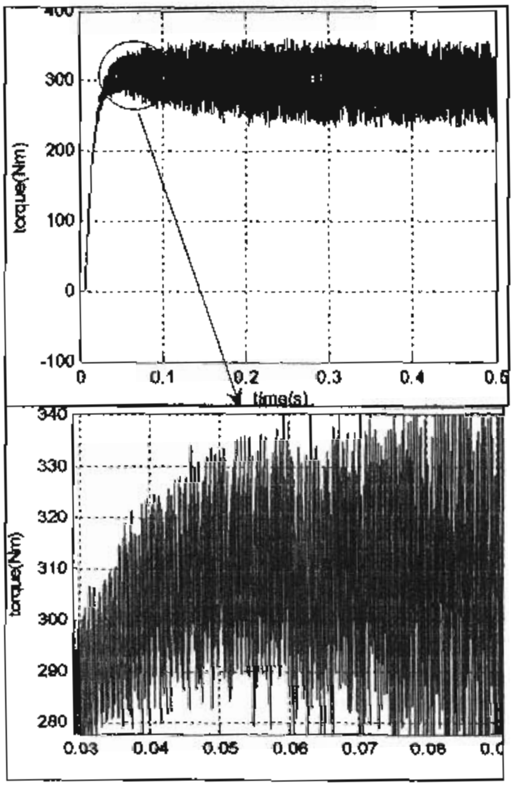

Fig. 9 – Torque developed in conventional DTC.

The neuro-fuzzy logic output for both the electromagnetic torque ripples varies between 300 Nm and 320Nm with 300 Nm steady state value and stator flux ripple varies between 0.82 Wb and 0.79 Wb with 0.8 Wb steady state value . That means that the direct torque neuro-fuzzy controller (DTNFC) Provides more accuracy than classical DTC. Where neuro-Fuzzy systems combine the advantageous of neural networks and fuzzy logic systems. Neural network-based fuzzy systems, which have the learning ability of neural networks to realize the fuzzy logic inference system, are gained popularity in the control of nonlinear systems. Fuzzy logic systems provide the neural networks with structural framework with high-level fuzzy IF–THEN rule thinking and reasoning.

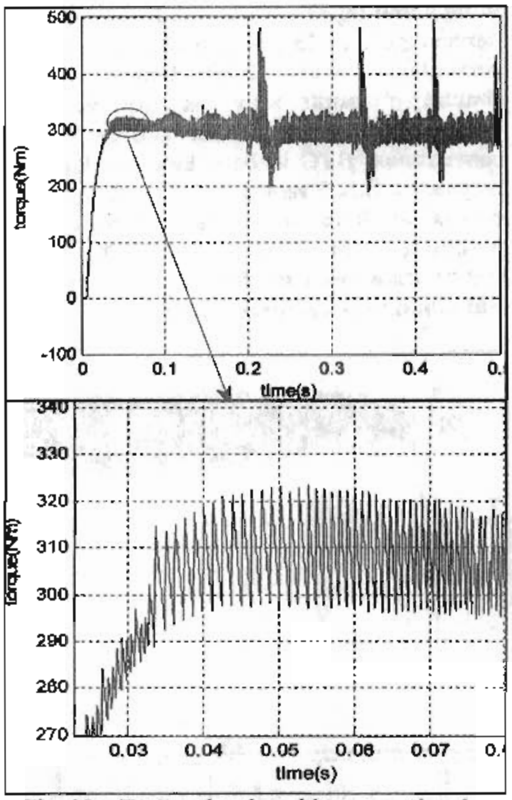

Fig. 10 – Torque developed in conventional DTNFC

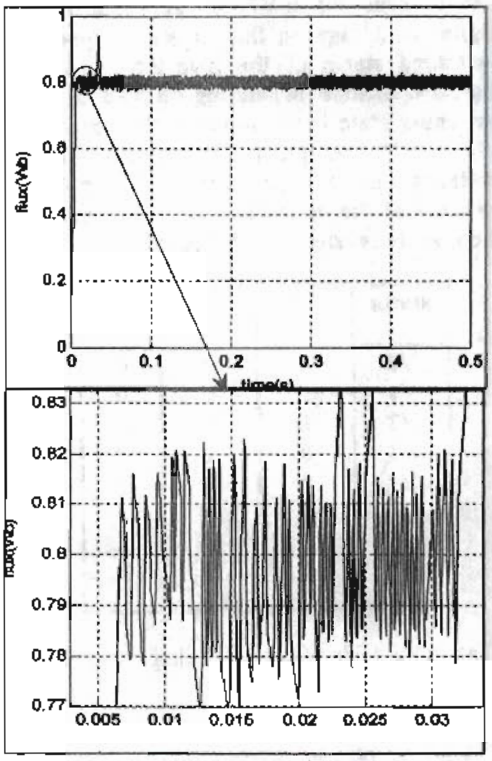

Fig. 11 Stator flux response in conventional DTC

6. Conclusion

In this paper DTNFC of induction machine has been proposed. An improved torque and flux response were achieved with the DTNFC 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 ripple in transient and steady state response as shown in tab.3 .**
- **Reduction of flux ripple in transient and steady state response as shown in tab.3.**
- **Fast stator flux response in transient state.**

SL NO.	CONTROL STRATEGIES	FLUX RIPPLE PERCENTAGE	TORQUE RIPPLE PERCENTAGE
1	Conventional DTC	3.75%	13.3%
2	DTNFC	2.3%	3.5%

Tab. 3:the percentage flux and torque error for DTC and DTNFC.

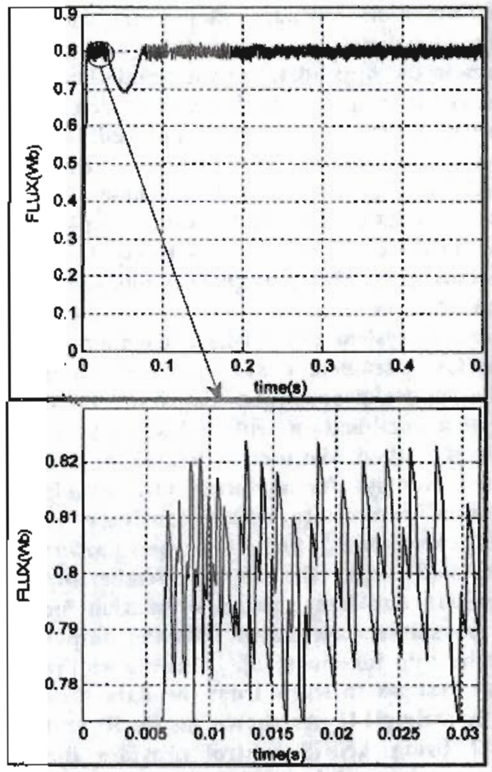

Fig. 12 Stator flux response in conventional DTNFC

7.Apendix

No	Definition	Symbols	Data/unit
1	Rated output	P_N	149.2e3(VA)
2	Rated Voltage	U_n	460(rms)V
3	Rated Frequency	f_N	60Hz
4	Moment of inertia	J	0.005kgm2.
5	Stator Resistance	R_s	14.85e-3Ω
6	Rotor Resistance	R_r	9.295e-3Ω
7	Stator inductance	L_s	0.3027e-3H
8	Rotor inductance	L_r	0.3027e-3H
9	Mutual inductance	L_m	10.46e-3H
10	Number of Poles	P	2

Tab. 4 Parameters of the selected Induction Motor

8. References

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