A Comparative Study between the Two Applications of the Neural Network and Space Vector PWM for Direct Torque Control of a DSIM Fed by Multi-Level Inverters

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Abstract. Nowadays, thanks to the development of control and power electronics, the dual stator induction machine DSIM has become among the most important multi-phase machines included in industrial application, this is due to its positive features among them is its high reliability and reduce both losses and rotor torque ripple.

This paper aims to apply both techniques of artificial intelligence represented by the neural network algorithm NNA and the Space Vector PWM SVM for direct torque control DTC of the DSIM to improve the machine performance and control algorithms DTNC and DTC-SVM.

Generalization capacity, the parallelism of operation, computational speed, and learning capacity all these features made it possible to exploit the neural network algorithm to control the machine. Fixed switching frequency obtained, dispensed with the vector selection table and the hysteresis controller, the three pros allowed the inclusion of SVM technique in DTC strategy.

Three-level NPC inverters are included to feed the DSIM. A several of the results obtained prove the two applied techniques (NNA, SVPWM) in improving the quality of both electromagnetic torque and flux and the dynamic responses of the DSIM.

Keywords: DSIM, Neural Network Algorithm NNA, Space Vector PWM SVM, DTNC, DTCSVM, Three-level NPC inverter.

1 Introduction

The continuous increase in industrial progress has led to an increase in the demand for the use of many multi-phase machines; this is due to its high reliability compared to the ordinary three-phase machine, in addition to the successful choice of reducing the weight of windings [1-2], the power divided between phases enables the voltage of each phase to be reduced and reduces distortions of phases currents. Most of the multi-level machines have high torque-free of undulations [3], the most important feature is the continuity of these machines' operation in the event of a fault in one or more phases [4-5].

The dual stator induction machine DSIM is more common among the family of multi-phases machines; the DSIM modeling with its control has been suggested by the authors [6-7].
There are many DSIM control strategy, the most famous of which is the direct torque control DTC that was proposed in the 1980s [8], the DTC strategy has a set of features including rapid dynamic response, robust performance, non-use of a mechanical sensor, simple implementation, control the speed, flux, and torque of the motor at the same time. However, there are some negative features, including the sensitivity of the DTC to physical variables such as the stator resistance, in addition to the emergence of ripple at the level of each electromagnetic torque and stator flux. Researchers are still seeking to improve the performance of the DTC strategy for DSIM [9].

Due to advances in power electronics and control, several topologies of static converters have emerged; these topologies provide a power source and adjustable speed with good performance.

The three-level NPC inverter is one of the most popular topologies in variable speed systems [10], the standard DTC strategy requires a hysteresis controller and switching table, these requirements make this strategy has constant switching frequency, This contributed to the suggestion of many studies urging inclusion the Space Vector PWM SVM technique within the DTC strategy to control the switching frequency to reduce the torque ripple, and improve the quality of stator flux with a wide speed range [11].

To overcome torque ripple caused by the switching table applied to the DTC strategy, a switching table based on several artificial intelligence techniques, such as neural network, has been proposed to obtain optimal switching table patterns [12]

This paper proposes a comparative study between the two applications of the Space Vector PWM SVM and the neural network included in the DTC strategy for the DSIM;

First, a DSIM modeling will be proposed. Second, the control strategies DTC-SVM and DTNC will be applied for DSIM. Third, a comparative study will be conducted between the two aforementioned applications.

