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Research Article

IMPROVEMENT IN SPEED PERFORMANCE OF AN INDUCTION MOTOR WITH SLIDING MODE CONTROLLER AND ANN FOR DTC

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ABSTRACT

To further improve the dynamic speed control performance of an induction motor (IM) using a controller based on sliding mode control (SMC) strategy, the switching table for direct torque control (DTC) is realized using a feed forward artificial neural network (ANN). The proposed feed-forward ANN consists of three layers: input, hidden and output layer. The input layer consists of three neurons (sector of flux vector, electromagnetic torque error and stator flux error), the hidden layer consists of a number of neurons that can be determined by experiment to obtain good results. The output layer consists of three neurons (three signals of the converter Sa, Sb and Sc). Simulation results under MATLAB environment are presented and compared with classical DTC using an Integral-proportional (IP) controller to verify the proposed approach.

Keywords: induction motor (IM); direct torque control (DTC); integral-proportional (IP) controller; artificial neural network (ANN); sliding mode control (SMC).

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1. INTRODUCTION

Among all methods of direct torque control developed for the induction motor (IM), the most widely used strategies may be classified within the vector control (VC) and direct torque control techniques. Although the first publication on VC appeared in 1971 [1], the direct control techniques, such as DTC [2] and DSC [3], seem to be accepted as they achieve better transient and steady-state torque control conditions than VC techniques [4-5].

The basic configuration of DTC scheme is very simple. It consists of DTC controller, flux and torque calculator and voltage source inverter. The configuration is simpler than the VC technique due to the absence of frame transformer, pulse width modulator (PWM) and position encoder, which, respectively, introduce delays and require mechanical transducers. Since its introduction in 1986 [6], many scientific papers have appeared in the literature principally to further improve the performance of DTC for IM [7].

With the development of micro-processors and power electronics, the realization of complex schemes is possible. New control techniques for AC speed drive systems include: sliding mode control, fuzzy logic, artificial neural networks (ANNs), and others.

To improve the characteristics of the classical configuration of DTC technique, the switching table can be replaced by another strategy based on the property of learning. The ANN strategy is capable of learning the desired mapping between the inputs and outputs of any complex system. Since the ANNs do not use a mathematical model of the system, they are excellent estimators for non-linear systems. Various ANN techniques based control strategies have been developed for the DTC of an IM to overcome the drawbacks of this scheme [8].

The DTC technique for an IM using an ANN technique to increase the system performance is described in [9]. An ANN technique with DTC based on space vector modulated to improve the performance of classical DTC is employed in [10]. Combination of DTC, SMC and space vector modulation is investigated in [11] to get high performance of the motor. In [12, 13] the sliding mode speed controller is implemented in real time for DTC of an IM to improve its control performance.

Many investigators have adopted the classical control laws with Integral-Proportional (IP) controller that is more suitable in the case of linear systems. In the case of non-linear systems, these laws may be insufficient because they are not robust, especially when the requirements on the accuracy and other dynamic characteristics of the system are strict. For this, other control laws that are insensitive to disturbances in non-linear cases must be considered.

In this paper, a feed-forward ANN is used to replace the switching table of the classical DTC, using an Integral-proportional (IP) controller, of an IM where the speed loop is controlled by a sliding mode controller. The proposed configuration has been investigated and implemented using MATLAB/Simulink software. Simulation results are presented to compare the conventional DTC-IP and the proposed configuration, where the results in the DTC-ANN-SMC case show higher accuracy and faster dynamic speed response with quick electromagnetic torque response and an instantaneous load rejection.

2. IM MATHEMATICAL MODEL

The state variables of the system are considered as stator currents, stator flux and rotor speed as shown in Fig. 1. The $\alpha\beta$ -phase model of the three-phase IM in the stationary reference frame is given, in the vector-matrix form, by (1) [13].

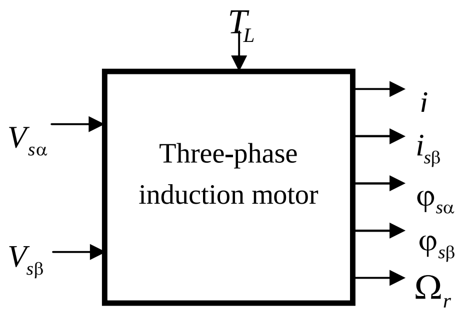


Fig.1. Induction motor block diagram

$$\frac{d}{dt}\begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \\ \varphi_{s\alpha} \\ \varphi_{sb} \end{bmatrix} = [A]\begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \\ \varphi_{s\alpha} \\ \varphi_{sb} \end{bmatrix} + [B]\begin{bmatrix} V_{s\alpha} \\ V_{s\beta} \end{bmatrix} \tag{1}$$

where:

$$[A]=\begin{bmatrix} -\frac{1}{\sigma}\left(\frac{1}{T_s}+\frac{L_m^2}{T_rL_r}\right) & 0 & \frac{L_m}{\sigma L_sL_rT_r} & \frac{L_m\omega_r}{\sigma L_sL_r} \\ 0 & -\frac{1}{\sigma}\left(\frac{1}{T_s}+\frac{L_m^2}{T_rL_r}\right) & -\frac{L_m\omega_r}{\sigma L_sL_r} & \frac{L_m}{\sigma L_sL_rT_r} \\ \frac{L_m}{T_r} & 0 & -\frac{1}{T_r} & 0 \\ 0 & \frac{L_m}{T_r} & \omega_r & -\frac{1}{T_r} \end{bmatrix},$$

$$[B]=\frac{1}{\sigma L_s}\begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

Electromagnetic torque in *dq* frame:

$$T_e = p(\varphi_{sd}.i_{sq} - \varphi_{sq}.i_{sd}) \tag{2}$$

Mechanical equation:

$$T_e - T_L = J\frac{d\Omega_r}{dt} + f\Omega_r \tag{3}$$

3. DIRECT TORQUE CONTROL TECHNIQUE

Direct torque control has become one of the high-performance control strategies for an induction machine to provide a very fast torque and flux control. The basic configuration of the DTC of an IM drive is presented in Fig. 2 [2], where the flux and torque are controlled directly and independently by the selection of optimum inverter voltage vectors to limit their errors.

Outputs of the three level torque hysteresis comparator, two level flux hysteresis comparator, and the stator flux position are used to obtain the optimum stator voltage vector through a switching table [14].

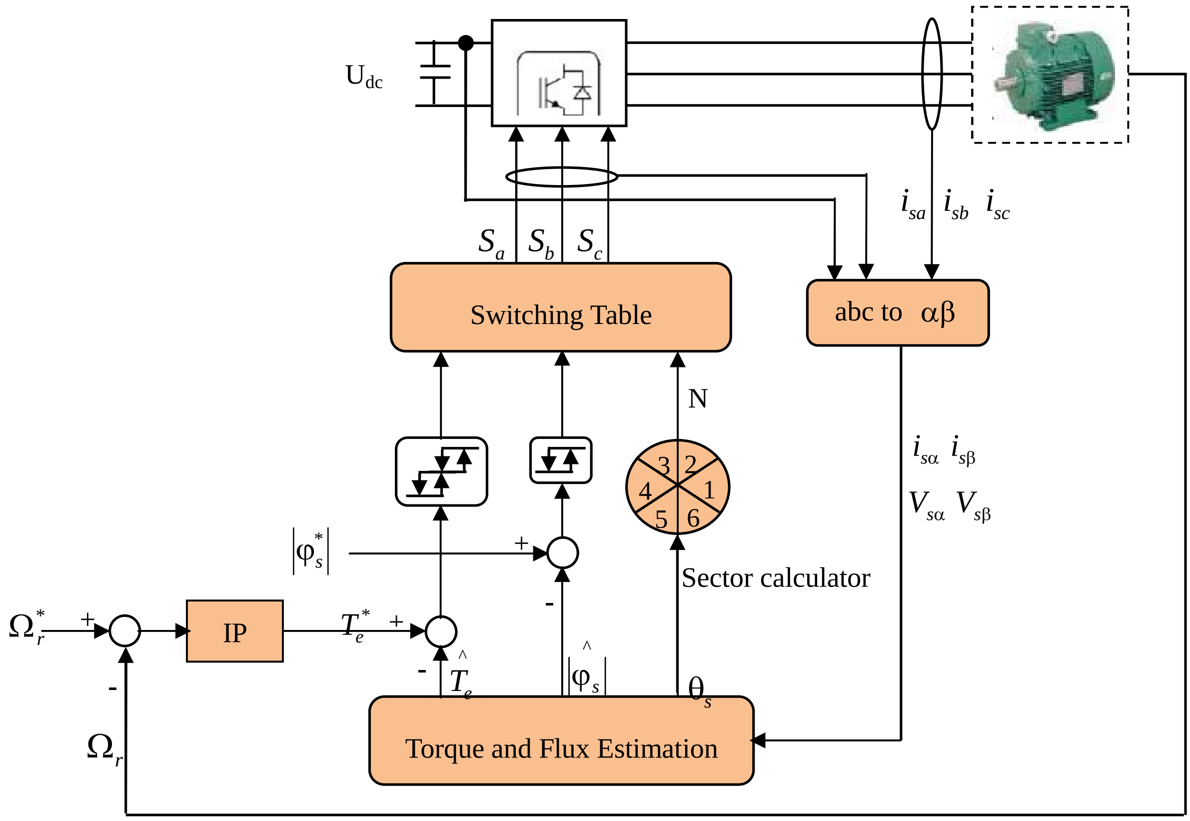


Fig.2. Classical DTC of an IM

3.1. Stator Flux Estimation

The stator flux magnitude can be estimated by [15]:

