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Fayez Areed
Professor of Computer & Systems Department., Faculty of Engineering., El-Mansoura University, Mansoura., Egypt.

Amira Haikal
Assistant Professor., Computer & Systems Department., Faculty of Engineering., El-Mansoura University., Mansoura., Egypt, amirayh@gmail.com

Reham Mohammed
Instructor., Computer & Systems Department., Faculty of Engineering., El-Mansoura University., Mansoura., Egypt.

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Comparative Analysis Methods of Direct Torque Control for Induction Motor

مقارنة تحليلية لطرق التحكم المباشر في عزم دوران المحرك التأثيري

Fayez G. Areed[1], Amira Y. Haikal[2], Reham H. Mohammed[3]

[1]Prof.Dr.Faculty of Engineering, Mansoura University, Computer& Systems Dept.

[2]Dr. Faculty of Engineering, Mansoura University, Computer& Systems Dept.

[3]Assistant research in Faculty of Engineering Mansoura University , Computer& Systems Dept.

الخلاصة:تعتبر المحركات التأثيرية وبخاصة القفص السنجابي هي الأوسع انتشارا في التطبيقات الصناعية. وتم تحسين أداء هذا النوع من المحركات التأثيرية عن طريق استخدام التحكم المباشر في عزم دوران المحرك التأثيري ونظرا لأن الطريقة التقليدية لهذا النوع من التحكم لا تأخذ في اعتبارها الإشارة الدالة على الفرق بين العزم المطلوب والمقاس أو المجال المطلوب والمقاس إذا كانت صغيرة نسبيا أو كبيرة بعض الشيء ، مما أدى إلى بطء في استجابة النظام خاصة في لحظة بدء التشغيل أو أثناء مراحل التغيير في مستوى العزم المطلوب أو المجال. من هذا المنطلق نشأت محاولة اقتراح لتقديم خطة جديدة لتحسين استجابة ما يسمى بالتحكم المباشر في العزم وذلك بإستخدام المنطق الغيمى والشبكات العصبية. وبمقارنة الخرج لكلا الطريقتين مع الطريقة التقليدية نلاحظ تحقيق التحكم المباشر في العزم والفيض بإستخدام كلا من الطريقتين المقترحتين بإستخدام المنطق الغيمى والشبكات العصبية عن التحكم بالطريقة التقليدية.

ABSTRACT

In this article we propose two approaches to improve the direct torque control (DTC) of an nduction motor (IM) such as fuzzy logic (FL) and artificial neural network (ANN), applied in witching select voltage vector . Simulation results of two approaches compared with those of onventional direct torque control (DTC). The comparison results of the (FL_DTC) and (ANN DTC) illustrate the reduction in the torque and stator flux ripples. The validity of the proposed ethods is confirmed by the simulative results. The two approaches are explained in clear details which are designed using SIMULINK under Matlab Ver.7.7 software package. Also, MATLAB2008/FUZZY toolbox is used to implement the fuzzy logic controller. Both systems are imulated under the same conditions.

Keywords: artificial neural network (ANN), direct torque control, Fuzzy logic, induction motor, witching 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 performance. The IM suffer from 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[20]. 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 methods is the Direct Torque Control (DTC). 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 [21]. 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.

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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].

2. DTC principles

The DTC scheme is given in Fig. 1, 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 , 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[22]. 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]

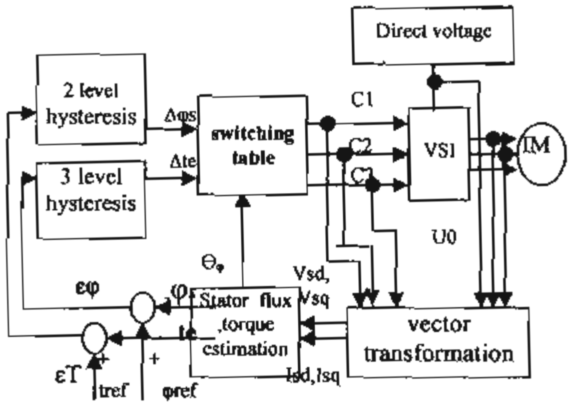


Fig. 1. Block diagram of the induction motor drive system based on DTC scheme

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

2.1 Three phases voltage inverter

In a voltage fed three phases voltage inverter as shown by fig. 2, 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.