2 Modeling of DSIM

The DSIM is a very complex system, thanks to the Park transformation, the mathematical model of the nine nonlinear differential equations has been simplified, this is to control the speed, and the torque and the stator flux at the same time.
Whereas, the following equations represent of the DSIM model in space α-β;

$$\begin{cases} \overline{v}_s = v_{\alpha s} + jv_{\beta s} \\ \bar{i}_s = i_{\alpha s} + ji_{\beta s} \\ \bar{i}_r = i_{\alpha r} + ji_{\beta r} \\ \overline{\varphi}_s = \varphi_{\alpha s} + j\varphi_{\beta s} \\ \overline{\varphi}_r = \varphi_{\alpha r} + j\varphi_{\beta r} \end{cases} \qquad \begin{cases} \overline{V}_s = r_s \bar{i}_s + p\overline{\varphi}_s \\ 0 = r_r \bar{i}_r + p\overline{\varphi}_r - j\omega_r \overline{\varphi}_r \\ \overline{\varphi}_s = L_s \bar{i}_s + L_m \bar{i}_r \\ \overline{\varphi}_r = L_m \bar{i}_s + L_r \bar{i}_r \\ \Gamma_{em} = \frac{1}{2} P(\varphi_{\alpha s} i_{\beta s} - \varphi_{\beta s} i_{\alpha s}) \end{cases} \tag{1}$$

$$[T_6]^{-1} = \frac{1}{\sqrt{3}}\begin{bmatrix} \cos(0) & \cos(\frac{2\pi}{3}) & \cos(\frac{4\pi}{3}) & \cos(\gamma) & \cos(\gamma+\frac{2\pi}{3}) & \cos(\gamma+\frac{4\pi}{3}) \\ \sin(0) & \sin(\frac{2\pi}{3}) & \sin(\frac{4\pi}{3}) & \sin(\gamma) & \sin(\gamma+\frac{2\pi}{3}) & \sin(\gamma+\frac{4\pi}{3}) \\ \cos(0) & \cos(\frac{4\pi}{3}) & \cos(\frac{2\pi}{3}) & \cos(\pi-\gamma) & \cos(\frac{\pi}{3}-\gamma) & \cos(\frac{5\pi}{3}-\gamma) \\ \sin(0) & \sin(\frac{4\pi}{3}) & \sin(\frac{2\pi}{3}) & \sin(\pi-\gamma) & \sin(\frac{\pi}{3}-\gamma) & \sin(\frac{5\pi}{3}-\gamma) \\ 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 1 \end{bmatrix} \tag{2}$$

The angle between the stator flux and the rotor flux is γ, Fig. 1 shows the input and output of the DSIM system.

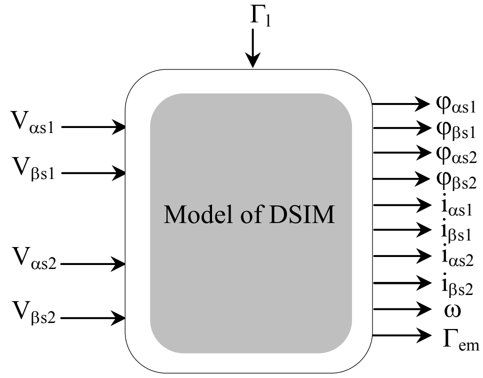

Fig. 1 Model of DSIM in the α-β coordinate plan

The state system is obtained as $\dot{X} = AX + BU$, with the matrices A and B given as:

$$A = \begin{bmatrix} 0 & 0 & 0 & 0 & -r_{s1} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -r_{s2} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -r_{s2} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -r_{s2} \\ r_r h_1 & -r_r h_2 & \omega L h_1 & -\omega L h_2 & -a & -b & -\omega & 0 \\ -r_r h_2 & r_r h_1^{'} & -\omega L h_2 & \omega L h_1^{'} & -c & -d & 0 & -\omega \\ -\omega L h_1 & \omega L h_2 & r_r h_1 & -r_r h_2 & \omega & 0 & -a & -b \\ \omega L h_2 & -\omega L h_1^{'} & -r_r h_2 & r_r h_1^{'} & 0 & \omega & -c & -d \end{bmatrix} \quad B = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ Lh_1 & -Lh_2 & 0 & 0 \\ -Lh_2 & Lh_1^{'} & 0 & 0 \\ 0 & 0 & Lh_1 & -Lh_2 \\ 0 & 0 & -Lh_2 & Lh_1^{'} \end{bmatrix} \tag{3}$$