$$|\hat{\varphi}_s| = \sqrt{\varphi^2{}_{s\alpha} + \varphi^2{}_{s\beta}} \tag{4}$$

where :

$$\phi_{s\alpha} = \int_0^t (V_{s\alpha} - R_s.i_{s\alpha})dt \tag{5}$$

$$\phi_{s\beta} = \int_0^t (V_{s\beta} - R_s.i_{s\beta})dt \tag{6}$$

Stator flux angle can be estimated by:

$$\theta_s = arctg\frac{\varphi_{s\beta}}{\varphi_{s\alpha}} \tag{7}$$

3.2. Electromagnetic Torque Estimation

Electromagnetic torque can be estimated by in ~ frame:

$$T_e = p(\varphi_{s\alpha}.i_{s\beta} - \varphi_{s\beta}.i_{s\alpha}) \tag{8}$$

3.3. Switching Table

Stator flux vector locus and its variation with respect to the voltage source inverter states chosen is shown in Fig. 3.

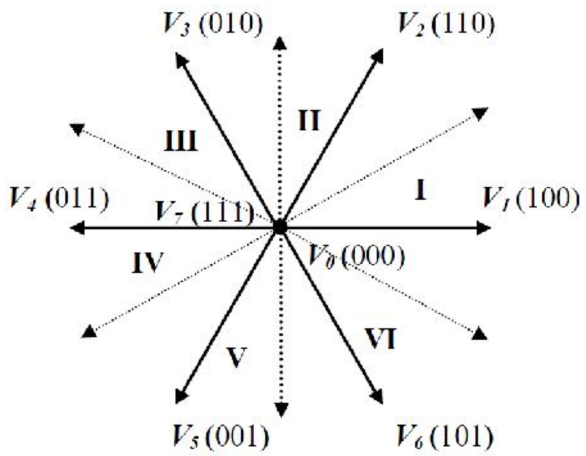


Fig.3. Stator flux vector locus and different possible switching vectors

Accordingly a six sector as shown in Fig. 3, switching table [16-17] is obtained as given in Table 1.

Table 1. Switching table for DTC

Flux	**Torque**	**Sector**					
$d\varphi_s$	dT_e	S_1	S_2	S_3	S_4	S_5	S_6
1	1	V_2	V_3	V_4	V_5	V_6	V_1
	0	V_0	V_7	V_0	V_7	V_0	V_7
	-1	V_6	V_1	V_2	V_3	V_4	V_5
0	1	V_3	V_4	V_5	V_6	V_1	V_2
	0	V_7	V_0	V_7	V_0	V_7	V_0
	-1	V_5	V_6	V_1	V_2	V_3	V_4

DTC is based on the flux orientation using the instantaneous values of the voltage vector. A voltage source inverter (VSI) provides eight voltage vectors, among which two are zeros [17]. These vectors are selected from the switching table according to the flux and torque errors as well as the stator flux vector position. The eight voltage vectors which correspond to possible inverter states are shown in Table 2.

Table 2. Switch positions with their voltage vectors

	V_0	V_1	V_2	V_3	V_4	V_5	V_6	V_7
S_a	0	1	1	0	0	0	1	1
S_b	0	0	1	1	1	0	0	1
S_c	0	0	0	0	1	1	1	1

3.4. IP Speed Controller

The regulation loop of the speed with an IP controller is shown in Fig. 4.

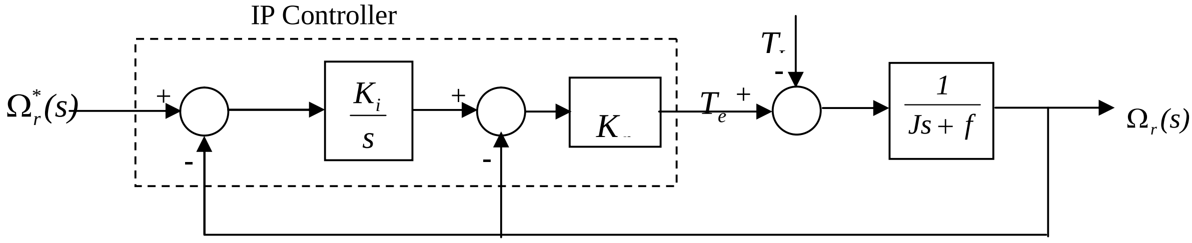


Fig.4. Speed control block diagram with IP controller

The closed-loop speed transfer function is given by:

$$\frac{\Omega_r(s)}{\Omega_r^*(s)} = \frac{1}{1 + \frac{K_p + f}{K_p K_i} s + \frac{J}{K_p K_i} s^2} \tag{9}$$

The closed-loop transfer function in form a standard second-order system is given by:

$$F(s) = \frac{1}{1 + \frac{2\xi}{\omega_n} s + \frac{1}{\omega_n^2} s^2} \tag{10}$$

Comparing Eq. (9) with Eq. (10), obtains:

$$\begin{cases} \dfrac{J}{K_p K_i} = \dfrac{1}{\omega_n^2} \\ \dfrac{K_p + f}{K_p K_i} = \dfrac{2\xi}{\omega_n} \end{cases} \tag{11}$$

where :

$$\begin{cases} K_p = 2J\xi\omega_n - f \\ K_i = \dfrac{J\omega_n^2}{K_p} = \dfrac{J\omega_n^2}{2J\xi\omega_n - f} \end{cases} \tag{12}$$

with:

K_p : proportional gain

K_i : integral gain

ξ : damping factor

ω_n : natural frequency

4. DTC BASED ANN AND SMC IN SPEED LOOP

4.1. Principle of ANN

ANN is considered as a mathematical programming technique designed to simulate the method of thinking and information processing by the human mind. Natural neural networks are composed of simple processing units called cells or neurons. All connections between the cells have specific values called weights. These cells store information to make it available to the user by adjusting the values of the weights [18].

In this paper, an ANN is used to replace the switching table and to improve the performance of the classical DTC. ANN applied to DTC is based on inputs and outputs. The proposed ANN consists of three layers: input, hidden and output layer. The input layer consists of three neurons (inputs of the classical switching table) which are: sector of flux vector, electromagnetic torque error and stator flux error where the output layer consists of three neurons (outputs of the classical switching table) that are the impulses (S_a, S_b and S_c) allowing the control of the inverter switches [19]. The outputs are connected to the inputs through the hidden layer in between input layer and output layer.

In ANN, the training or learning phase is necessary to track the estimated output of the network its target (desired output). To start this process the initial weights are chosen randomly. Then, the training begins. In addition, during this phase the network weights are corrected. Until finally, the error between the target and estimated output can be minimized. The error back-propagation algorithm is considered to release the training phase in this paper.

In order to create this ANN by Simulink, the ANN structure adopted has 3 linear layers with 3 neurons in the input layer and 3 neurons at the output layer. In hidden layer, big a number of neurons lead to complicate the training of the ANN and small a number of neurons lead to bad results.

The structure of the proposed DTC of the IM is presented in Fig. 5, where, the block SMC represents the speed controller by sliding mode control.

