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Amelioration Effectiveness of Torque and Rotor Flux Control Applied to the Asynchronous Generator for Dual-rotor Wind Turbine using Neural Third-order Sliding Mode Approaches

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ABSTRACT

In this paper, a neural third-order sliding mode-direct torque control (NTOSM-DTC) for an asynchronous generator (AG) based dual-rotor wind turbine (DRWT) is proposed. The classical DTC strategy with traditional proportional-integral (PI) controllers has been widely applied to induction machines in recent years due to the high characteristics that it provides in comparison with the classical DTC switching technique. Meanwhile, it has a major drawback that are the significant current, rotor flux and torque ripples generated by the traditional PI controllers. To overcome these drawbacks, the improvement of this control technique by removing these controllers is designed in this paper. The proposed intelligenet nonlinear control technique is based on replacing the classical PI controllers with neural TOSM controllers which will have the same inputs as these controllers. The simulation was performed in Matlab software, and the results obtained make it possible to evaluate the characteristics of the proposed intelligenet nonlinear control technique over the traditional one.

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1. INTRODUCTION

In recent years, the demand for electric power has been increasing. This is due to an increase in number of engines used in our daily lives, as well as the abandonment of traditional energy sources such as petroleum. The latter has become a threat to human life. Conventional energies (fossil fuels and natural gas) are among the causes of global warming. This made several governments across the world search for other clean and economically inexpensive sources of energy. Among these solutions, we find solar energy, wind energy, the potential energy of water, these energies are inexpensive, and renewable energies. Moreover, it is clean and easily exploitable energies [1].

Wind energy is among the most widely used renewable energies in the field of electric power generation. This is because of the simplicity of use, clean energy, inexpensive and gives a significant value of electrical energy [2]. This method is based on placing the turbines on shafts against the wind. The rotation of the turbine leads to the rotation of the generator and thus the generation of electric power. Several generators can be used in wind energy, such as the asynchronous generator [3] and the synchronous generator [4]. However, the asynchronous generator is the most widely used in the field of electric power generation using wind energy, especially in the case of variable wind speed. This is due to the advantages and characteristics of the asynchronous generator such as ease of control, efficiency, durability, and low cost [5].

As is known, there are several ways to control electrical machines (generators), such as direct torque control (DTC) [6], filed-oriented control (FOC) [7], direct power control (DPC) [8], backstepping control [9], synergetic control [10], nonlinear control [11-13], etc. However, the direct torque control strategy is the most prevalent and widely used method for controlling

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electrical machines such as induction motor and synchronous motor, and this is because of the advantages and characteristics that it has compared to other methods. The direct torque control strategy is an easy algorithmic method, can be implemented easily, low cost, and gives very satisfactory results compared to other methods. This method relies on the use of hysteresis comparators and a lookup table to control the torque and flux of the electric machine. This method has been used to control several electrical machines such as the asynchronous motor [14], synchronous motor [15], multi-phase induction motor [16], synchronous generator [17], multi-phase synchronous motor [18], and asynchronous generator [19].

In the field of electric power generation from wind, this method is used to control the asynchronous generator, due to the simplicity of the algorithm and the dynamic response. In this case, the torque and flux of the asynchronous generator are controlled. Controlling these two amounts leads to controlling the current and the output active power generated by the generator (AG).

Despite the advantages of this method, it has several disadvantages like any other method. Among the disadvantages of the direct torque control method are ripples at the level of current, torque, and rotor flux. Plus, the direct torque control method gives a large total harmonic distortion (THD) ratio [20].

As it is known, these defects affect the yield and life span of the electric generator. The fluctuations in torque affect the quality of the current and the effective power [21].

There are several studies and scientific research conducted on the method of direct torque control in order to reduce the ripples of torque and current resulting from the asynchronous generator using several methods such as nonlinear methods (sliding mode control and super twisting algorithm), artificial intelligence (fuzzy logic, genetic algorithm, neural network, etc) and a combination of artificial intelligence and nonlinear methods (neuro-sliding mode control, fuzzy-super twisting algorithm, etc) in order to obtain a more robust method and thus, obtaining very satisfactory results. Fuzzy DTC control was proposed by Ayrira et al. [22] to control the asynchronous generator-based wind turbine. The proposed DTC strategy is more robust compared to the traditional DTC technique. On the other hand, the fuzzy DTC control reduces more the THD value of stator current and active power ripple compared to the traditional DTC technique.

A new method is proposed by Benbouhenni [23], based on the use of both space vector modulation (SVM) and proportional-integral (PI) controller. This is in order to reduce the fluctuations in both current and torque. This method is based on replacing lookup table and hysteresis comparators with SVM technique and PI controllers, respectively. The proposed method is more robust and can be easily accomplished. The simulation results showed the effectiveness of the proposed method in reducing torque ripples and THD value compared to the classical method. PI controller and neural networks are combined to improve the performance and effectiveness of direct torque control [24]. The results showed the effectiveness of the proposed method in improving the quality of the current produced by the asynchronous generator compared to the classical method.

Chattering is defined as the disadvantages of the traditional sliding mode approach at very high frequencies which creates noises in the system. A higher-order sliding mode approach is suitable for the elimination of this chattering phenomenon which was explained by Kelkouland Boumediene [25]. Many strategies like super twisting algorithm, terminal synergetic control, second-order continuous sliding mode, third-order sliding mode control, and fast terminal sliding mode approach are available in the works. These strategies are used to improve the characteristics of an asynchronous generator [26-28]. On use, the settling time and chattering are eliminated or minimized which was presented in the traditional sliding mode approach. These nonlinear methods have been relied upon in some works in order to improve the effectiveness of the direct torque control method in order to obtain a high quality in the current produced by the asynchronous generator. A second-order continuous sliding mode approach was used by Boudjema et al. [29] to improve the DTC method for an asynchronous generator-based wind turbine. The results showed the effectiveness of the DTC method with a second-order continuous sliding mode approach in reducing torque and current ripples compared to the classical DTC method with PI controllers. It also shows the effectiveness of the proposed nonlinear DTC method. Boudjema et al. [29] discussed about the value of THD of stator current, as we find out that the proposed nonlinear DTC method gave a much lower value than the classical DTC method. Another nonlinear technique was proposed by Benbouhenni and Bizon [30] to improve the performances of the DTC control technique of the asynchronous generator-based dual-rotor wind turbine (DRWT) system. This new nonlinear technique is based on a third-order sliding mode controller. However, the proposed DTC with third-order sliding mode is simple to control, easy to implement, robust algorithm, and reduces the THD value of stator current and power ripple compared to the DTC strategy with PI controllers. Fractional-order second-order continuous sliding mode approach was proposed to improve the characterisitics of DTC control with a modified SVM technique to control the asynchronous generator-based wind turbine [31]. The proposed nonlinear DTC control is more robust than classical DTC with a modified SVM technique. On the other hand, the DTC strategy with fractional-order second-order sliding mode approach reduces the ripples in the torque, current, and rotor flux compared to the DTC strategy with the traditional second-order sliding mode approach. A new method for DTC control has been proposed based on the modified super twisting algorithm [32]. This new DTC method is a modification of the DTC-PI method, where PI controllers are replaced by modified super twisting algorithms.