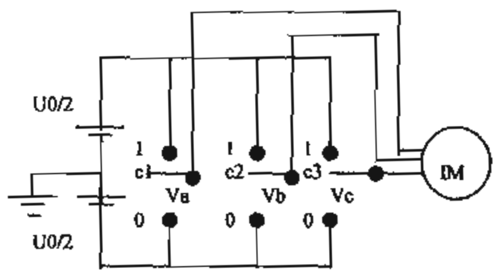


Fig. 2 Three phase voltage inverter

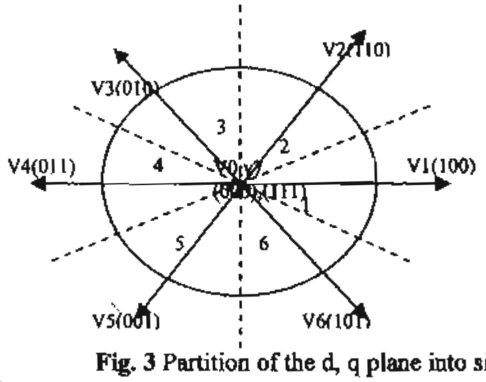


Fig. 3 Partition of the d, q plane into six sectors

Since there are 3 independent legs there will be eight different states, so 8 different voltages.
Applying the vector transformation described as:

$$Vs=\sqrt{\frac{2}{3}}U_0\left[C_1+C_2e^{j\frac{2\Pi}{3}}+C_3e^{j\frac{4\Pi}{3}}\right] \quad (1)$$

As it can be seen in fig 3, 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].

2.2 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]:

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

$$V_{sq} = \frac{1}{\sqrt{2}} U_0 (C_2 - C_3) \quad (3)$$

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

$$I_{sd} = \sqrt{\frac{2}{3}} I_{sa} \quad (4)$$

$$I_{sq} = \frac{1}{\sqrt{2}} (I_{sb} - I_{sc}) \quad (5)$$

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 (6):

$$\bar{\phi} s = \int_0^t (\bar{v} s - Rs \bar{I} s) dt \quad (6)$$

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.3. 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.3. 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].

2.3 Stator flux and torque estimation

The magnitude of stator flux, which can be estimated by (7, 8):

$$\bar{\phi}_{sd} = \int_0^t (\bar{v}_{sd} - Rs \bar{I}_{sd}) dt \quad (7)$$

$$\bar{\phi}_{sq} = \int_0^t (\bar{v}_{sq} - Rs \bar{I}_{sq}) dt \quad (8)$$

The stator flux linkage phasor is given by:

$$\phi s = \sqrt{\phi_{sd}^{\ 2} + \phi_{sq}^{\ 2}} \quad (9)$$

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 (7),(8), current components (4),(5) and *P*, which is the pair pole number of the induction machine [6],[9]:

$$T_{em} = P(\phi_{sd} I_{sq} - \phi_{sq} I_{sd}) \quad (10)$$

As shown in Fig.3, 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

3. Neural direct torque control

3.1. Principles of Artificial Neural Networks

Artificial neural networks use a dense interconnection of computing nodes to

approximate nonlinear functions [10], [11]. 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 multilayer layer perceptron (A MLP) consists of an input layer, several hidden layers, and an output layer [12],[13]. Node *l*, also called a neuron, in a MLP network is shown in Fig.4. It includes a summer and a nonlinear activation function *g*.

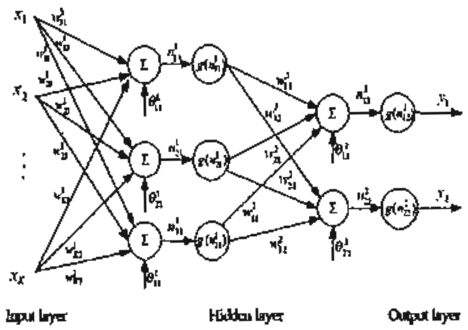


Fig 4. A multilayer perceptron network with one hidden layer.