With:

$$\begin{cases} a = [h_3 h_1 - r_r l_m h_2], b = [r_r l_m h_2 - h_2 h_4], \; c = [r_r l_m h_1^{'} - h_2 h_3], d = [h_4 h_1^{'} - r_r l_m h_2] \\ h_1 = \dfrac{l_m(l_r + l_{s1}) + l_r + l_{s2}}{y}, h_1^{'} = \dfrac{l_m(l_r + l_{s1}) + l_r + l_{s1}}{y} \\ h_2 = \dfrac{l_m l_r}{y}, h_3 = [r_r(l_{s1} + l_m) + r_{s1}.(l_{s1} + l_m)] \quad h_4 = [r_r(l_{s2} + l_m) + r_{s2}.(l_r + l_m)] \\ y = [l_m.(l_r + l_{s1}) + l_r l_{s1}].[l_m.(l_r + l_{s2}) + l_r l_{s2}] - l^2{}_m.l^2{}_r \quad L = l_m + l_r \end{cases} \tag{4}$$

3 DTC Strategy Control

3.1 Control strategy of flux

The DSIM relies on two three-level inverters separated from each other to be feed, to control the two stator fluxes $\varphi_{s\alpha}$,$\varphi_{s\beta}$ at the same time, the angle between them must be 30°, as shown in Fig. 2, the half resulting flux φ_{sres} is equivalent to modules of the individual fluxes φ_{s1} and $\varphi_{s2.}$ The estimated flux and the currents measurement contribute to the calculation of the electromagnetic torque.

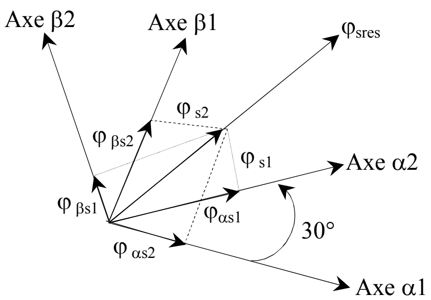

Fig. 2 Description of the various fluxes representation

$$
\begin{cases}
|\varphi_{s1}| = \sqrt{\varphi_{\alpha s1}^2 + \varphi_{\beta s1}^2} \\
|\varphi_{s2}| = \sqrt{\varphi_{\alpha s2}^2 + \varphi_{\beta s2}^2} \\
\vec{\varphi}_s = \vec{\varphi}_{sres} = \vec{\varphi}_{s1} e^{-j15^0} + \vec{\varphi}_{s2} e^{+j15^0} \\
\Gamma_{em1} = P(\varphi_{\alpha s1} i_{\beta s1} - \varphi_{\beta s1} i_{\alpha s1}) \\
\Gamma_{em2} = P(\varphi_{\alpha s2} i_{\beta s2} - \varphi_{\beta s2} i_{\alpha s2}) \\
\Gamma_{em} = \Gamma_{em1} + \Gamma_{em2}
\end{cases}
\quad (5)
$$

4 Principal of DTC-SVM

The values of V_{ds1},V_{ds2}, V_{qs1},V_{qs2}, are calculated from the error values of φ_{s1}, φ_{s2}, $\omega_1$with Γ_{em1}, ω_1 with Γ_{em2} respectively, for the SVM Blocks, depend on the four voltages $V_{ds1,2}$,$V_{ds1,2}$, in Fig.3, two three-level inverters are included in control strategy DTC-SVM.