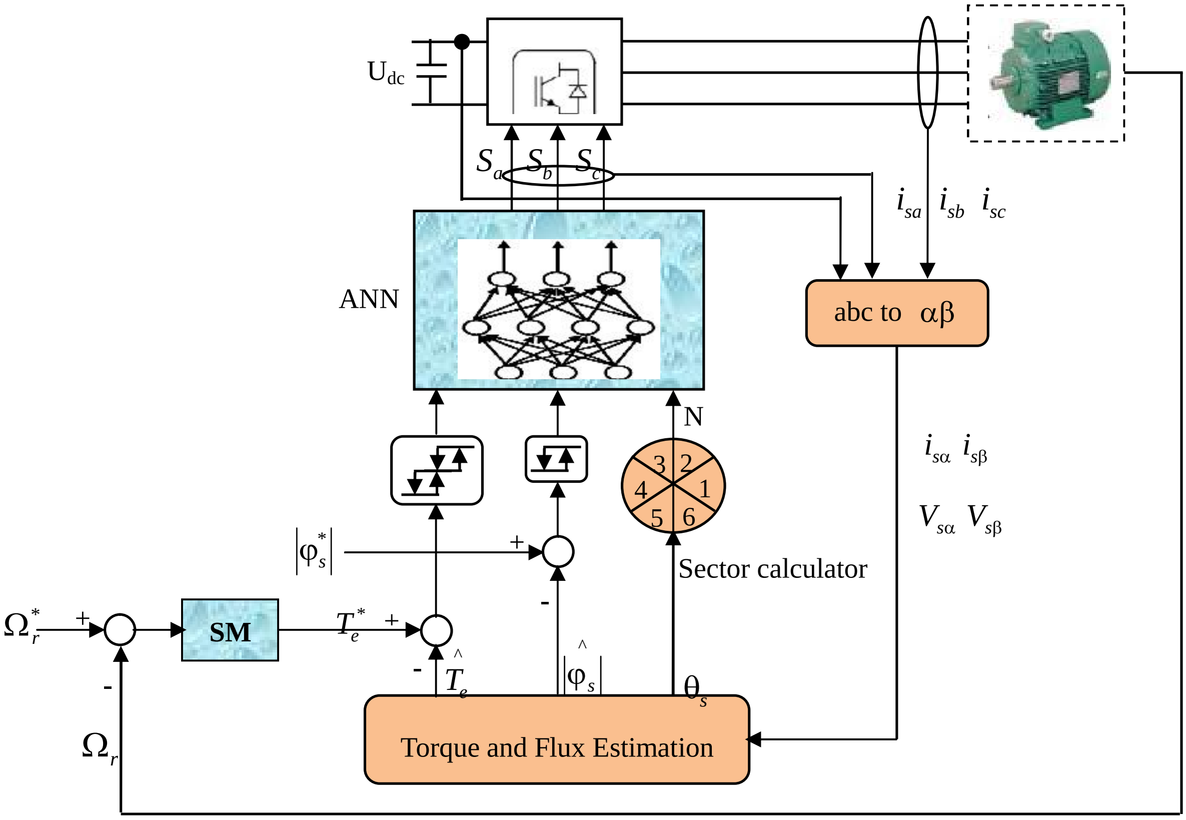


Fig.5. Proposed DTC diagram of the induction motor

4.2. Speed Sliding Mode Controller

A first order SMC is used in this work. The sliding surface 'σ_s' of this controller is given as a function of speed error '*e*'. The speed error is defined by [13]:

$$e = \Omega_r^* - \Omega_r \tag{13}$$

The speed control surface and its derivative are obtained as follows:

$$\sigma_s(\Omega_r) = e = \Omega_r^* - \Omega_r \tag{14}$$

$$\frac{d\sigma_s(\Omega_r)}{dt} = \frac{d\Omega_r^*}{dt} - \frac{d\Omega_r}{dt} \tag{15}$$

As $\varphi_{sq} = 0$, from Eq. (2):

$$T_e = p\varphi_{sd}.i_{sq} \tag{16}$$

and from Eq. (3):

$$\frac{d\Omega_r}{dt} = \frac{1}{J}\left(T_e - T_L - f\Omega_r\right) \tag{17}$$

Substituting Eq. (16) in Eq. (17) gives:

$$\frac{d\Omega_r}{dt} = \frac{1}{J}\left(p\varphi_{sd}.i_{sq} - T_L - f\Omega_r\right) \tag{18}$$

Substituting Eq. (18) in Eq. (15) gives:

$$\frac{d\sigma_s(\Omega_r)}{dt} = \frac{d\Omega^*}{dt} - \frac{1}{J}\left(p\varphi_{sd}.i_{sq} - T_L - f\Omega_r\right) \tag{19}$$

In sliding mode, take:

$$i_{sq} = i_{sq}^{eq} + i_{sq}^{n} \tag{20}$$

with :

i_{sq}^{eq} : equivalent control,

i_{sq}^{n} : switching control,

In the sliding mode and in permanent regime:

$$\sigma_s(\Omega_r) = 0, \quad \frac{d\sigma_s(\Omega_r)}{dt} = 0 \quad \text{and} \quad i_{sq}^{n} = 0 \tag{21}$$

So, the equivalent control is:

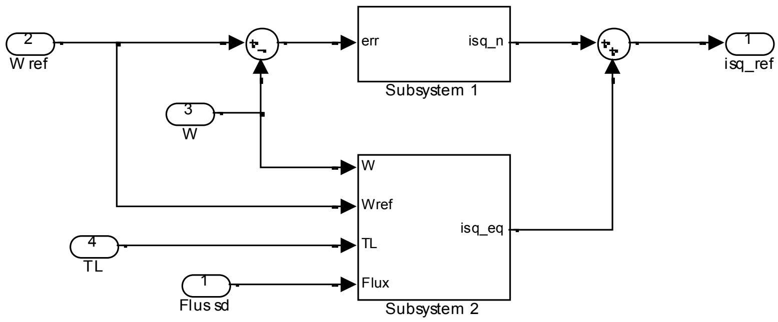
$$i_{sq}^{eq} = \frac{1}{p.\varphi_{sd}}\left(J\frac{d\Omega_r^*}{dt} + T_L + f\Omega_r \right) \tag{22}$$

Therefore, the switching control is given by:

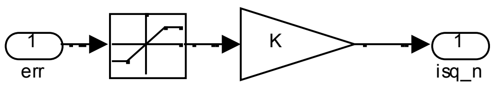
$$i_{sq}^{n} = K.sat(\sigma_s(\Omega_r)) \tag{23}$$

where, K : positive gain, and *sat*: saturation function.

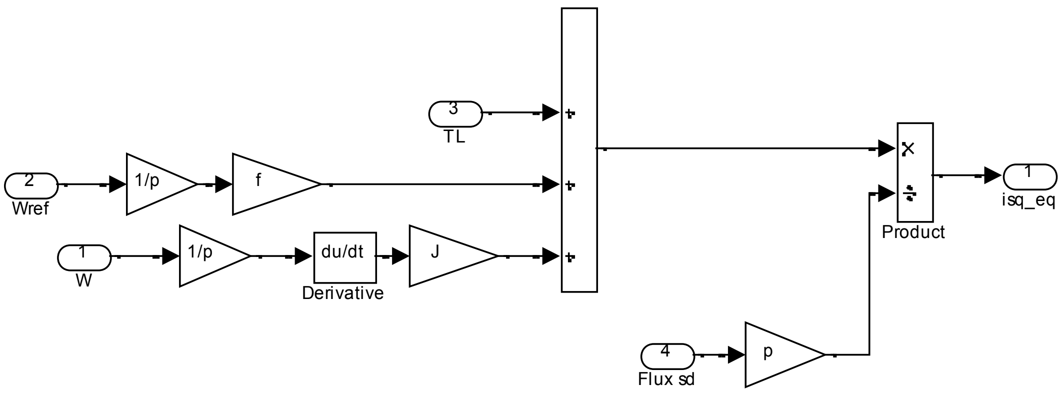
The speed controller by SMC under Simulink is shown in Fig. 6.



(a)



(b)



(c)

Fig.6. (a) Block diagram of speed control with SMC under Simulink,

(b) Subsystem 1, (c) Subsystem 2

5. SIMULATION RESULTS

To validate the feasibility of the proposed DTC-ANN-SMC scheme, computer simulations based on the IM were realized under Simulink as shown in Fig. 7.

IM is rated at 4 kW. Motor parameters used in the simulation studies are illustrated in appendix B. The block diagram was realized and executed on an Intel(R) Core(TM) i3 PC having 2.20 GHz CPU, 4 GB RAM.