The inputs *xk*, *k* = 1...*K* to the neuron are multiplied by weights w_{kl} and summed up together with the constant bias term θ*l*. The resulting *n* $_l$ is the input to the activation function *g*. The activation function was originally chosen to be a relay function, but for mathematical convenience a hyperbolic tangent (*tanh*) or a sigmoid function are most commonly used [12]. The mathematical model of a neuron is given by(11) :

$$y_l = g_l = g\left(\sum_{l=1}^{N} w_{jl} x_j + \theta_l\right) \qquad (11)$$

3.2. Structure of DTC System Based ANN

The algorithm used to train the neural network is the back propagation with momentum factor. The proposed neural network controller was designed to have three inputs nodes , ten neurons in the hidden layer and one neuron in the output layer as shown in fig.5.

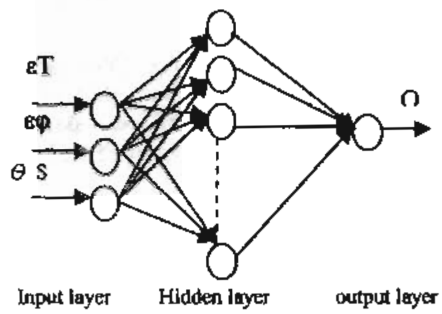


Fig. 5 Structure of Neural network proposed for DTC scheme.

Where εT is the motor torque error, εφ is the stator flux error signal, and θS is the stator flux vector position. The output O is crisp by using relational operators, as shown in figure (6), to generate three digital logic signals that select the proper switching states of the inverter [8].

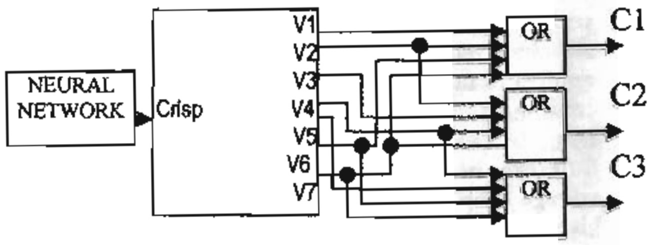


Fig.6 MATLAB/SIMULINK block diagram used to convert the crisp fuzzy output to three digital signals.

4. Fuzzy direct torque control

4.1. Principles of fuzzy logic

Fuzzy logic foundation by Zadeh in 1965. It has been set of important investigations. It is a mathematical tool for dealing with uncertainty and also it provides a technique to deal with imprecision and information granularity .Fuzzy logic offers a particularly convenient way to generate a keen mapping between input and output spaces thanks to fuzzy rules' natural expression. There are some modules: first stage transformed the classification tables into a major continuous classification, this process is called Fuzzification .These are then processed in fuzzy domain by inference engine based on knowledge base (rule base and data base) supplied by domain experts. Finally the process of translating back fuzzy numbers into single "real world" values is named Defuzzification [14].

4.2. Structure of DTC System Based fuzzy logic

The principle of direct torque control using fuzzy logic (FL_DTC). The fuzzy controller is designed to have three fuzzy state Variables and one control variable for achieving direct torque Control of the induction machine[14],[15]. There are three variable input fuzzy logic controllers, the electromagnetic torque error" εT ", stator flux error " εφ ", and angle of flux stator "θ s " respectively the output it is the voltage space vector[14]. The first variable " εT ", which is the motor torque error signal, defined as the difference between desired torque value Tref and real torque value Te, they are subject to equation (12):

$$\varepsilon T = T_{ref} - T_e \quad (12)$$

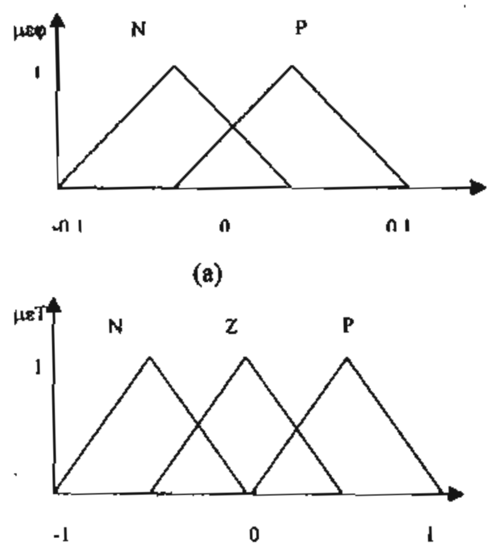
The second variable " εφ ", which is the stator flux error signal, defined as the difference between stator's flux φref and real value of stator's φs, they are subject to equation (13):