In this work, a new nonlinear method is proposed in order to improve the efficiency and performance of the DTC control method, and thus improve the quality of the current and the active power generated by the asynchronous generator-based dual-rotor wind turbine system.

In addition, in this work, a new intelligent high-order sliding mode approach was proposed to improve the performance of the DTC control technique. this proposed high-order sliding mode approach is named the neural third-order sliding mode (NTOSM) strategy. This proposed intelligent nonlinear controller is a more robust, simple algorithm and easy to implement. The objective is to reduce the ripples in the current, rotor flux, and torque of asynchronous generator-based dual-rotor wind turbine systems. The principle of the schematic and the disadvantages or advantages of DTC with neural TSOM controllers are proposed.

The parameters used to observe the characteristics of the proposed intelligent nonlinear DTC control strategy are the THD value of stator current, rotor flux ripple, torque ripple, steady-state error, robustness, response time, and current ripple.

Summarizing, the novelty and main findings of this work are as follows:

- A new neural TOSM strategy based on the DTC technique is proposed to reduce the THD value of stator current;
- Neural TOSM controllers minimize the tracking error for torque and rotor flux towards the references of AG-based DRWT systems.
- The DTC-NTOSM technique with modified SVM technique minimizes ripples of torque, rotor flux, and stator current of AG-based DRWT systems.

Thus, the structure of the work is as follows. In section 2 dual-rotor wind turbine system models are presented. In section 3 the model of the AG is presented using Park transformations. In section 4 the proposed neural TOSM controller is presented. Section 5 includes the DTC control technique with designed neural TOSM controllers. Section 6 presents and discusses the results of the present research.

2. DUAL-ROTOR WIND TURBINE

Dual-rotor wind turbine is a new technology that has emerged in recent years to generate electricity from wind power. Studies on it have shown how effective this new technology is compared to classic turbines. This new technology is detailed in literature [33, 34]. This new technology offers more pneumatic torque than a single-rotor turbine. The dual-rotor wind turbine is not affected by the wind currents generated by the wind farm like this classic turbine, which in the future will be widely spread. Among the disadvantages of this technology is that it contains a larger number of mechanical components and is difficult to control compared to the classic turbine. But it offers a greater return compared to the rest of the existing technologies to this day.

The total aerodynamic torque of DRWT is the auxiliary rotor (AR) torque add to the main rotor (MR) torque as shown by the following equation [35]:

$$T_{DRWT} = T_{MR} + T_{AR} \tag{1}$$

with:

$$T_{AR} = \frac{1}{2\,\lambda_{AR}^{3}}.A.\rho.\pi.R_{AR}^{5}.C_{p}.w_{AR}^{2} \tag{2}$$

$$T_{MR} = \frac{1}{2\,\lambda_{MR}^{3}}.A.\rho.\pi.R_{AR}^{5}.C_{p}.w_{MR}^{2} \tag{3}$$

where, λ_{AR}, λ_{MR}: the tip speed ration of the main and auxiliary turbines, R_{MR}, R_{AR} : Blade radius of the auxiliary and main rotors, ρ : the air density and w_{AR}, w_{MR} the mechanical speed of the auxiliary and main rotors.

The tip speed ratios of the AR is given :

$$\lambda_{AR} = \frac{w_{AR}.R_{AR}}{V_1} \tag{4}$$

The tip speed ratios of the MR is given :

$$\lambda_{MR} = \frac{w_{MR}.R_{MR}}{V_{MR}} \tag{5}$$

where, V_{MR} is the speed of the unified wind on main rotor and V_1 is the wind speed on an auxiliary rotor.

The wind speed on the main turbine is given by Yahdou et al. [36]:

$$V_x = V_1(1 - \frac{1-\sqrt{(1-C_T)}}{2}(1 + \frac{2.x}{\sqrt{1+4.x^2}})) \tag{6}$$

with Vx : is the velocity of the disturbed wind between rotors at point x and C_T the trust coefficient, which is taken to be 0.9; x: the non-dimensional distance from the auxiliary rotor disk. So, with respect to x=15, the value of the Vx close to the main rotor is computable (rotors are located 15 meters apart from each other) [37].

The power coefficient C_P equation is approximated using a non-linear function according to following expression [10].

$$C_P = (0.5-0.167)(\beta-2)\sin\left[\frac{\pi(\lambda+0.1)}{18.5-0.3(\beta-2)}\right] - 0.0018(\lambda-3)(\beta-2) \tag{7}$$

3. THE AG MODEL

The Park model of the AG is largely used. The equations of fluxes and voltages for the AG rotor and stator in the Park reference frame are given as follows [38, 39]:

$$\begin{cases} V_{ds} = R_s I_{ds} + \frac{d}{dt}\psi_{ds} - \omega_s \psi_{qs} \\ V_{qs} = R_s I_{qs} + \frac{d}{dt}\psi_{qs} + \omega_s \psi_{ds} \\ V_{dr} = R_r I_{dr} + \frac{d}{dt}\psi_{dr} - \omega_r \psi_{qr} \\ V_{qr} = R_r I_{qr} + \frac{d}{dt}\psi_{qr} + \omega_r \psi_{dr} \end{cases} \tag{8}$$

$$\begin{cases} \psi_{ds} = L_s I_{ds} + M I_{dr} \\ \psi_{qs} = L_s I_{qs} + M I_{qr} \\ \psi_{dr} = L_r I_{dr} + M I_{ds} \\ \psi_{qr} = L_r I_{qr} + M I_{qs} \end{cases} \tag{9}$$

The electrical model of the AG is completed by the following mechanical equation:

$$T_{em} = T_r + J \cdot \frac{d\Omega}{dt} + f \cdot \Omega \tag{10}$$

The torque (T_{em}) can be written as follows:

$$T_{em} = \frac{3}{2} p \frac{M}{L_s} (\psi_{qs} I_{dr} - \psi_{ds} I_{qr}) \tag{11}$$

4. NEURAL THIRD-ORDER SLIDING MODE CONTROLLER

In this part, it is explained how to implement this new method (neural TOSM) and its advantages. This new method is a modification of the TOSM technique published by Benbouhenni and Bizon [30].