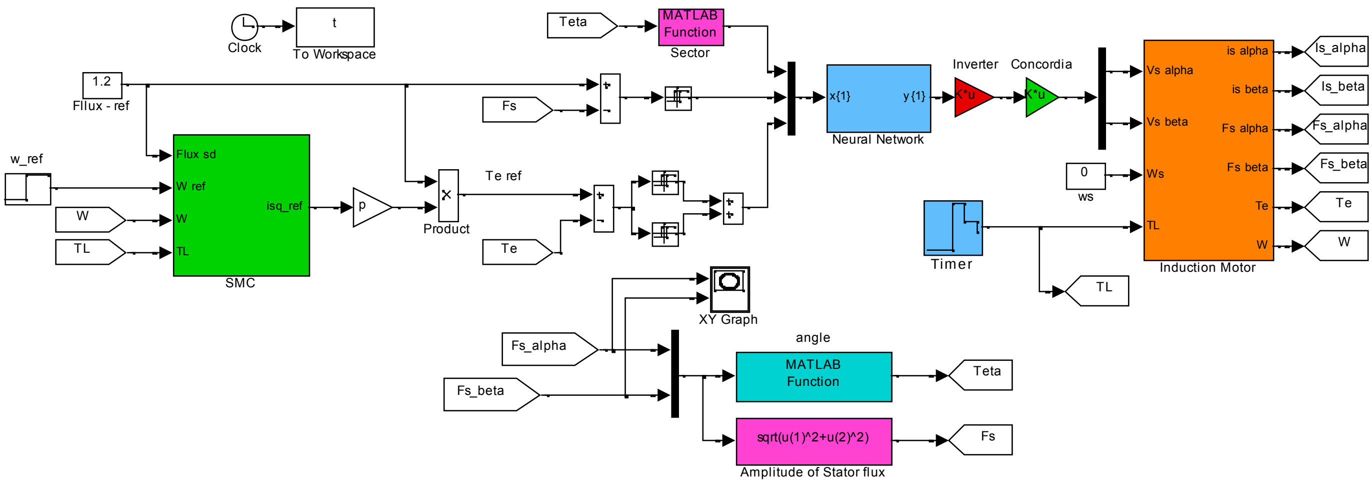


Fig.7. Block diagram of the proposed control under Simulink

5.1. Simulation Model of DTC-ANN-SMC

Training performance between the target and estimated output is presented in Fig. 8 and the Mean Squared Error (MSE) versus the number of epochs is shown in Fig. 9. Neural network was trained using backpropagation, appendix C, and its performance is presented in Fig. 10. It can be seen from Figs. 9 and 10 that the ANN training is completed in 465 epochs with a negligible error (2.32e-32) between the target and the estimated output of the ANN.

Simulink block of the neural network switching table, Fig. 11, is composed of two layers as shown in Fig. 12, where the blocks “Layer 1” and “Layer 2” are presented in Fig. 13.

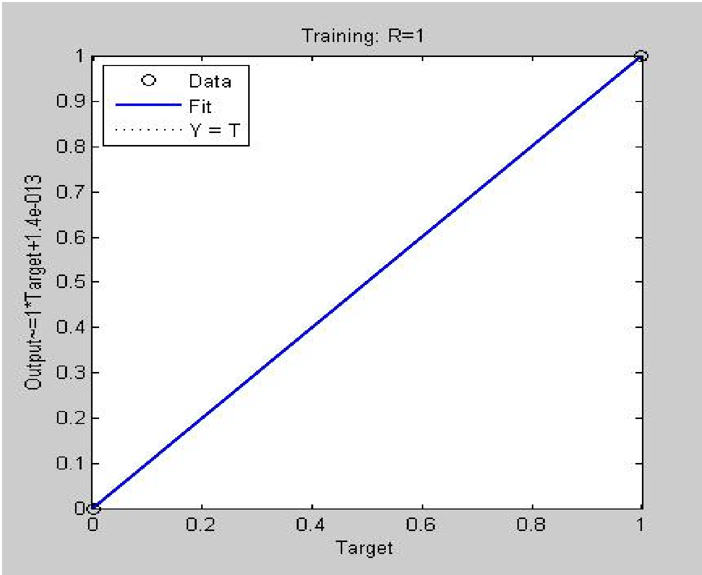


Fig.8. Training performance between the target and estimated output

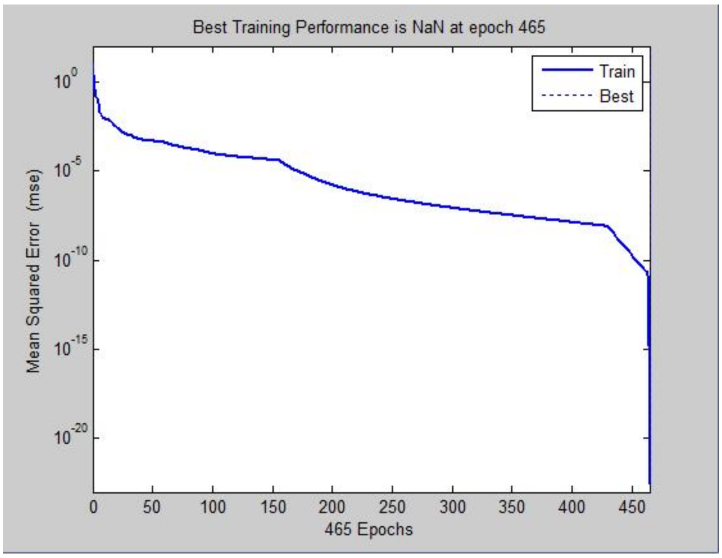


Fig.9. MSE versus the number of epochs

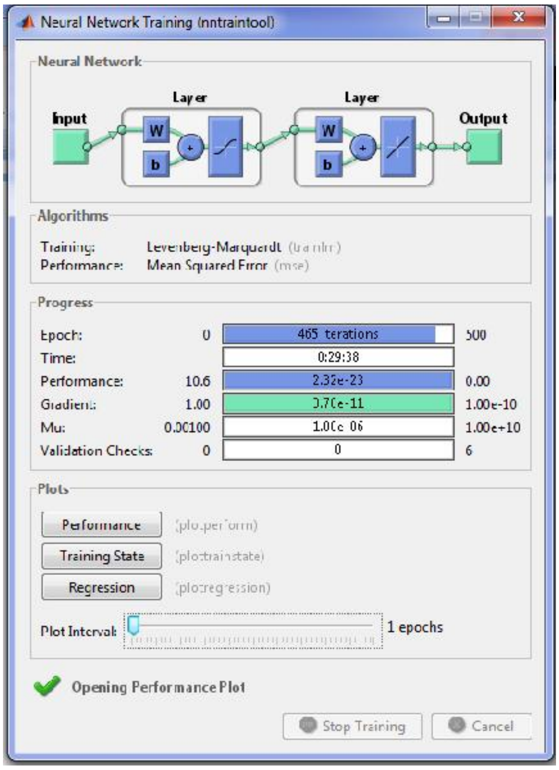


Fig.10. Neural network training performance

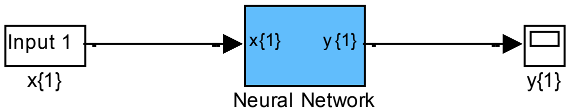


Fig.11. Simulink block of the neural network switching table

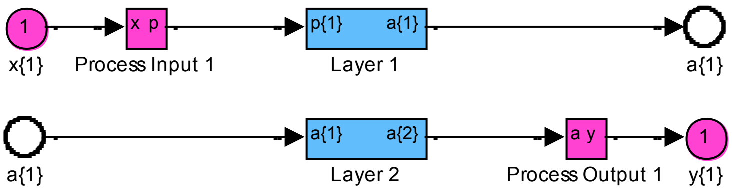
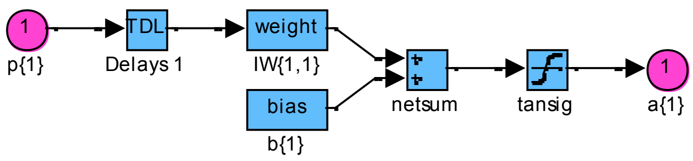
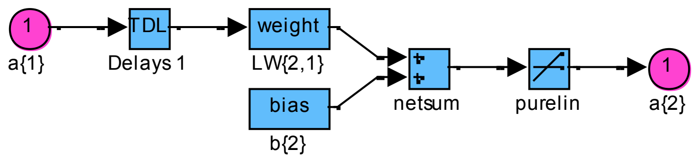


Fig. 12. “Neural Network” block



(a)



(b)

Fig.13. Details of ANN blocks in Fig. 12: (a) “Layer 1” and (b) “Layer 2”.