$$\varepsilon\phi = \phi_{ref} - \phi_s \quad (13)$$

The third fuzzy state variable is the stator flux vector position (θ s), defined as the angle between stator's flux φs and a reference axis is defined by equation(14):

$$\theta_s = \tan^{-1}\left(\frac{\phi_{sq}}{\phi_{sd}}\right) \quad (14)$$

In equation (14) φ_{sd} and φ_{sq} are the component of flux linkage φs in the plan (d,q). Then, the three input variables are divided into their fuzzy segments, where the number of fuzzy segments is chosen to have maximum control with a minimum number of rules. The universe of discourse of the stator flux error is divided into two linguistic variables with triangular membership functions, where N and P denotes for negative and positive value of stator flux error, respectively, as shown in fig. (7-a). The universe of discourse of the motor torque error is divided into three linguistic variables with triangular membership functions, where N ,Z and P denotes for negative ,Zero and positive value of motor torque error, respectively, as shown in fig. (7-b).



(b)

Fig.7 (a) Membership functions for flux error signal
(b) Membership functions for torque error signal

For more accuracy, the universe of discourse of the stator flux vector position (θs) is divided into twelve fuzzy sets denoted (θ1) to (θ12), as shown in fig.8.

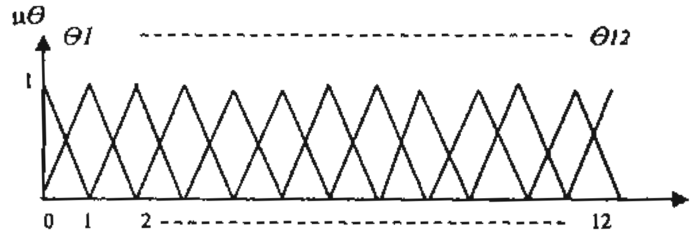


Fig. 8 Membership function for stator flux position

From the rules, the controller has been designed using sugeno inference method, it is similar to the Mamdani method in many respects. The first two parts of the fuzzy inference process[16], fuzzifying the inputs and applying the fuzzy operator, are exactly the same. The main difference between Mamdani and Sugeno is that the Sugeno output membership functions are either linear or constant. A typical rule in a Sugeno fuzzy model has the form:

If Input 1 =x=εT, Input 2 =y= εφ and Input 3 =z= θs, then Output is
$O = ax + by + dz + c$

For a zero-order Sugeno model, the output level O is a constant $(a=b=d=0)$. The output level O_i of each rule is weighted by the firing strength w_i of the rule. For example, for an AND rule with Input 1 = εT , Input 2 = εφ and Input 3 =Θs , the firing strength is

$$w_i = \text{AndMethod}\,(F_1(\varepsilon T), F_2(\varepsilon\varphi), F_3\,(\Theta s))$$

Where $F_1(\varepsilon T)$, $F_2(\varepsilon\varphi)$ and F_3 (Θs) are the membership functions for Inputs 1 , 2 and 3. The final output of the system is the weighted average of all rule outputs, computed as:[16]

$$final\_output = \frac{\sum_{i=1}^{n} w_i O_i}{\sum_{i=1}^{n} w_i} \qquad (15)$$

According to the all constant rules and zero-order Sugeno method and all the variable membership function, a fuzzy control have72 rules can gain, as shown by Tab.2, The fuzzy control table be queried in real time, deposited the table into memory of microcomputer.

θ	Φp			Φn		
T	Tp	Tz	Tn	Tp	Tz	Tn
S1	V2	V2	V1	V3	V4	V7
S2	V3	V2	V1	V4	V4	V5
S3	V3	V3	V2	V4	V5	V0
S4	V4	V3	V2	V5	V5	V6
S5	V4	V4	V3	V5	V6	V7
S6	V5	V4	V3	V6	V6	V1
S7	V5	V5	V4	V6	V1	V0
S8	V6	V5	V4	V1	V1	V2
S9	V6	V6	V5	V1	V2	V7
S10	V1	V6	V5	V2	V2	V3
S11	V1	V1	V6	V2	V3	V0
S12	V2	V1	V6	V3	V3	V4

Tab. 2 Switching table for the FL_DTC.