4. 1. Design of the TOSM Controller There are many nonlinear controllers proposed to control the flux/torque of AC machines in the literature. Among all the strategies proposed for the high-order sliding mode approach, the super twisting controller is an exception, which requires only information on the sliding surface [11]. The third-order sliding mode approach is an effective technique for uncertain systems and it overcomes the main disadvantages of the classical sliding mode approach described. TOSM is a non-linear controller and is an alternative to linear and nonlinear techniques. This method was first proposed in order to improve the performance and efficiency of the direct power control (DPC) of asynchronous generator-based DRWT system [40] and then applied to DTC control of an asynchronous generator-based DRWT system. However, this technique is based on the super twisting algorithm. The control input of the TOSM controller comprises of three inputs as Equation (12).

$$u(t) = u_1 + u_2 + u_3 \tag{12}$$

With :

$$u_1(t) = \lambda_1 \sqrt{|S|} \times sign\ (S) \tag{13}$$

$$u_2(t) = \lambda_2 \times \int sign\ (S) \times dt \tag{14}$$

$$u_3(t) = \lambda_3 \times sign\ (S) \tag{15}$$

The control input of the TOSM controller is obtained as Equation (16).

$$u(t) = \lambda_1 \sqrt{|S|}.sign(S) + \lambda_2 \int sign(S)dt + \lambda_3 sign(S) \tag{16}$$

where, λ1, λ2 and λ3 are tuning constants of the TOSM controller.

Figure 1 shows block diagram representation of TOSM controller. Through this figure, the TOSM controller is a simple algorithm and easy to implement.

The stability condition is given by the following relation:

$$S\dot{S}\langle 0 \tag{17}$$

4. 2. Design of the Neural TOSM Controller Neural TOSM controller is a new nonlinear technique, where this proposed technique is a simple algorithm, easy to implement, and more robust. This proposed new nonlinear technique based on a combined neural algorithm and TOSM controller in order to obtain a robust controller. This new nonlinear method (neural TOSM) is a modification of the TOSM method, where *sign(U)* of the TOSM controller is compensated by neural networks. Figure 2 shows the proposed neural TOSM controller. Through this figure, the proposed neural TOSM controller is a simple algorithm and easy to implement.

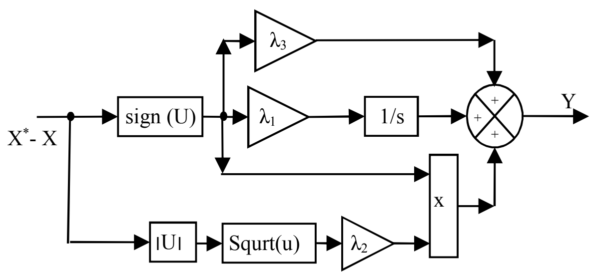


Figure 1. Structure of the TOSM controller

In the proposed neural TOSM controller, feedforward neural network controllers were used to the replace the *sign(U)* functions.

This proposed controller is used in this paper for reducing a stator current, torque, and rotor flux ripples in an AG-based DRWT system using the DTC technique which the inverter was controlled by the modified SVM strategy.

5. DTC CONTROL WITH NEURAL TOSM CONTROLLERS

5. 1. DTC-TOSM Strategy The DTC-TOSM principle is to control the torque and the rotor flux of the AG-based DRWT systems. The rotor flux is controlled utilizing the direct axis voltage V_{dr}, while the torque is controlled utilizing the quadrature axis voltage V_{qr} [41].

As is known, flux and torque ripples which represent the big problems of the classical DTC control with PI controllers can be very hurtful for the AG-DRWT because of the use of the hysteresis comparators and switching table or PI controllers [30]. The major idea was to replace the PI controllers with TOSM controllers and at the same time to conserve the major characteristics of the whole system.

The DTC-TSOM technique, which is proposed to control the torque and rotor flux of the AG-DRWT system is shown in Figure 3.

The magnitude of rotor flux, which can be estimated by the following experssions [23]:

$$\begin{cases} Q_{r\alpha} = \int_0^t (V_{r\alpha} - R_r I_{r\alpha})dt \\ Q_{r\beta} = \int_0^t (V_{r\beta} - R_r I_{r\beta})dt \end{cases} \tag{18}$$

The rotor flux amplitude is given below:

$$Q_r = \sqrt{Q_{r\alpha}^2 + Q_{r\beta}^2} \tag{19}$$

with:

$$\left|\overline{Q_r}\right| = \frac{\left|\overline{V_r}\right|}{w_r} \tag{20}$$

The rotor flux angle is calculated by Equation (21):

$$\theta_r = arctg\left(\frac{Q_{r\beta}}{Q_{r\alpha}}\right) \tag{21}$$

The electromagnetic torque, which can be estimated by Equation (22):

$$T_{em} = -\frac{3}{2}p \cdot (Q_{r\alpha} I_{r\beta} - Q_{r\beta} I_{r\alpha}) \tag{22}$$

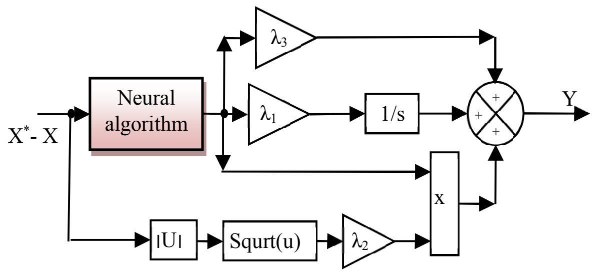


Figure 2. Structure of the command law of the proposed neural TOSM controller

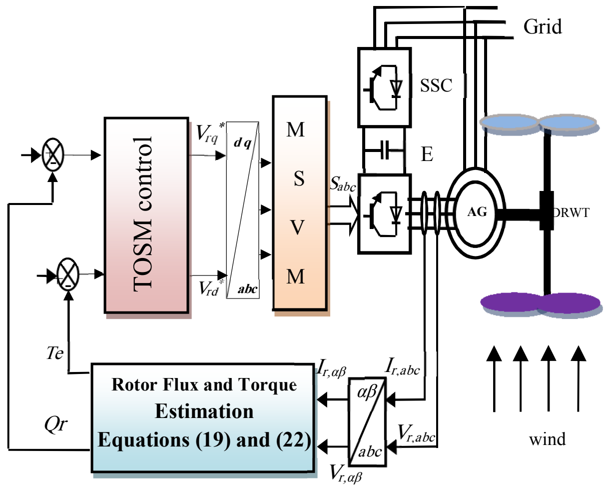


Figure 3. Bloc diagram of the AG with DTC-TOSM

The errors of the electromagnetic torque and rotor flux are shown in Equations (23) and (24).