5.2. Results and Discussion

Comparative performance of the IM for a test performed under the same conditions, a sudden change in load, is observed with DTC-ANN-SMC and classical DTC with IP controller, and the motor operating at the command speed of 157 rad/sec under no-load. At t=0.8 s, a 25 N.m load torque is suddenly applied. This load changes to 15 N.m and then to 10 N.m at t=1.2s and t=1.6s, respectively, as shown in Fig. 14.

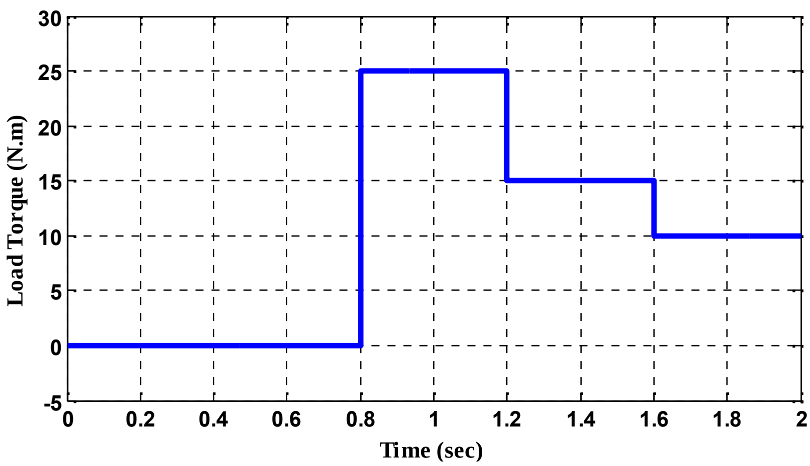


Fig.14. Load torque values versus time applied in the test of the motor

Speed responses in the two cases, DTC-IP and DTC-ANN-SMC, are presented in Figs. 15 and 16, respectively, and a comparison of speed response between classical DTC and

DTC-ANN-SMC is shown in Fig. 17.

The IP controller, used in the classical DTC, rejects the load disturbance slowly in 0.8 s with an overshoot and with a steady-state error as shown in Figs. 18 and 19. An undershoot appeared at t=1.2 s when the load reduced to 15 N.m as shown in Fig. 18.

With DTC-ANN-SMC, the proposed ANN was able to train and to work as a switching table. The SMC rejects the load disturbances with no overshoot, without undershoot and with no steady-state error as shown in Fig. 16. The DTC-ANN-SMC presents good performance to achieve tracking of the desired trajectory.

The performance of the proposed control is compared to the conventional DTC in the same conditions. It can be seen that the DTC-ANN-SMC gives minimum response time and robust speed response compared to the conventional DTC as shown in Figs 17, 18 and 19.

The torque response in the two cases, DTC-IP and DTC-ANN-SMC, is shown in Figs, 20 and 21, respectively. Comparison of the torque response between the two controls is presented in Fig. 22.

The stator flux magnitudes and their trajectories, 2D and 3D, are presented, respectively, in Figs. 23, 24 and 25 for classical DTC. DTC-ANN-SMC stator flux magnitudes and their trajectories, 2D and 3D, are illustrated in Figs. 26, 27 and 28, respectively.

According to the results of the stator flux trajectory, the comparison between the two cases, classical and proposed DTC, is divided into two states: transient state and steady state. In transient state, the proposed has good performance than the conventional DTC except small perturbations in start-up. In addition, DTC-ANN-SMC gives 0.00758 sec response time small than 0.01427 sec given by conventional DTC as shown in Table 3 and Figs. 23 and 26. In steady state, the stator flux trajectory of the proposed presents almost the same performance which obtained by the conventional DTC as shown in Figs. 24, 25, 27 and 28. In addition, DTC-ANN-SMC has a very quick response in electromagnetic torque (Fig. 22) compared to the classical DTC.

The three phase stator currents in the two cases, DTC-IP and DTC-ANN-SMC, Figs. 29 and 30, respectively, show good sinusoidal currents.

It can be seen that DTC-ANN-SMC shows a fast response and good improvement in performance compared to that with the conventional DTC. The proposed and the conventional DTC behaviour can be better compared using standard performance where the results are described in Table 3.

Performance of the proposed DTC-ANN-SMC compared to that of the classical DTC, summarized in Table 3, confirms the improved performance of DTC-ANN-SMC. The proposed control surpasses the conventional DTC, taking into account many performance indices:

- Speed response time is reduced more than 55% (0.3459 s for conventional DTC while it is 0.1507 s for the proposed DTC-ANN-SMC).
- Speed overshoot is reduced from 1.4640 % for conventional DTC to 0% using DTC-ANN-SMC.
- Speed undershoot is reduced from 3.9465 % for conventional DTC to 0% using DTC-ANN-SMC.
- Steady-state error is reduced from 0.0637% for conventional DTC to a negligible value using the proposed DTC-ANN-SMC.
- Stator flux response time is reduced more than 45% (0.01427 % for conventional DTC instead of 0.00758 % for DTC-ANN-SMC).

Table 3. Comparison between classical DTC and DTC-ANN-SMC

	Speed performance		**Stator Flux performance**	
Control	**Classical DTC**	**DTC-ANN-SMC**	**Classical DTC**	**DTC-ANN-SMC**
Response time ($T_{r\ 5\%}$) (sec)	0.3459	**0.1507**	0.01427	**0.00758**
Overshoot (%)	1.4640	**0**	**0**	**0**
Undershoot (%)	3.9465	**0**	**0**	**0**
Steady-state error (%)	$\approx$0.0637	**Neglected**	**Neglected**	**Neglected**