5. Simulation Results of ANN-DTC& FL-DTC

The Induction motor can be modeled with stator flux and rotor flux as given in [18]-[19]. 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.

5.1. Neural Network Direct Torque Controller

The neural network is trained using the MATLAB 2008 package. This network consists of a three layer neural – network with three input nodes connected to ten tan sigmoid neurons and one pure output node (3-10-1) shown in Fig. 5. The training strategy consists the parallel recursive error prediction was chosen as a learning technique for simulation purposes to update the weights of the neural network. The hybrid algorithm was chosen because of its learning speed, robustness and high learning capability. This algorithm is so powerful when complicated and nonlinear functions are to be learned by the neural network [17]. Simulation results were determined using an electromagnetic torque and stator flux . As shown in Fig. 10and fig.13 the ripple of torque and flux in steady state is reduced remarkably compared with conventional DTC in fig.9 and fig.12, the torque changes through big oscillation and the torque ripple is bigger in conventional DTC. where the torque ripple percentage is 8.3%., and the flux ripple percentage is 3.12% While the conventional DTC have a relatively large ripple, where the torque ripple percentage was 13.3% and the flux ripple percentage was 3.75%.

5.2. Fuzzy Logic Direct Torque Controller

Direct torque control of induction motor using fuzzy logic was also simulated using the MATLAB2008 / SIMULINK toolbox. In conventional DTC, the flux space was divided into six sectors, while in fuzzy logic control it is divided to twelve sectors to avoid the borderline effect of some states during the switching states selection. As shown in Fig.11 and fig.14 using fuzzy logic control provides the system with minimum ripple for both torque and flux, where the torque ripple percentage is 6.6% and the flux ripple percentage is 2.5%.While the conventional DTC have a relatively large ripple as shown in fig.9 and fig.12 , where the torque ripple percentage was 13.3% and the flux ripple percentage was 3.75%.Finally, the simulation results show an improvement with fuzzy controller over the conventional DTC in both flux and torque responses. The steady state response for both controllers was found to be relatively the same.

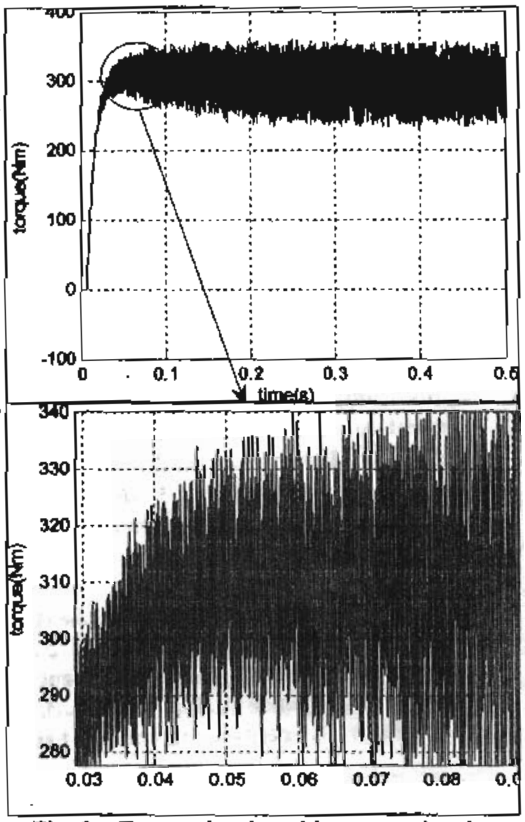


Fig. 9 – Torque developed in conventional DTC.