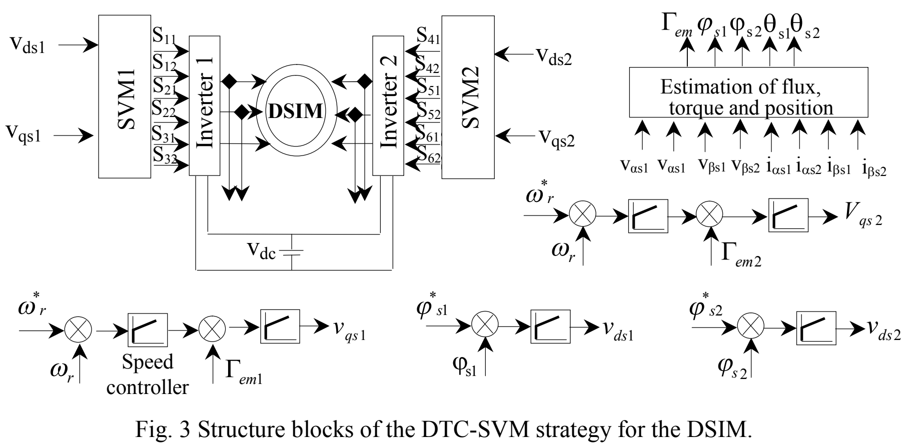

Fig. 3 Structure blocks of the DTC-SVM strategy for the DSIM.

5 DTC based on Neutral Network DTNC

5.1 Artificial neural network principle

The neural network model is considered a non-linear function, this model is inspired by the neuron model proposed by McCulloch and Pitts, This model has a simple mathematical explanation derived from biological reality, it is a system that has a set of inputs and output, shown in Fig.4

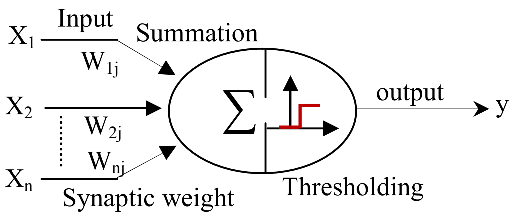

Fig.4 Neural network multi-layer structure.

5.2 Principal of DTNC

To eliminate the faults caused by the voltage vectors within the switching table (ripple, harmonics,…etc), a neural network algorithm based on reverse propagation learning is included in the DTNC strategy as shown in Fig.5.

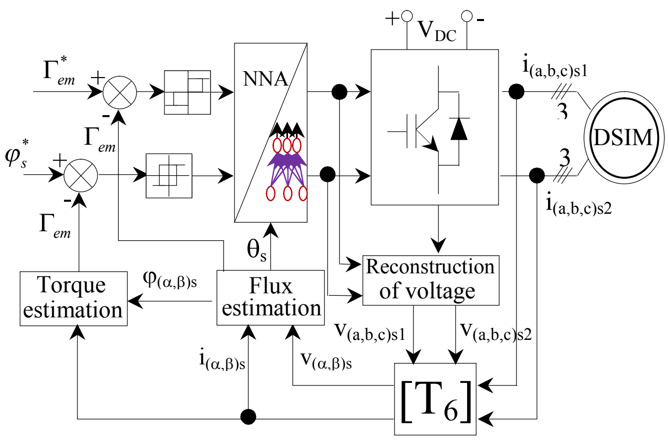

Fig. 5 Blocks structure of the DTNC strategy for the DSIM.

To describe the neural network used in the DTNC strategy, a matrix of inputs (torque error, flux error, sectors) and outputs (pulses) must be implemented, as shown below:

% Input matrices (E_Torque, E_Flux, Sector).

P=[311;211;111;011;301;301;101;001;312;212;112;012;302;202;102;002;313;213;113;013;303;203;103;003;314;214;114;014;304;204;104;004;315;215;115;015;305;205;105;005;316;216;116;016;306;206;106;006;317;217;117;017;307;207;107;007;318;218;118;018;308;208;108;008;319;219;119;019;309;209;109;009；3110;2110;1110;0110;3010;2010;1010;0010;3111;2111;1111;0111;3011;2011;1011;0011；3112;2112;1112;0112;3012;2012;1012;0012］

% Output matrices (Switching case or pulses)