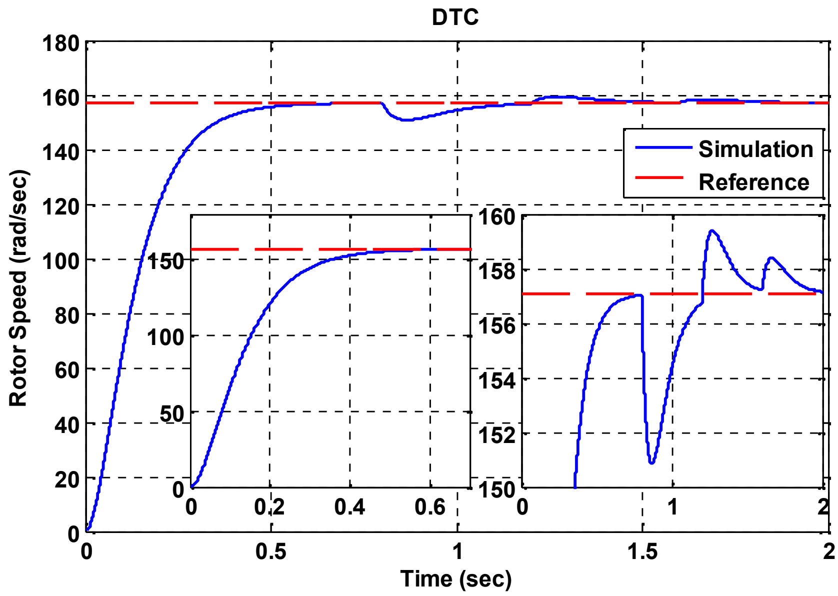


Fig.15. Speed response in DTC-IP case

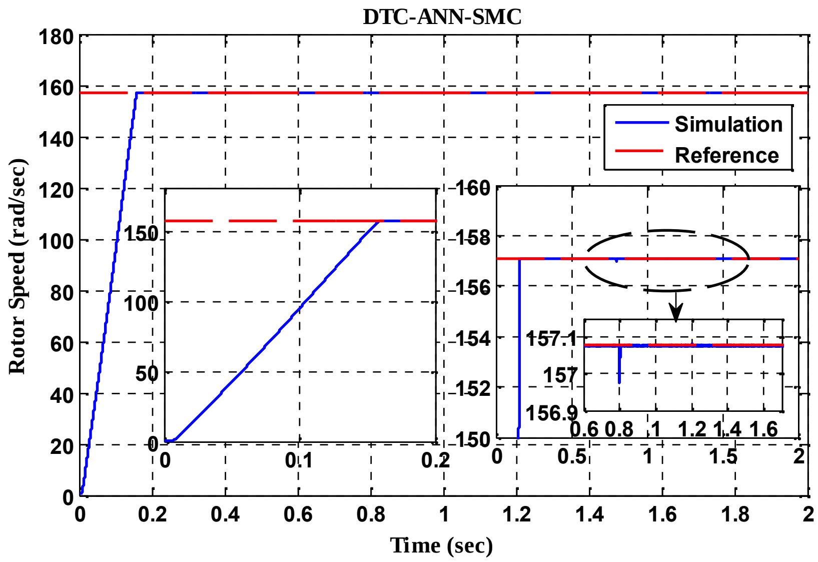


Fig.16. Speed response in DTC-ANN-SMC case

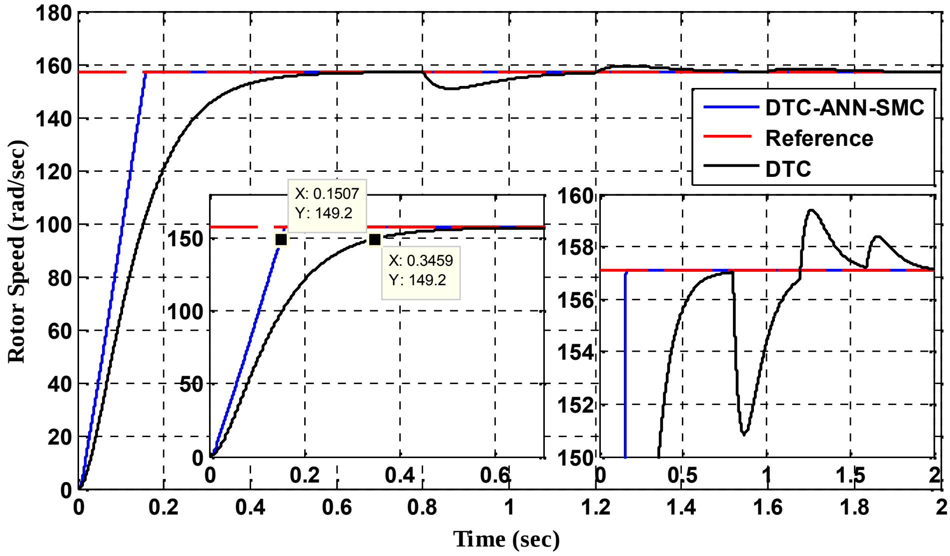


Fig.17. Comparison of speed response between DTC-IP and DTC-ANN-SMC

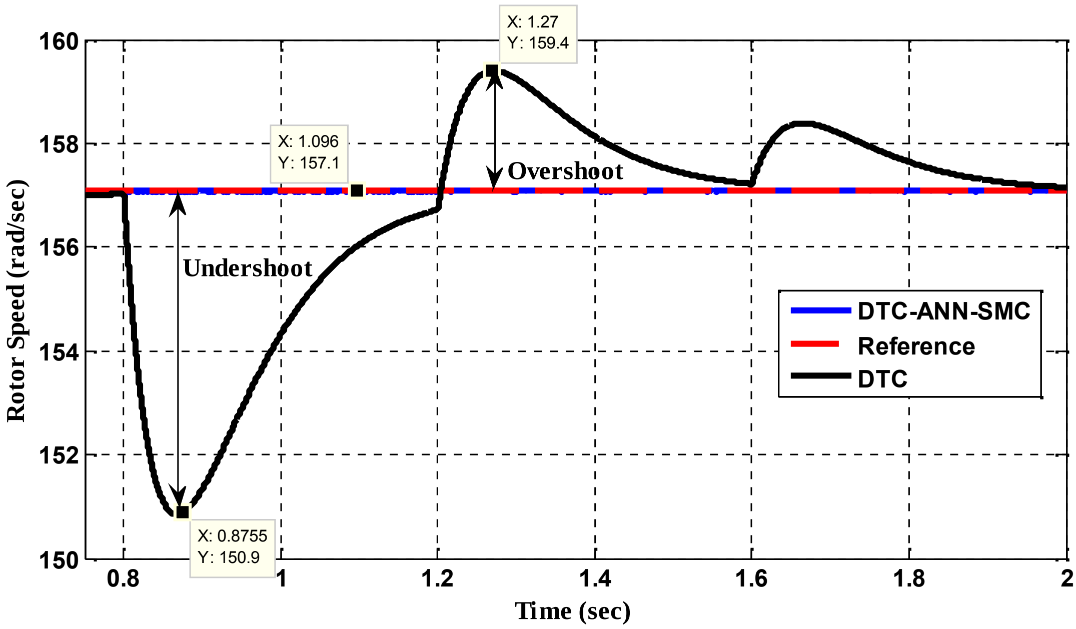


Fig.18. Performance of undershoot and overshoot

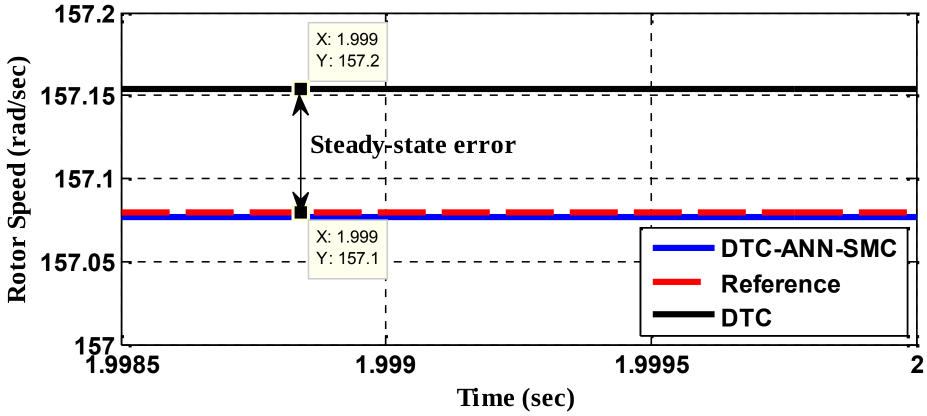


Fig.19. Comparison of steady-state error

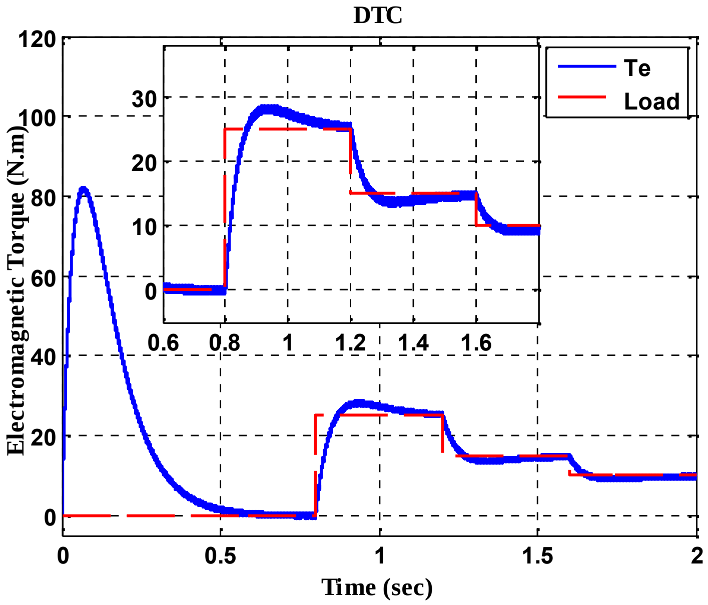


Fig.20. Torque response in DTC-IP case

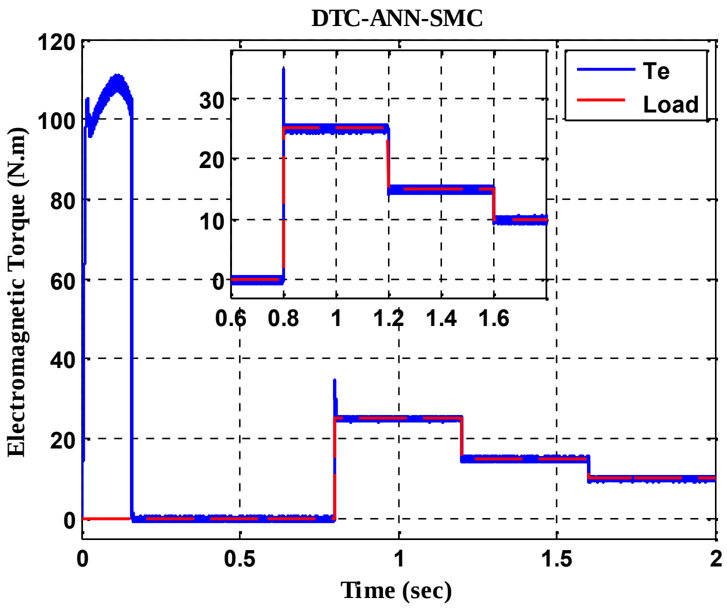


Fig.21. Torque response in DTC-ANN-SMC case

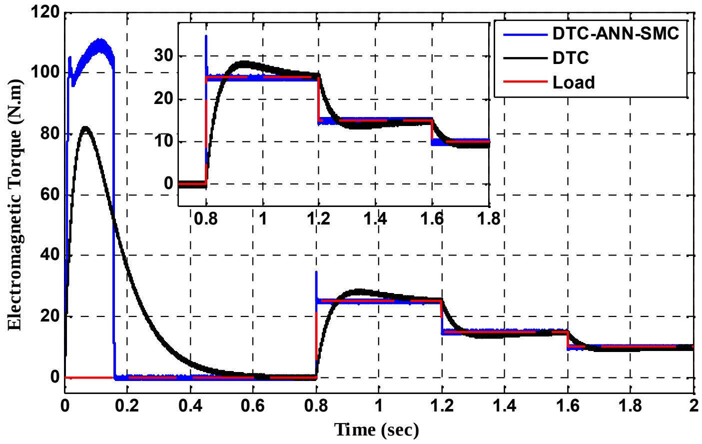


Fig.22. Comparison of torque response of DTC-IP and DTC-ANN-SMC

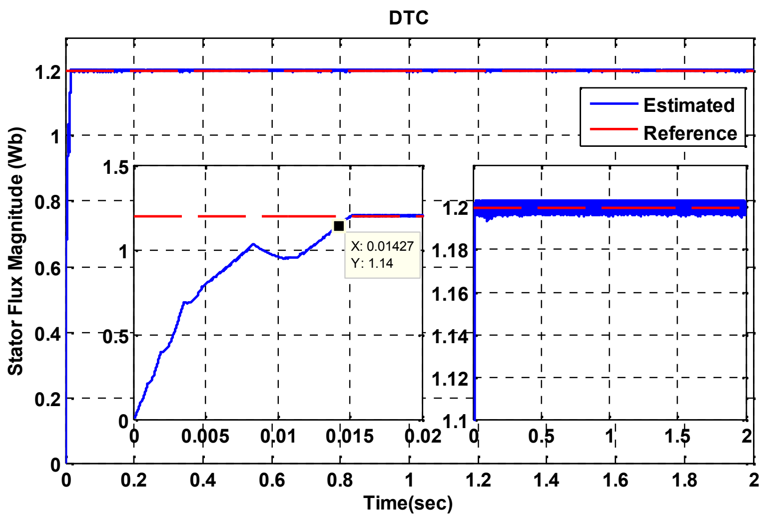


Fig.23. Stator flux magnitude in DTC-IP case

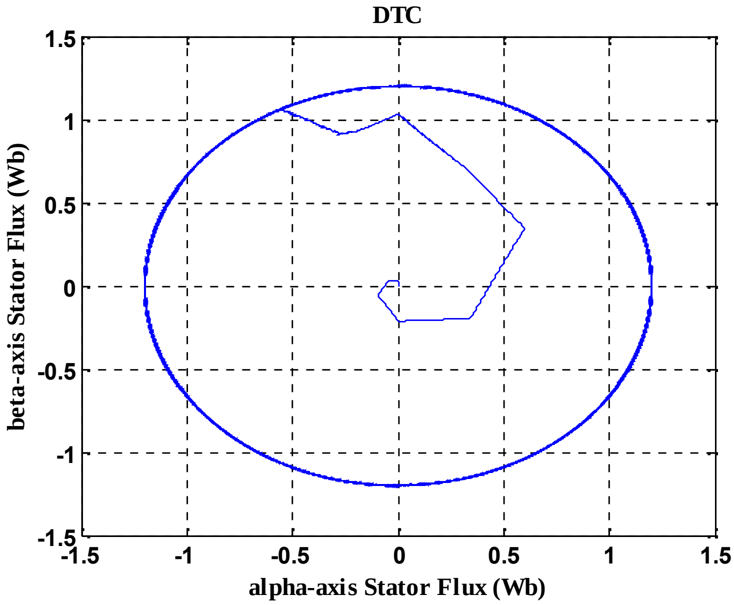


Fig.24. Stator flux trajectory in DTC-IP case

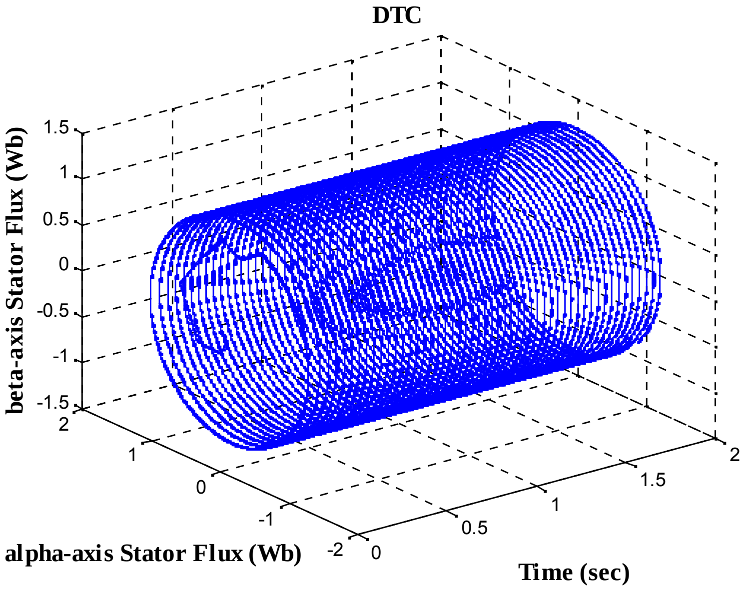


Fig.25. 3D representation of stator flux trajectory in DTC-IP case

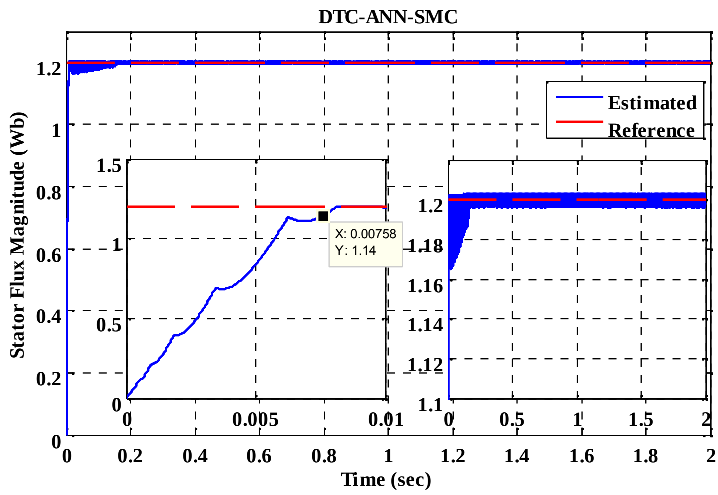


Fig.26. Stator flux magnitude in DTC-ANN-SMC case

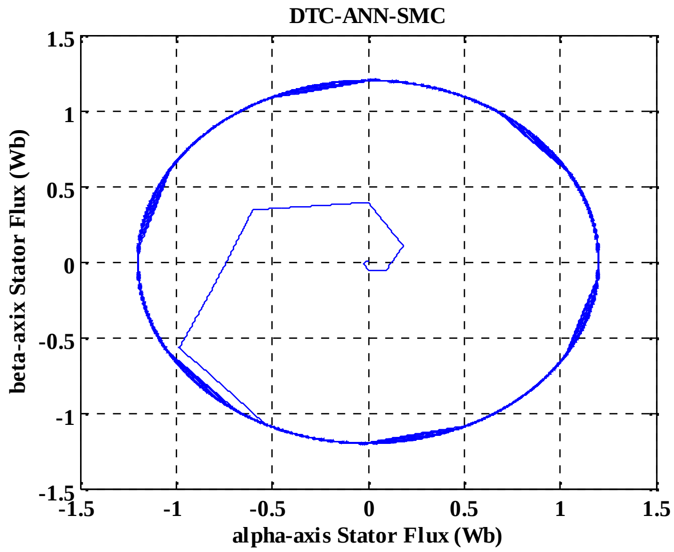


Fig.27. Stator flux trajectory in DTC-ANN-SMC case

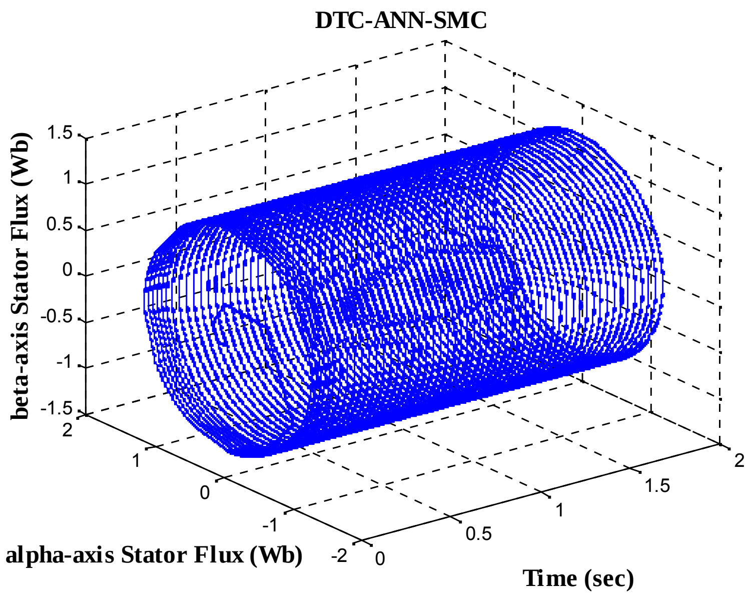


Fig.28. 3D representation of stator flux trajectory in DTC-ANN-SMC case

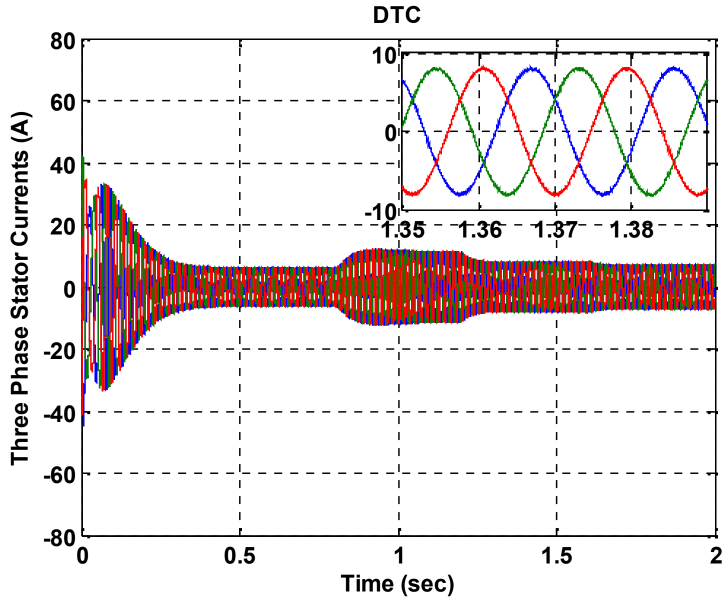


Fig.29. Three phase stator currents in DTC-IP case

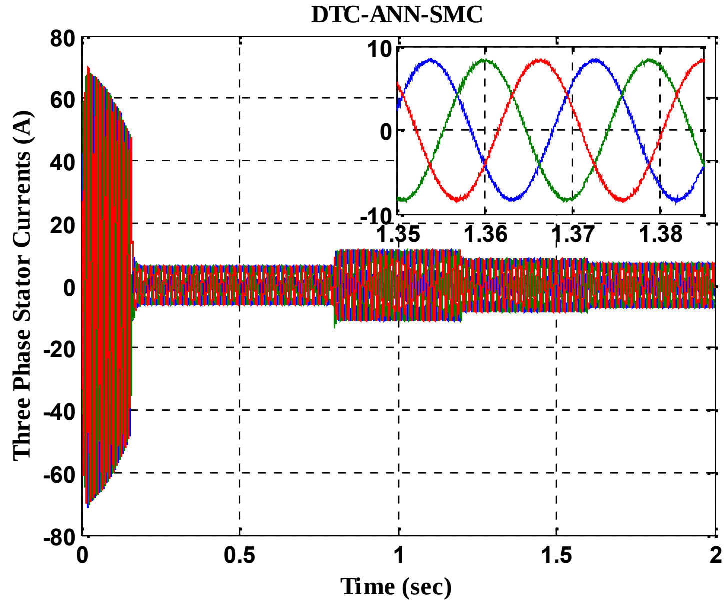


Fig.30. Three phase stator currents in DTC-ANN-SMC case

