ВЕСТНИК ГОСУДАРСТВЕННОГО УНИВЕРСИТЕТА МОРСКОГО И РЕЧНОГО ФЛОТА ИМЕНИ АДМИРАЛА С. О. МАКАРОВА

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IMPROVING THE EFFICIENCY OF DIRECT FLUX AND TORQUE CONTROL TECHNOLOGY FOR DOUBLY-FED INDUCTION GENERATOR WITH A ROBUST CONTROL USING MODIFIED SUPER-TWISTING ALGORITHMS

A. N. J. Almakki[1], A. A. Mazalov[1,2]

[1] — Kazan National Research Technical University named after A. N. Tupolev — KAI, Kazan, Russian Federation
[2] — Southern Federal University, Rostov-On-Don, Russian Federation

A robust direct flux and torque control (DFTC) technique of a doubly-fed induction generator (DFIG) for wind turbine applications (WTA) is presented in the paper. The main advantages of traditional DFTC control method are its simple structure, robust technique and good dynamic response compared to the field-oriented control (FOC). The use of a classical hysteresis comparator and a predefined lookup table will inevitably lead to select a non-optimal rotor voltage vector in terms of reducing rotor flux errors, harmonic distortion (THD) current, and electromagnetic torque undulations. In this research work, a new approach of DFTC technique of DFIG based modified super-twisting algorithms (MSTA) and modified space vector modulation (MSVM) is developed by replacing the traditional lookup table and two hysteresis comparators. Theoretical principles of this method are presented along with simulation results. Analysis of DFTC–MSVM control scheme based MSTA controllers have been done in MATLAB/Simulink environment. The machine (DFIG 1,5MW) is tested in association with a wind turbine. Simulation results are presented. The proposed DFTC control technique takes full advantage and the electromagnetic torque regulation objective of DFIG is confirmed by the numerical simulation results compared to the traditional DFTC control technique.

Keywords: robust direct flux and torque control, doubly-fed induction generator, variable-speed wind turbine applications, modified super-twisting algorithms, modified space vector modulation.

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ПОВЫШЕНИЕ ЭФФЕКТИВНОСТИ ТЕХНОЛОГИИ ПРЯМОГО УПРАВЛЕНИЯ ПОТОКОМ ДЛЯ АСИНХРОННОГО ГЕНЕРАТОРА С ДВОЙНЫМ ПИТАНИЕМ С ИСПОЛЬЗОВАНИЕМ МОДИФИЦИРОВАННЫХ АЛГОРИТМОВ СУПЕРСКРУЧИВАНИЯ

А. Н. Д. Алмакки[1], А. А. Мазалов[1,2]

[1] — ФГБОУ ВО «Казанский национальный исследовательский технический университет им. А. Н. Туполева–КАИ», Казань, Российская Федерация
[2] — ФГБОУ ВО «Южный федеральный университет», Ростов-на-Дону, Российская Федерация

В данной работе представлена технология прямого управления потоком и крутящим моментом (DFTC) асинхронного генератора с двойным питанием (DFIG) для применения в ветроэнергетических установках. Отмечается, что основными преимуществами традиционного прямого управления потоком и крутящим моментом (DFTC) являются его простая структура, надежность и хорошая динамическая реакция в сравнении с технологией управления полем (FOC). Использование классического гистерезисного компаратора и заранее заданной таблицы значений неизбежно приведет к выбору неоптимального вектора напряжения ротора с точки зрения уменьшения колебаний потока ротора, токов гармонических искажений (THD) и колебаний электромагнитного момента. Рассмотрен новый подход к методу DFTC на основе *модифицированного алгоритма суперскручивания (MSTA) и модифицированной пространственной векторной модуляции (MSVM), главной особенностью которого является замена традиционной таблицы значений и двух гистерезисных компараторов. Теоретические принципы этого метода представлены вместе с результатами моделирования. Анализ системы управления DFTC–MSVM на основе метода MSTA был проведен в MATLAB/Simulink. Работа асинхронного генератора с двойным питанием (1,5 МВт) была проверена вместе с ветровой турбиной. В работе приведены также результаты моделирования. Предложенный метод управления DFTC в полной мере использует преимущества регулирования электромагнитного момента DFIG, имеет улучшенные характеристики по сравнению с традиционным методом управления DFTC, что подтверждено результатами численного моделирования.*

Ключевые слова: робастное управление, прямой поток, асинхронный генератор с двойным питанием, ветротурбина с переменной скоростью, модифицированные алгоритмы сверхскручивания, модифицированная пространственная векторная модуляция.