$$S_{Tem} = T_{em}^* - T_{em} \tag{23}$$

$$S_{Qr} = Q_r^* - Q_r \tag{24}$$

where the surfaces are the flux magnitude error $S_{\varphi r} = \varphi_r^* - \varphi_r$ and the electromagnetic torque error $S_{Tem} = T_{em}^* - T_{em}$.

The sliding surfaces shown in Equations (23) and (24) are used as input to the TOSM control law. Torque and rotor flux TOSM controllers are used to influence respectively on the two rotor voltage components as in Equations (25) and (26).

$$V_{dr}^* = \lambda_1 \sqrt{|S_{Qr}|}.sign(S_{Qr}) + \lambda_2 \int sign(S_{Qr})dt + \lambda_3 sign(S_{Qr}) \tag{25}$$

$$V_{qr}^* = \lambda_1 \sqrt{|S_{Tem}|}.sign(S_{Tem}) + \lambda_2 \int sign(S_{Tem})dt + \lambda_3 sign(S_{Tem}) \tag{26}$$

The controller structure for the TOSM controller for the torque and rotor flux of the DTC control strategy is presented in Figures 4 and 5, respectively.

The DTC-TOSM control technique is proposed by Benbouhenni and Bizon [30] to obtain a minimum rotor flux and torque ripples and to minimize the chattering phenomenon. The DTC-TOSM strategy improves the performances of the asynchronous generator compared to DTC with PI controllers.

5. 2. DTC-NTOSM Control strategy The DTC control with neural TSOM controllers, which is proposed to control the torque and rotor flux of the AG-DRWT system is shown in Figure 6. This proposed strategy is more simple, easy to implement. This proposed strategy is robust compared to traditional DTC and DTC-TOSM techniques.

The DTC-NTOSM method is a modification of the DTC-TOSM method, where the proposed NTOSM method is used instead of the TOSM controller. The newly proposed method is based on a combination of the TOSM controller and feedforward neural networks in order to improve the characteristics and advantages of the DTC method of the AG-DRWT system.

The controller structure for the neural TOSM algorithms for the torque and rotor flux of the DTC control strategy of the AG-DRWT system is presented in Figures 7 and 8, respectively.

In order to make the feedforward neural networks, we used the Levenberg-marquardt backpropagation algorithm. This algorithm is a simple algorithm. However, the feedforward neural networks structure consists of three layers: hidden layer, output layer, and input layer. The characteristics of the feedforward neural networks used to improve the TOSM controller are summarized in Table 1.

The feedforward neural network training of torque is shown in Figure 9. Figure 10 shows the training plot of the feedforward neural networks for torque and rotor flux. From this figure, the best training performance is 3.6315e^{-006} at epoch 29 for torque and 3.4867e^{-008} at epoch 3 for rotor flux. The error plot of feedforward neural networks is shown in Figure 11. Through this figure, we find that the targeting field is [-0.5 0.5] and the training value is R=0.99997, and the output is given by (output = 1*Target+2.6e^{-005}) for torque and for rotor flux the training value is R=0.99912, and the output is given by (output = 1*Target+3.3e^{-006}). On the other hand, Gradiant, Mu, and Validation Checks are shown in Figure 12 and they represent the properties of the feedforward neural networks of torque. From this figure, the best Gradiant, Mu, and validation checks are 7.1107e^{-006}, 0.08, and 0 at epoch 29, respectively.