6. CONCLUSIONS

In this paper, a DTC based ANN, with sliding mode control, used as a speed controller has been implemented and simulated under Simulink. The ANN has been implemented to produce voltage inverter switching states according to the switching table of the conventional DTC-IP. The IP controller has been replaced by an SMC to improve the dynamic performance of the conventional DTC. The simulation results presented show that the classical DTC rejects the load slowly with an overshoot (load decrease), with steady-state error and with undershoot (load increase). However, the DTC-ANN-SMC responds to the load change immediately with no overshoot, with no steady-state error and without undershoot. As the DTC-ANN-SMC provides a better performance compared to the classical DTC, the proposed DTC-ANN-SMC is more efficient and better for use in induction motor drives compared to the conventional DTC.

7. APPENDIX

Appendix A. Nomenclature

IM

$V_{s\alpha}$, $V_{s\beta}$	stator α,β frame voltages
$i_{s\alpha}$, $i_{s\beta}$	stator α,β frame currents
$\varphi_{s\alpha}$, $\varphi_{s\beta}$	stator α,β frame fluxes
¤ $_{sd}$, ¤ $_{sq}$	stator *dq* frame fluxes
i_{sd} , i_{sq}	stator *dq* frame currents
R_s	stator resistance
R_r	rotor resistance
L_s	stator inductance
L_r	rotor inductance
L_m	mutual inductance
T_s , T_r	stator and rotor time-constant
±	leakage factor
J	moment of inertia
f	friction coefficient
P	number of pole pairs
Ω_r	rotor speed