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Introduction

The direct flux and torque control (DFTC) strategy has been widely used in the AC machines drive because of its many properties such as robustness against the AC machines parameter variation, simplicity, and quick electromagnetic torque response [1]. In [2], the authors proposed the use of a DFTC method to control the induction motor drive. In [3], the DFTC technique was proposed to reduce the flux and electromagnetic torque undulation of permanent magnet synchronous motor (PMSM). Classical DFTC technique is proposed to regulate the rotor flux and torque of a doubly-fed induction generator (DFIG) [4]. The numerical simulation shows the superiority of the DFTC technique compared to field-oriented control. In [5], the authors proposed the use of a DFTC method to regulate the torque and flux of the dual stator induction motor (DSIM). DFTC control was proposed to control the squirrel cage induction generator (SCIG) [6]. In [7], the DFTC method was proposed to reduce the torque ripple of the brushless DC electric motor. The performance and efficiency of the five-phase PMSM drive were improved by using the fuzzy DFTC control method, and this was confirmed by the results obtained during the application of this method [8]. In [9], the authors designed the use of a DFTC with feedforward neural network controllers and five-phase neural modified space vector modulation (MSVM) strategy applied to the five-phase IMPSM drive. In [10], four-level DFTC method based on neural algorithm has been proposed. The electromagnetic torque ripple was reduced when use the neural algorithm.

In the basic DFTC technique, both the stator flux and electromagnetic torque errors between estimated and reference values are directly compared, and the appropriate voltage vector is produced by a traditional lookup table. This simple structure allows quick flux and electromagnetic torque responses to be achieved while increasing the robustness against the parameter variations. However, the DFTC technique shows some disadvantages such as switching frequency varies according to the change of the AC machine parameters and the rotor speed and large electromagnetic torque and stator flux undulations in the low-speed region and cannot guarantee the robustness of speed control against unmodeled uncertainties. On the other hand, the electromagnetic torque ripples are large in the case of high-power applications and this is due to the low switching frequency of the inverter [11].

Recently, several research works have been carried out in order to improve the performance of the classical DFTC technique. Among these, a voltage selection and electromagnetic torque ripple reduction algorithm for a three-level inverter system [12], and a flux and electromagnetic torque undulations minimization algorithm for a traditional inverter [13] are presented. Particularly, for high-power AC machines applications, the electromagnetic torque undulations can be drastically minimized using a three-level inverter DFTC system [14]. In the DFTC technique, speed control effectiveness is still affected by external load disturbances and parameter variations. A hybrid control strategy was designed in [15], where the neural algorithm is used a switching table to generate the switching states of the inverter, whereas the fuzzy logic controller (FLC) was used to generate the reference electromagnetic torque. The work in [16] suggests SVM strategy-based DFTC for DFIG-based wind turbines and the references for the SVM are generated from the classical PI controllers. The neural algorithms are also used in place of the switching table [17]. The neural algorithms are having issues with weight convergence, stability, and learning speed. The work designed in [18] uses a neural-based controller for DFTC fed DFIG-based wind power. In [19], the DFTC method based on closed-loop torque control has been proposed. However, the magnitude of torque linkage is adjusted to improve the effectiveness of the induction motor. In [20], the DFTC method based on closed-loop stator flux control has been proposed. In this proposed DFTC technique, the magnitude of flux linkage is adjusted to improve the effectiveness of the induction motor. In [21], the authors proposed the use of a DFTC with both closed-loop torque and flux controls applied to the induction motor drive.

In literature, many implementations are designed to the nonlinear DFTC with SVM technique to improve the dynamic performance and to minimize the electromagnetic torque/flux undulations of the DFIG-based wind turbine. In [22], the authors proposed the use of the DFTC with super twisting algorithms (STA) applied to the DFIG-based wind turbine. A novel DFTC technique using FLC and second-order sliding mode controllers was proposed to improve the performance of the DFIG-based wind turbines [23]. The simulation results show the performance of the proposed DFTC technique compared to the classical DFTC method. STA controller and neuro-fuzzy are combined to improve the performance of the DFTC method for the DFIG-based wind turbine [24]. The simulation results show the performance of the design of the proposed DFTC method compared to the classical DFTC technique. The major disadvantage of DFTC-STA, are the oscillations of the electromagnetic torque and the harmonics of the stator currents generated by the DFIG, because of the variable switching frequency. For this, in this work, we proposed a new nonlinear method to improve the performance and effectiveness of the control by STA controllers. Thus, reducing ripples at the level of electromagnetic torque and rotor flux. Another method based on the FLC method is proposed in order to improve the performance of the DFTC technique of the DFIG-based wind turbine [25]. In [26], a modified DFTC technique was proposed based on hysteresis comparators and variable gain PI controllers, where a PI controller was adjusted by a particle swarm optimization (PSO) algorithm.

In this work, rotor flux and electromagnetic torque controller using the modified super twisting algorithms (MSTA) and modified SVM technique (MSVM) is proposed. The drawbacks of the DFIG system including electromagnetic torque ripple, harmonic distortion of current, and rotor flux ripple are minimized by the MSTA controllers and MSVM technique, and the responses dynamic is improved compared to the traditional DFTC technique with PI controllers. The advantages of the designed MSTA controller are (d) simple in design, (c) simple control strategy, (e) easily tunable (b) no additional hardware is required, and (a) accurate response in dynamic conditions. The stability of the modified STA is proven using the Lyapunov theorem. Numerical simulation results are presented to verify the feasibility and performances of the DFTC with designed MSTA controllers and MSVM techniques.