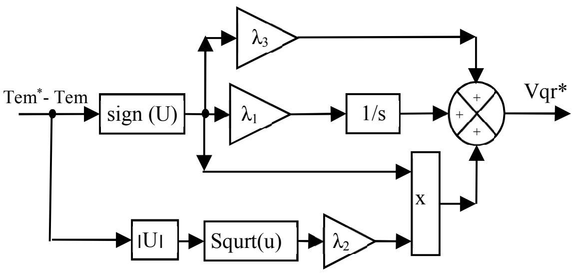


Figure 4. Structure of the TOSM torque controller

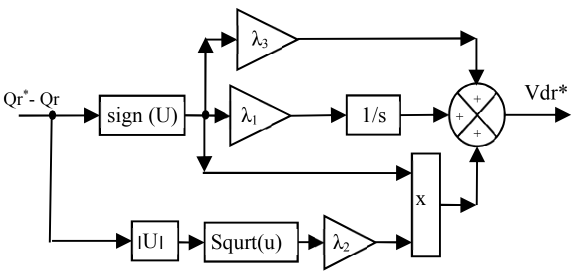


Figure 5. Structure of the TOSM flux controller

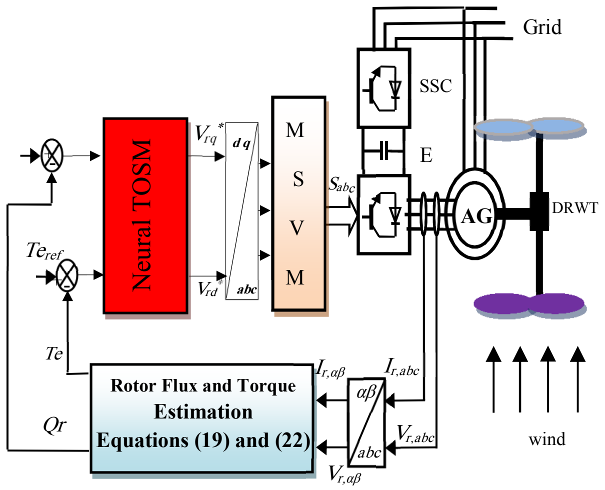


Figure 6. Bloc diagram of the AG with DTC-NTOSM

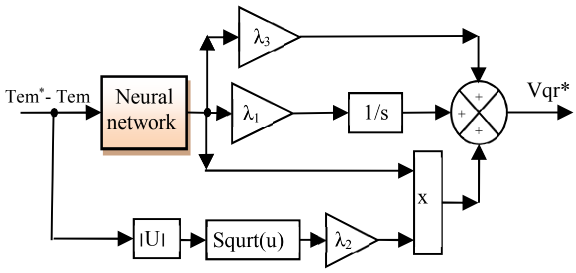


Figure 7. Proposed neural TOSM torque controller

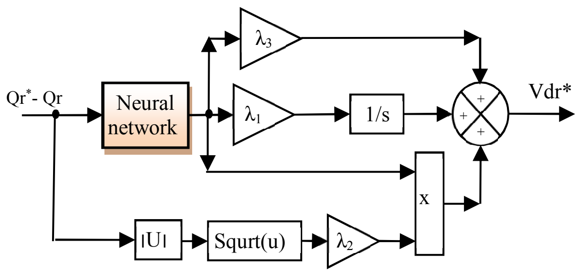


Figure 8. Proposed neural TOSM flux controller

TABLE 1. Parameters of the feedforward neural networks

4	Values
Performances	Mean Squard Error (mse)
Training	Levenberg-Marquardt algorithm (trainlm)
TrainParam.show	50
TrainParam.Lr	0.05
Neurons of output layer	1
TrainParam.goal	0
TrainParam.mu	0.8
Neurons of input layer	1
Coeff of acceleration of convergence(mc)	0.9
Derivative	Default (default deriv)
Neurons of hidden layer	12
Number of hidden layer	1
Functions of activation	Tensing, Purling, trainlm
Number of output layer	1
TrainParam.eposh	200
Number of input layer	1

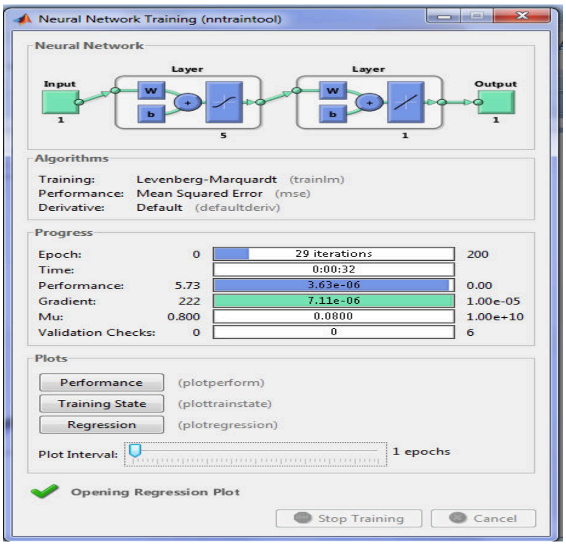
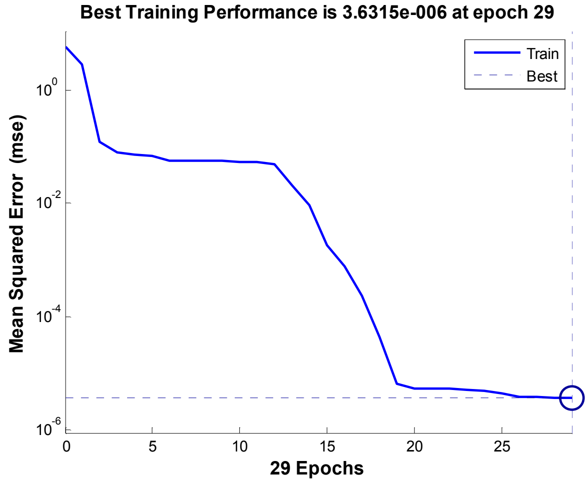


Figure 9. Feedforward neural networks training

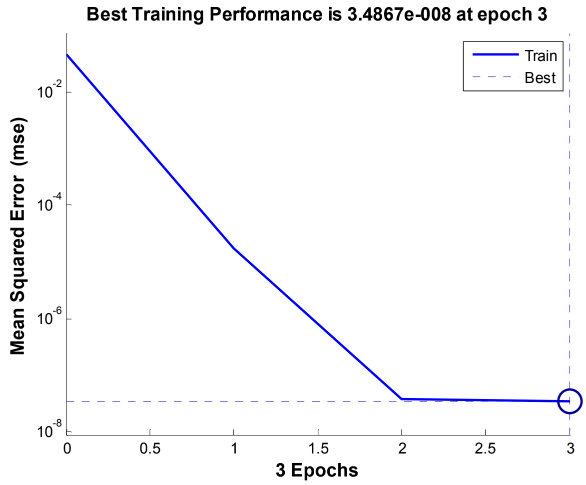
6. ANALYSIS AND SIMULATION RESULTS

The designed control techniques are simulated and compared regarding stator current harmonics distortion, rotor flux ripple, reference tracking, torque ripples, and robustness against AG parameter variations.

The simulations are carried out with a 1.5 MW AG attached to a 398 V/50 Hz grid, by using the simulation numerique. The generator parameters used in this work