P=[110;110;100;101;010;011;111;001;010;110;100;100;011;011;101;010;010;110;100;011;001;000;101;011;010;110;110;001;001;100;100;011;011;010;110;001;101;111;100;001;011;010;101;001;100;110;001;001;011;010;101;100;000;110;101;001;011;011;100;100;110;010;101;101;001;011;100;010;111;010;100;101;001;001;110;110;011;011;100;100;101;001;110;010;000;011;110;100;101;101;010;010;011; 001］

b2=min(a); b1=max(a); RNA=newff([b2' b1'],[24 3],{'logsig' 'logsig'}); %bdids.IW{1}=A'; %bdids.LW{2,1}=B'; %bdids.LW{3,2}=C; RNA.trainParam.epochs =207; [RNA,tr] = train(RNA,a',d'); %gensim(RNA)
Where RNA: Artificiel Neural Network

6 Simulation Results and discussion of DTC-SVM & DTNC

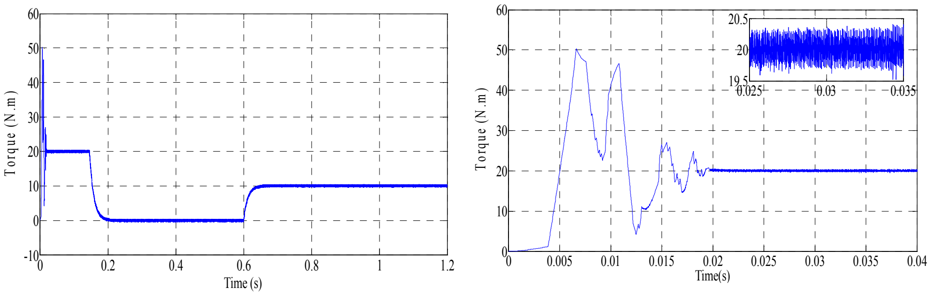

Fig. 6 Change and evolution of torque versus time of DTC-SVM strategy

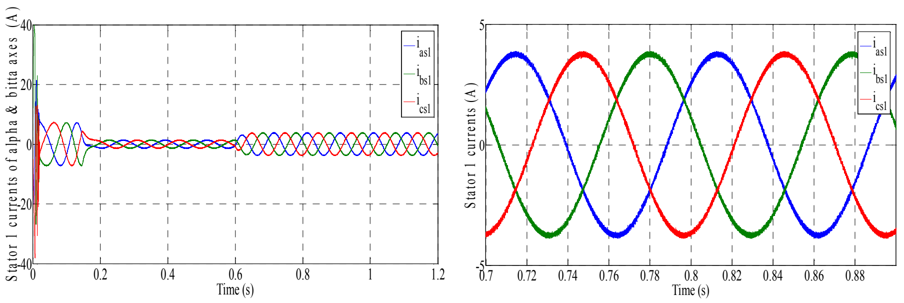

Fig.7 Stator1 currents of α and β phases of DTC-SVM strategy.

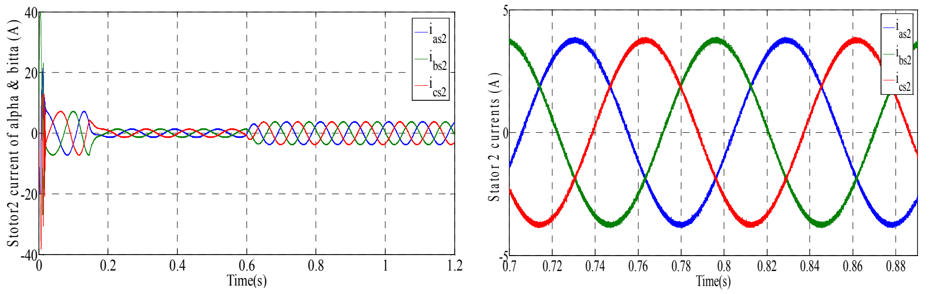

Fig.8 Stator2 currents of α and β phases of DTC-SVM strategy.