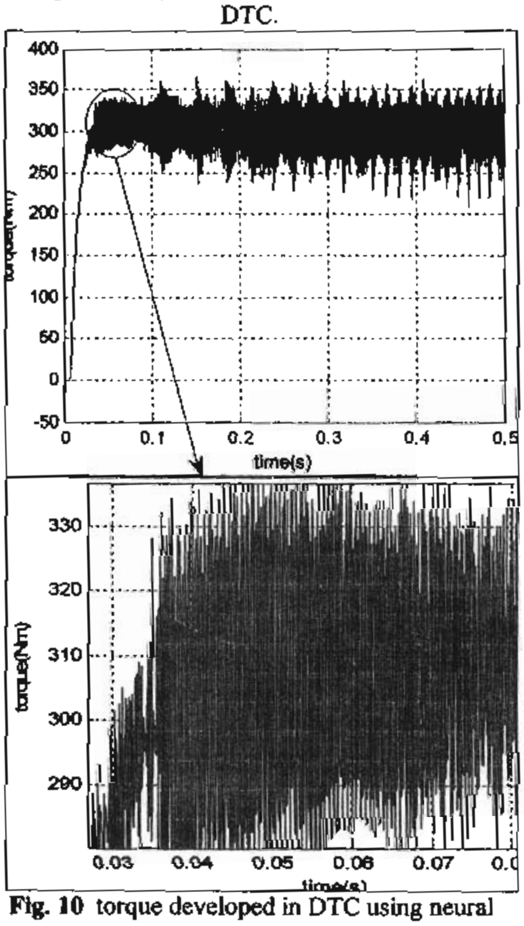


Fig. 10 torque developed in DTC using neural network.

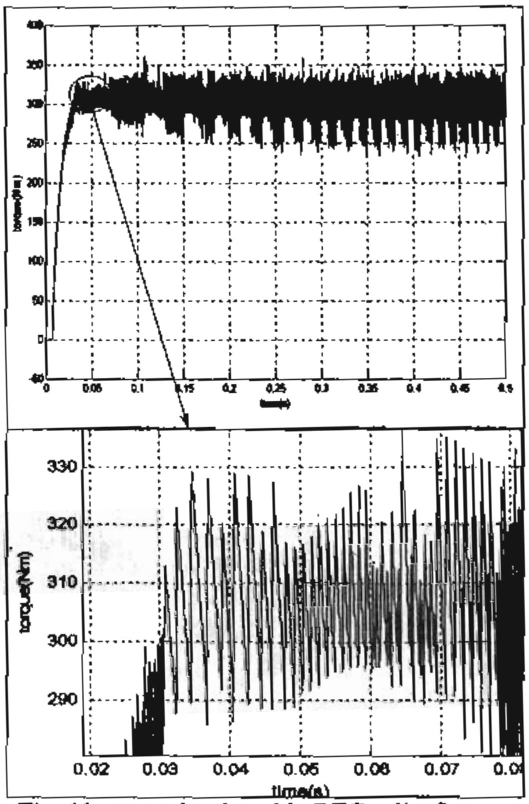


Fig. 11 torque developed in DTC using fuzzy logic.