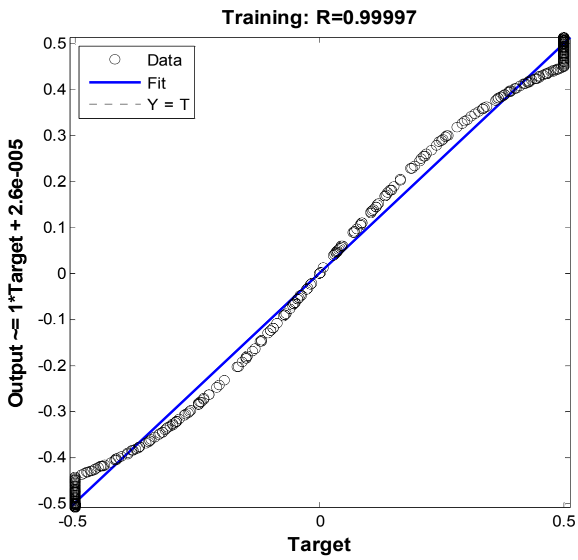


(a) Torque

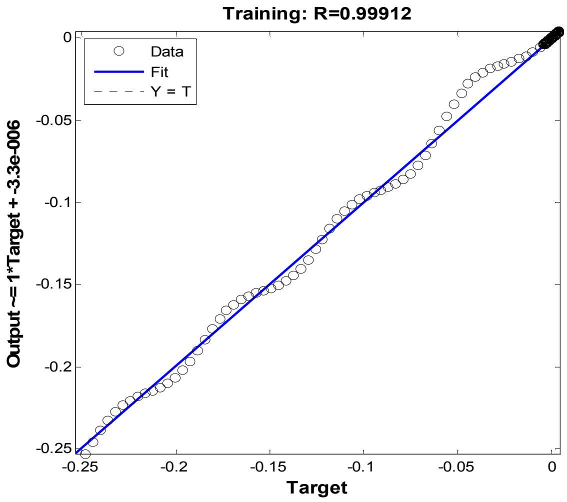


(b) Rotor flux

Figure 10. Training plot



(a) Torque



(b) Rotor flux

Figure 11. Error plot

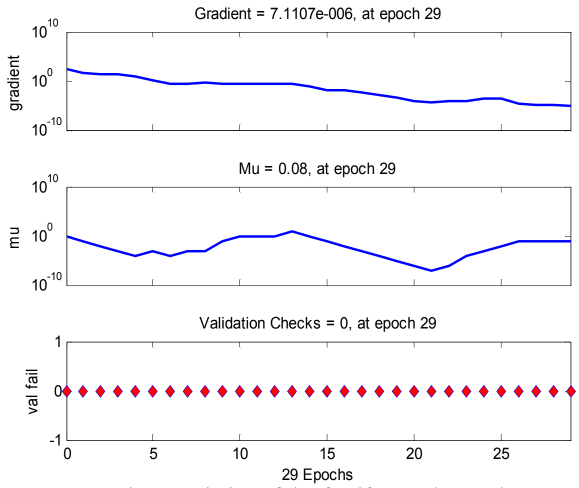


Figure 12. Characteristics of the feedforward neural network for torque

are the same as the generator parameters used in the literature [29-32]. The two nonlinear DTC strategies; DTC-TOSM and DTC-NTOSM are simulated and compared in terms of torque ripple, reference tracking, current ripple, THD value of current, and rotor flux ripple.

A. First test: This test represents the reference tracking test. This test aims to study the behavior of the proposed strategies of nonlinear DTC control by taking the generated speed as constant and equal to the nominal value. As well as knowing which DTC method provides the best results and minimizes electromagnetic torque and rotor flux ripples together. The results obtained are shown in Figures 13 to 20. As it's shown in Figures 15-16, for the two nonlinear DTC strategies, the rotor flux, and torque track almost perfectly their reference values.

Figure 17 shows the stator current of both nonlinear DTC control techniques. It, therefore, confirms that the amplitudes of the currents depend on the state of the drive system and the value of the load rotor flux and torque.

Figures 13 and 14 show the THD value of stator current of the AG-based DRWT system for both nonlinear DTC control strategies. It can be clearly observed through these figures that the THD value is reduced for the DTC-NTOSM (THD = 0.32%) when compared to the DTC-TOSM (THD = 0.50%).

The zoom in the torque, rotor flux, and stator current is shown in Figures 18, 19 and 20, respectively. It can be seen that the DTC-NTOSM control strategy reduced the ripples in torque, rotor flux, and stator current compared to the DTC-TOSM control technique. Based on the results above, it can be said that the proposed DTC-NTOSM control strategy has proven its efficiency in reducing ripples and chattering phenomena in addition to keep the same advantages of the DTC-TOSM control strategy.

The results of this test are summarized in Table 2. Through this table, it can be said that the proposed DTC-

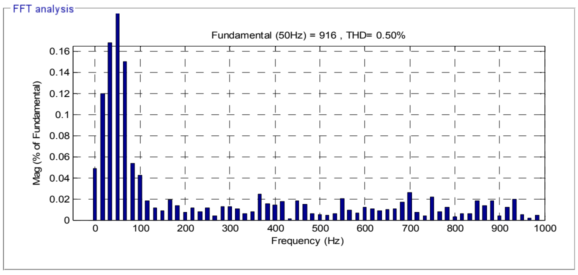


Figure 13. THD (DTC-TOSM)

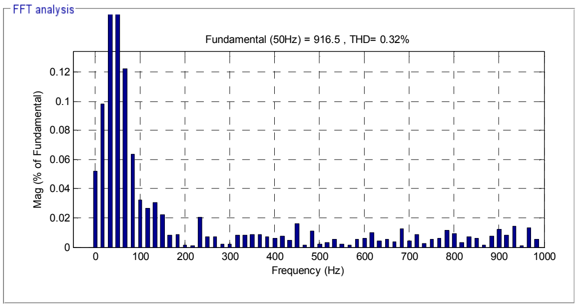


Figure 14. THD (DTC-NTOSM)

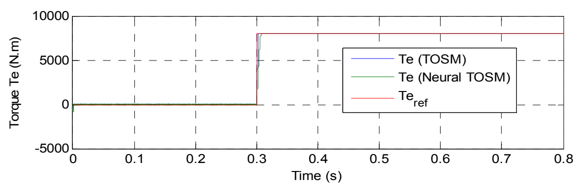


Figure 15. Torque

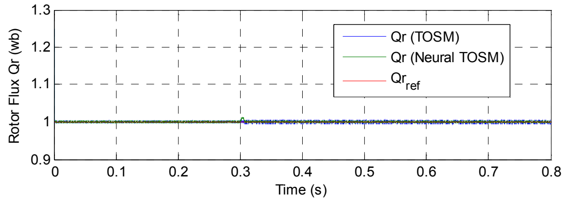


Figure 16. Rotor flux

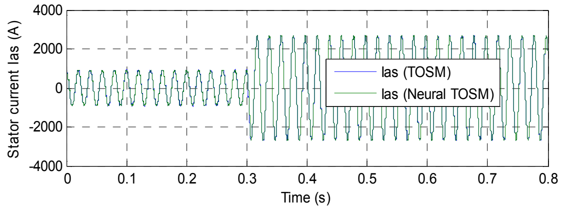


Figure 17. Stator current

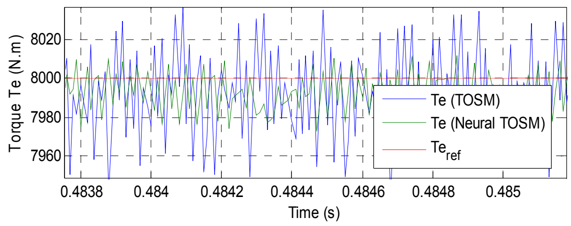


Figure 18. Zoom (torque)

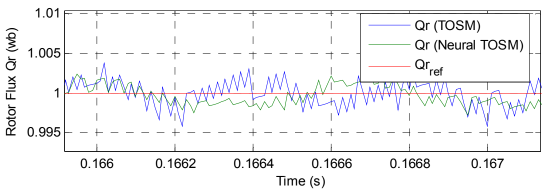


Figure 19. Zoom (rotor flux)

NTOSM control method is better than the DTC-TOSM control strategy in terms of reducing current, torque and rotor flux ripples. Also, in terms of dynamic response. On the other hand, the proposed DTC-NTOSM control method minimized the ripples of current, torque, and rotor flux by about 75%, 70 and 62.50%, respectively, compared to the DTC-TOSM control strategy.