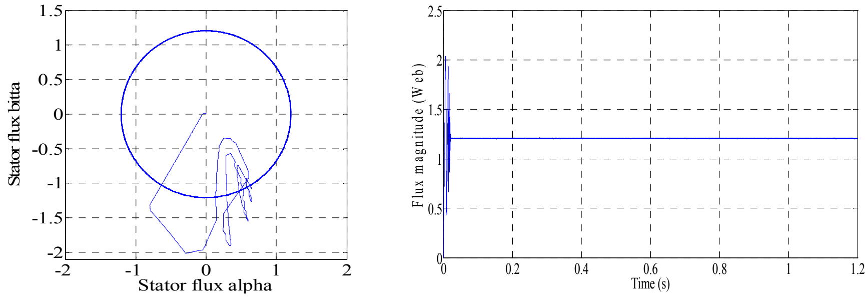

Fig. 9 Evolution of flux versus time for a reference φ_{s0} = 1.2 Web of DTC-SVM strategy.

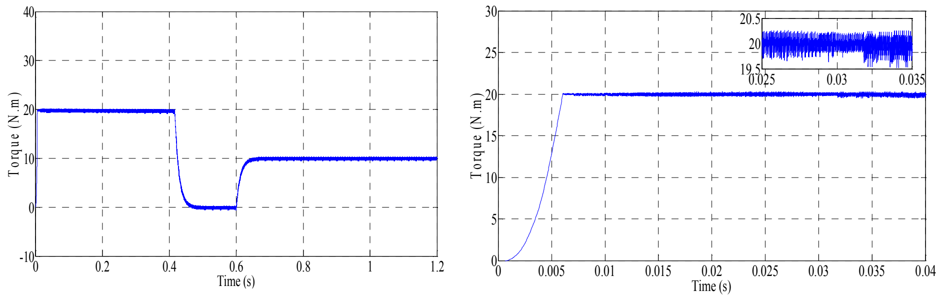

Fig. 10 Change and evolution of torque versus time of DTNC strategy

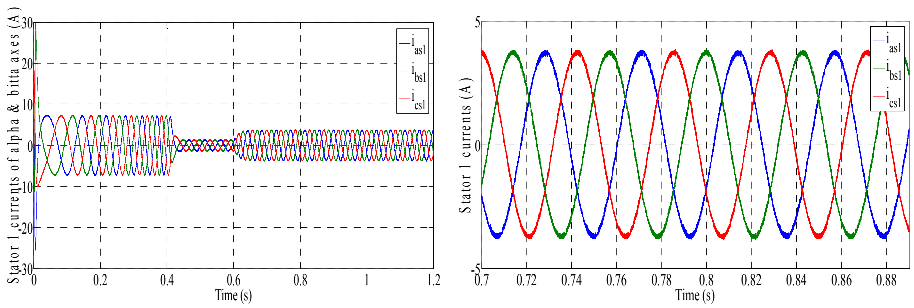

Fig.11 Stator2 currents of α and β phases of DTNC strategy

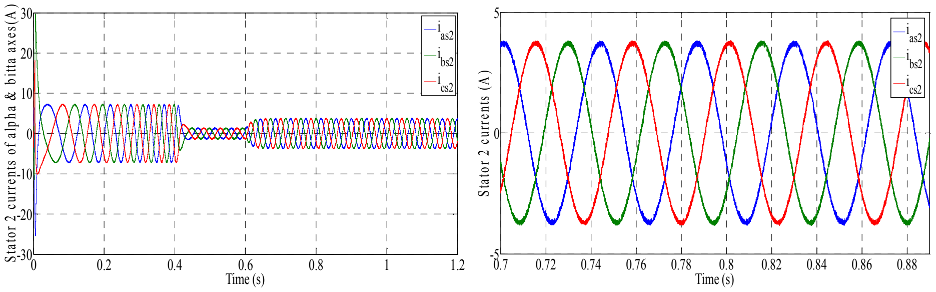

Fig.12 Stator2 currents of α and β phases of DTNC strategy

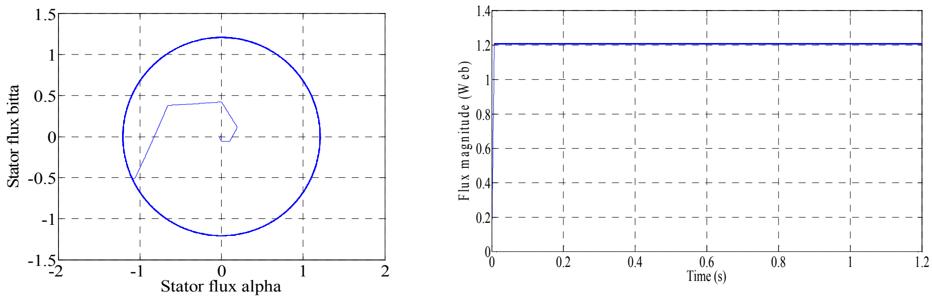

Fig. 13 Evolution of flux versus time for a reference φ_{s0} = 1.2 Web of DTNC strategy.

Fig.6,7,8,9 illustrate the behavior of the structure of the direct torque control applied to the DSIM supplied by voltage inverters at three levels for switching by Space Vector PWM (SVM) with the corrector multi-level of torque and stator flux.
These results show a good performance of the torque which precisely follows its reference value, this precision depends on the variation of the load.
The flux path describes a circle, the use of torque three-level corrector allows good control of the variation of the torque. Torque fluctuations change between the two values 19.7 and 20.3 N.m, the sectoral representation is for a position of the flux is detected in space, broken down into twelve symmetrical sectors.
The simulation results of Fig.10,11,12,13 show better performance than that obtained by DTC-SVM. It is interesting to notice in Fig.6 a torque response dynamic with a very fast transient regime Fig.10. The stator flux presents a very good response Fig.13, where we notice that there is less overshoot compared to those of the DTC-SVM, see the magnifying effect of flux Fig.9. Fig.13, shows a fast transient of the static flux modulus that to a perfectly circular shape without any steady-state ripple where the torque and flux follow their references with static errors which are virtually zero. As well as a significant attenuation of current ripples which appear sinusoidal Fig.12, the DTNC strategy achieves a constant switching frequency.
From these results, it can be seen that the performance of the system, controlled by a neural controller, is unsatisfactory, despite the online adaptation of the neural network.