ω_r	rotor angular speed
T_e	electromagnetic torque
T_L	load torque

Sliding mode control

σ_s	sliding surface
sat	saturation function
e	error

Acronyms

IM	*Induction Motor*
DTC	*Direct Torque Control*
SMC	*Sliding Mode Controller*
DSC	*Direct Self-Control*
ANN	*Artificial Neural Network*
IP	*Integral-Proportional*
VSI	*Voltage Source Inverter*

Superscripts

“ * ”	reference value
“ . ”	derivative value

Appendix B. IM parameters

Nominal values:
4 kW, 220/380 V, *50Hz*, 15/8.6 A, , 1440 rpm
Nominal parameters:

R_s = 1.2 Ω

R_r = 1.8 Ω

L_s = 0.1554 H

L_r = 0. 1568 H

L_m = 0.15 H
P = 2
Mechanical constants:
J = 0.2 Kg.m^2
f = 0.0 N.m.s/rad

Appendix C. ANN program

To create a feed-forward back-propagation network using " *newff* ":

```
Consider this example:
X =[-1 -1 2 2; 0 5  0 5]
Y =[-1 -1 1 1]
Where:
X is input vector,
Y is target.
To create a feed-forward ANN use the following:

net_example=newff(minmax(X),[3 1],{'tansig' 'purelin'},'traingdm');
net_example = train(net_example,X,Y);
Z = sim(net_example,X);
plot(X,Y,X,Z,'*-')
%-----------------------------------------------------------
```

To generate a Simulink block to simulate a neural network " *gensim* " can be used.

In Matlab command, just simply use the following command:

```
>> gensim(net)
```

The result of this command is as shown in Fig. 31.

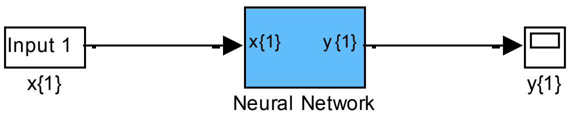


Fig.31. Simulink block of a neural network by using the command "*gensim*".

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