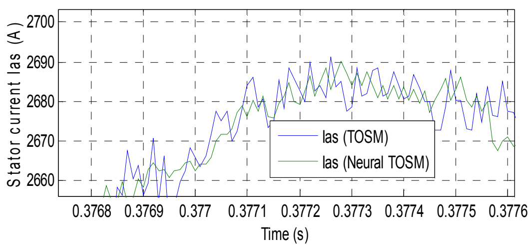


Figure 20. Zoom (current)

TABLE 2. Compare the results obtained from the proposed method with the classical method

Criteria	Strategies	
	DTC-TOSM	**DTC-NTOSM**
Dynamic response (s)	Medium	Fast
Settling time (ms)	High	Medium
Overshoot (%)	Remarkable ≈ 3%	Neglected near ≈ 1%
Torque and flux tracking	Good	Excellent
Sensitivity to parameter change	Medium	Low
Rise Time (s)	Medium	Low
THD (%)	0.50	0.32
Simplicity of converter and filter design	Simple	Simple
Torque: ripple (N.m)	Around 100	Around 30
Simplicity of calculations	Simple	Simple
Rotor flux: ripple (wb)	Around 0.008	Around 0.003
Improvement of transient performance	Good	Excellent
Stator current: ripple (A)	Around 20	Around 5
Quality of stator current	Good	Excellent

The proposed DTC-NTOSM control strategy reduced the THD value of current by about 36% compared to the DTC-TOSM control strategy.

B. Second test: The principal objective of this test is to examine the influence of an asychronous generator parameters variation on the rotor flux, stator current, and torque and behavior for the proposed intelligent nonlinear DTC control strategy. The simulation results are shown in Figures 21 to 28. These figures show that the torque and rotor flux follows the references with high accuracy for all the proposed methods (see Figures 23 and 24). However, the stator current remains sinusoidal (see Figure 25) and is related to the system and the reference value of the torque and rotor flux. On the other hand, we notice by looking at Figures 26 to 28 that the proposed intelligent nonlinear DTC-NTOSM control method significantly reduced the ripples of stator current, torque, and rotor flux compared to the DTC-TOSM control strategy.

Figures 21 to 22 show the THD value of stator current for two proposed DTC control strategies. It can be clearly observed that the THD value is reduced for the proposed intelligent nonlinear DTC-NTOSM control method (0.32%) when compared to the DTC-TOSM control strategy (0.55%). This result is attractive for dual-rotor wind turbine applications to guarantee the quality and stability of the generated power when the generator parameters are changing. Thus, it can be said that the proposed intelligent nonlinear DTC-NTOSM control method provided better performance than the DTC-TOSM control strategy, and this is what we observed through two tests, as well as the THD ratio and the value of torque and rotor flux ripples (see Table 3).

Table 3 summarizes the results obtained. Through this table, the proposed intelligent nonlinear DTC-NTOSM control method minimized the ripples in the stator current, torque, and rotor flux by about 66.66%, 61.11%, and 60%, respectively compared to the DTC-TOSM control strategy. On the other hand, the proposed DTC-NTOSM control strategy reduced the THD value by about 41.81% compared to the DTC-TOSM control strategy.

On the other hand, this proposed intelligent nonlinear DTC-NTOSM control strategy minimized the THD value of stator current compared to other strategies (see Table 4).

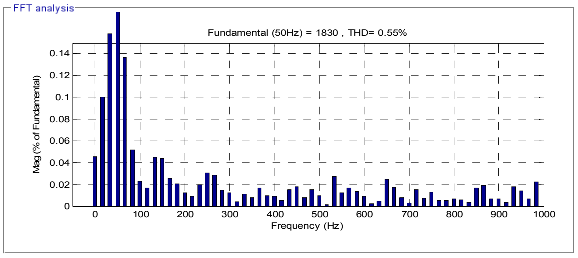


Figure 21. THD (DTC-TOSM)

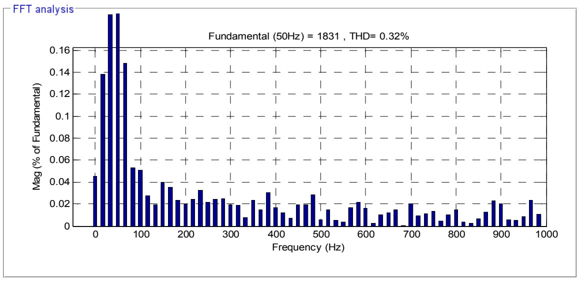


Figure 22. THD (DTC-NTOSM)

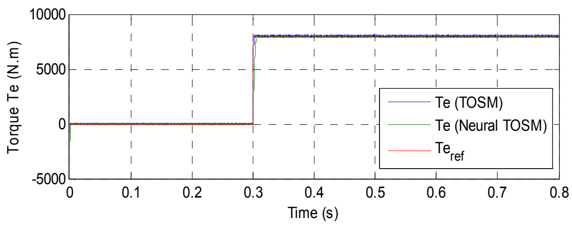


Figure 23. Torque

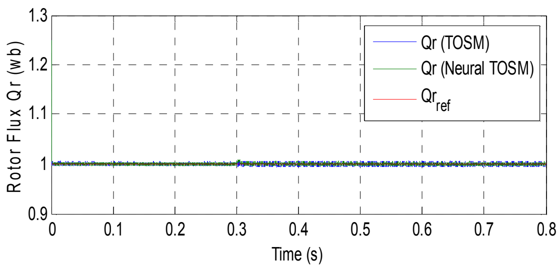


Figure 24. Rotor flux

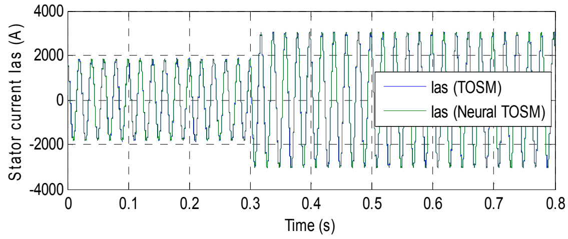


Figure 25. Stator current

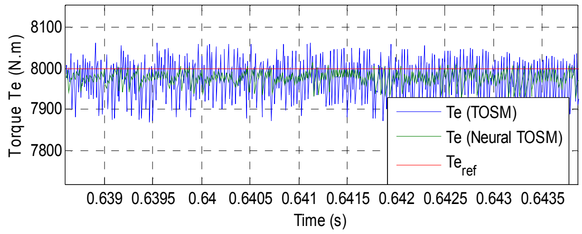


Figure 26. Zoom (torque)