This phenomenon is because there is not a general rule for choosing the parameters of the neural network (the learning rate, the number of neurons in the hidden layer), as well as the weighting values in the cost function. It is usually difficult to determine this choice just based on trial and error.

7 Study comparative between the DTC-SVM & DTNC strategies

The following table illustrates a comparative study between the two control strategies applied in this paper.

Table.1 adnavtages and disadvantages of DTC-SVM and DTNC strategies

Strategy	Advantages	Disadvantages
DTC-SVM	-Flux and torque are well controlled -The sinusoidal stator currents -Constant switching frequency around 3kHz	-The flux is slowly established. - The algorithm is more complicated
DTNC	- The Torque is well controlled - The flux and the torque perfectly follow its references - The sinusoidal stator currents	- Variable switching frequency around 3kHz. - Problem of choice of apprentice

8 Conclusion

This paper aims to compare the dynamic performance of direct torque control strategies by the Space Vector PWM (DTC-SVM) and neural network algorithm (DTNC), also, to know the effect of the two proposed strategies on the dynamic performance of the dual stator induction machine (DSIM) fed by three-level NPC inverters.
The obtained results prove that the electromagnetic torque of DTNC has less fluctuation compared to the torque obtained at DTC-SVM.
Both stator currents of the proposed strategies have a sinusoidal form, and the DTNC strategy stator currents are of better quality than DTC-SVM stator currents.
The stator flux trajectory mesh of alpha and bitta axes has a thin circular trajectory in two proposed strategies.
On the negative side, it can be said that the DTC-SVM strategy algorithm is more complicated, there is a problem of choice of apprentice in DTNC strategy.
From the above, it can be said that the application of artificial intelligence technique by the neural network algorithm has led to improving the dynamic performance of the direct torque control strategy DTNC for the DSIM compared to the space vector PWM application performance.

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