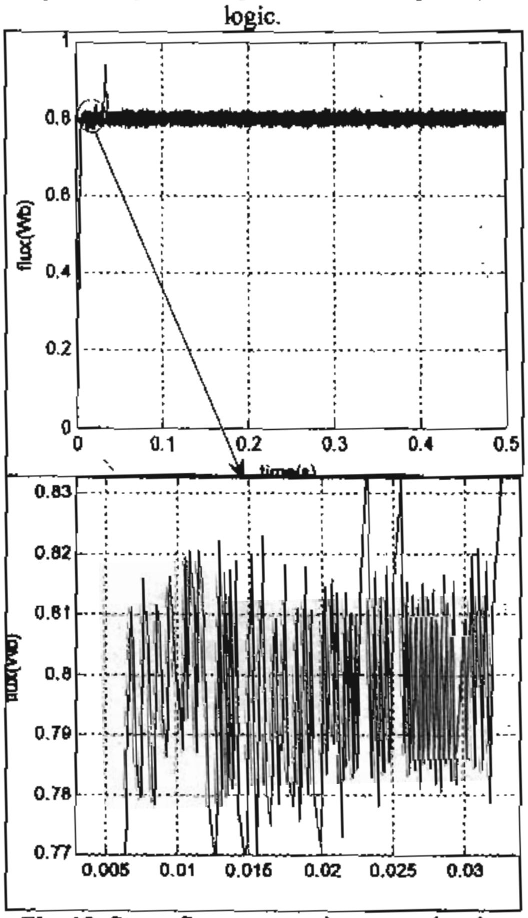


Fig. 12 Stator flux response in conventional DTC

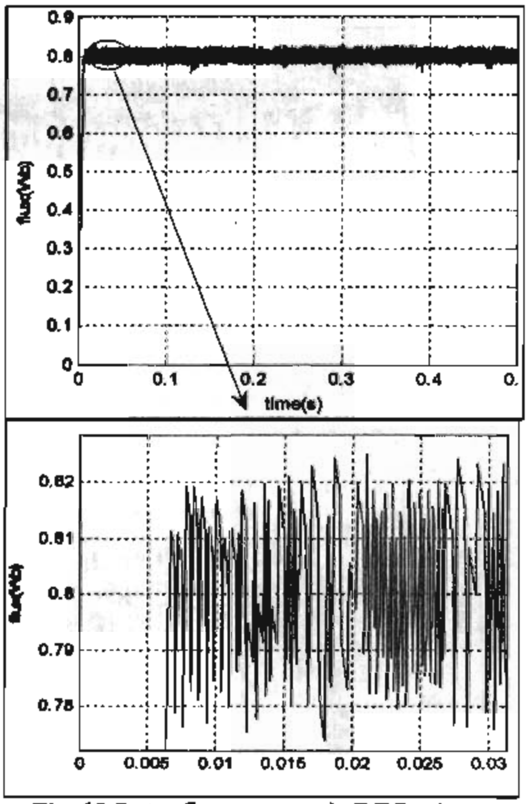


Fig. 13 Stator flux response in DTC using neural network

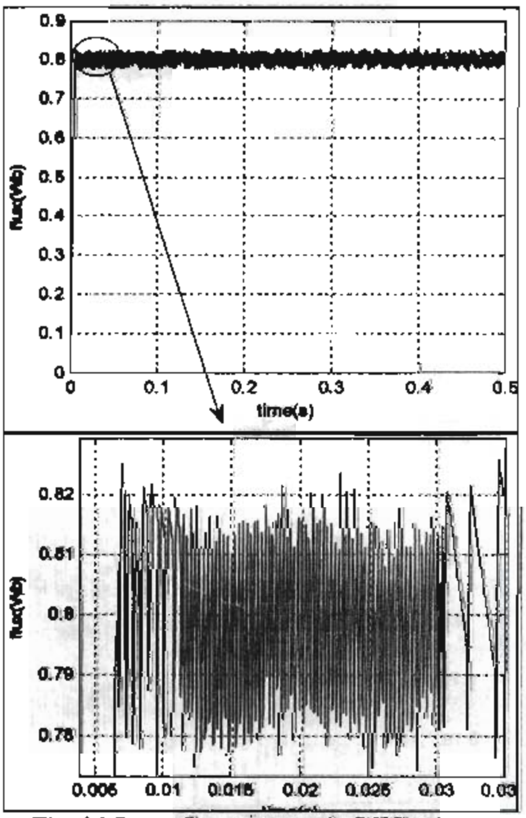


Fig. 14 Stator flux response in DTC using fuzzy logic.

6. Conclusion

In this paper a comparison of various direct torque control methodologies (Conventional DTC, DTC using Neural Network, and DTC using Fuzzy Logic) have been made in order to evaluate the influence of the motor operating condition on transient state performance. A particular emphasis on stator flux, torque ripple has been made. The simulation results suggest that modification by conventional DTC of induction motor can achieve precise control of the stator flux and torque. Compared to conventional DTC, presented method can be easily implemented, and the steady performances of ripples of both torque and flux are considerably improved. The main improvements shown are:

- **Reduction of torque ripple in transient and steady state response as shown in tab. 3 .**
- **Reduction of flux ripples 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	DTC using Neural Network	3.12%	8.3%
3	DTC using Fuzzy Logic	2.8%	6.6%

Tab.3 comparison between flux ripple Percentage and torque ripple percentage for (C- DTC, FL-DTC and ANN -DTC).

7. Appendix

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. 3 Parameters of the selected Induction Motor

8. References

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