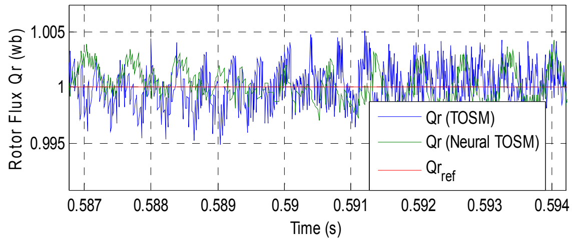


Figure 27. Zoom (rotor flux)

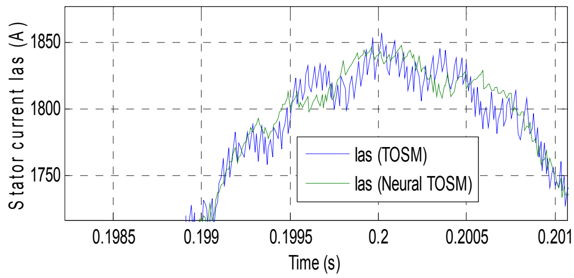


Figure 28. Zoom (current)

TABLE 3. Comparative ripples obtained from the DTC-TOSM with the proposed DTC-NTOSM strategy

	DTC-TOSM	Proposed DTC-NTSOM technique	Ratios
THD (%) of current	0.55	0.32	41.81 %
Rotor flux ripple (wb)	Around 0.01	Around 0.004	60 %
Stator current ripple (A)	Around 60	Around 20	66.66 %
Torque ripple (N.m)	Around 180	Around 70	61.11 %

TABLE 4. Compare the THD value obtained from the proposed method with values for several published methods

Techniques	THD (%)	Reference
DPC control with STA controller	1.66	Ref. [42]
DPC	4.88	Ref. [43]
VF-DPC	4.19	
Fuzzy SMC control	3.05	Ref. [44]
DPC-IP	0.43	Ref. [45]
PI controller	0.77	Ref. [46]
STA-SOSMC controller	0.28	
DPC control with intelligent metaheuristics	4.05	Ref. [47]
Intelligent super twisting sliding mode controller	0.52	Ref. [48]
DTC-SOCSMC	0.98	Ref. [29]
FOC	3.70	Ref. [7]
ISMC	9.71	Ref. [12]
MRSMC	3.14	
Direct FOC with synergetic sliding mode controller	0.50	Ref. [33]
DTC method	7.54	Ref. [49]
DTC method with genetic algorithm	4.80	
Traditional DTC strategy	6.70	Ref. [22]
Fuzzy DTC technique	2.04	
FOC with Type 2 fuzzy logic controller (FOC-T2FLC)	1.14	Ref. [50]
FOC with neuro-fuzzy controller (FOC-NFC)	0.78	
Two-level DTC method	9.87	Ref. [51]
Three-level DTC method	1.52	
Fuzzy 12 sector DTC control	1.74	Ref.[52]
DTC-NTOSM	0.32	Designed technique

where, DPC is the direct power control, VFDPC is the virtual flux direct power control, FOC is the field-oriented control, MRSMC is the multi-resonant-based sliding mode controller and SOCSM is the second-order continuous sliding mode

7. CONCLUSION

This work presents the simulation results of the rotor flux and electromagnetic torque neural third-order sliding mode control technique of a AG-based dual rotor wind turbine, using the modified SVM technique. With results obtained from the numerical simulation, it is clear that for the same operation condition, the proposed nonlinear DTC control with neural TOSM controllers had high effectiveness and performance than the DTC control using TOSM controllers and that is clear in the THD value of stator current which the use of the neural TOSM controller, it is minimized of harmonics more than the TOSM controller.

So, summarizing, the main findings of this research are as follows:

- Minimizes the rotor flux, current and torque ripples.
- Simple nonlinear DTC control was proposed.
- Minimization of the total harmonic distortion of stator current by 36%.
- A new intelligent nonlinear controller was presented and confirmed with numerical simulation.

The work can be extended with neuro-fuzzy-TOSM controllers (NFTOSM) to obtain minimum torque ripple, zero settling time, minimum flux ripple, robust control, and zero steady-state error. DPC-based neural TOSM controllers can also be taken up as an extension of this work.

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Persian Abstract

چکیده

در این مقاله، یک کنترل گشتاور مستقیم حالت لغزشی مرتبه سوم عصبی (NTOSM-DTC) برای یک ژنراتور ناهمزمان (AG) مبتنی بر توربین بادی دو روتور (DRWT) پیشنهاد شده‌است. استراتژی DTC کلاسیک با کنترل‌کننده‌های سنتی انتگرال متناسب (PI) به دلیل ویژگی‌های بالایی که در مقایسه با تکنیک سوئیچینگ DTC کلاسیک ارائه می‌دهد، در سال‌های اخیر به طور گسترده در ماشین‌های القایی اعمال شده است. در همین حال، یک اشکال عمده دارد که جریان قابل توجه، شار روتور و موج‌های گشتاور تولید شده توسط کنترل‌کننده‌های PI سنتی است. برای غلبه بر این اشکالات، بهبود این تکنیک کنترل با حذف این کنترلرها در این مقاله طراحی شده است. روش کنترل غیرخطی هوشمند پیشنهادی مبتنی بر جایگزینی کنترل‌کننده‌های PI کلاسیک با کنترل‌کننده‌های TOSM عصبی است که ورودی‌های مشابه این کنترل‌کننده‌ها را خواهند داشت. شبیه‌سازی در نرم‌افزار Matlab انجام شد و نتایج به‌دست‌آمده امکان ارزیابی ویژگی‌های تکنیک کنترل غیرخطی هوشمند پیشنهادی را نسبت به روش سنتی ممکن می‌سازد.