The remaining paper is organized as follows: Section 2 presents the mathematical model of wind turbine and the DFIG, followed by a brief discussion on STA controller in Section 3. In section 4, the novel DFTC control using modified STA controllers is applied to the DFIG control. Section 5 presents the simulation results followed by the conclusion.

Methods and Materials

System modeling

Wind turbine model. Wind energy is one of the most widely used and popular sources in recent times. A wind turbine is a device that transforms the kinetic energy of the wind into mechanical energy, known as wind energy, which is then most often transformed into electrical energy. The mechanical power obtained from the turbine is given by the following equation [23], [24]:

$$P_t = \frac{1}{2} R^2 \rho\, v^3 C_P(\lambda, \beta). \tag{1}$$

Where, v is the wind speed (m/s), ρ is the air density (kg/m^3), R is the radius of the turbine (m), and C_P is the power coefficient which is a function of both blade pitch angle β (deg), and tip speed ratio λ.

In this work, the power coefficient C_P equation is approximated using a non-linear function according to [27].

$$C_P(\lambda, \beta) = (\beta - 2)(0{,}5 - 0{,}167)\sin\left[\frac{\pi(\lambda + 0{,}1)}{18{,}5 - 0{,}3(\beta - 2)}\right] - 0{,}0018\ (\beta - 2)(\lambda - 3). \tag{2}$$

The tip speed ratio is given by:

$$\lambda = \frac{\Omega_t R}{v}. \tag{3}$$

Where Ω_t is the rotational speed of the wind turbine.

Dynamic model of DFIG. The DFIG is the most widely used generator in the field of electric power generation using wind energy, and this is due to its advantages. DFIG is a machine that uses the kinetic energy of the wind to produce an electric current. In [22], the Park model is more used in giving a mathematical model of the DFIG. The dynamics model of the DFIG is written as follow [27]:

$$\begin{cases} V_{dr} = R_r I_{dr} - \omega_r \psi_{qr} + \dfrac{d}{dt}\psi_{dr}; \\ V_{qr} = R_r I_{qr} + \omega_r \psi_{dr} + \dfrac{d}{dt}\psi_{qr}; \\ V_{ds} = R_s I_{ds} - \omega_s \psi_{qs} + \dfrac{d}{dt}\psi_{ds}; \\ V_{qs} = R_s I_{qs} + \omega_s \psi_{ds} + \dfrac{d}{dt}\psi_{qs} \end{cases} \tag{4}$$

The rotor and stator pulsations and rotor speed are interconnected by the following equation: $\omega_s = \omega_r + \omega$. Where ω_r and ω_s are respectively the rotor and stator electrical pulsations, while ω is the mechanical one. The rotor and stator flux can be written as follows:

$$\begin{cases} \psi_{dr} = MI_{ds} + L_r I_{dr}; \\ \psi_{qr} = MI_{qs} + L_r I_{qr}; \\ \psi_{ds} = MI_{dr} + L_s I_{ds}; \\ \psi_{qs} = MI_{qr} + L_s I_{qs} \end{cases} \tag{5}$$

$(V_{dr}, V_{qr}, V_{ds}, V_{qs})$, $(\psi_{dr}, \psi_{qr}, \psi_{ds}, \psi_{qs})$, $(I_{dr}, I_{qr}, I_{ds}, I_{qs})$, are respectively the stator and rotor voltages, fluxes and currents, Rr and Rs are respectively the resistances of the stator and rotor windings, L_r, L_s, and M are respectively the inductance own rotor, stator, and the mutual inductance between two coils.

The mechanical equation of the DFIG is:

$$T_e = T_r + J\frac{d\Omega}{dt} + F_r\Omega. \tag{6}$$

The electromagnetic torque established by the DFIG can be written in terms of flux and currents by (7):

$$T_e = \frac{3}{2}\frac{M}{L_s} n_p(-\psi_{ds} I_{qr} + \psi_{qs} I_{dr}). \tag{7}$$

Where J is the inertia, Ω is the mechanical rotor speed, T_r is the load torque, and F_r is the viscous friction coefficient. The reactive and active powers of the stator side are defined as:

$$\begin{cases} Q_s = 1{,}5(-V_{ds} I_{qs} + V_{qs} I_{ds}); \\ P_s = 1{,}5(V_{qs} I_{qs} + V_{ds} I_{ds}). \end{cases} \tag{8}$$

In order to develop a decoupled control of the reactive and active powers, we use a Park reference frame linked to the stator flux. By supposing that the *d-axis* oriented along the stator flux position and basing on equation (9) with neglecting R_s we can write [28]:

$$\psi_{qs} = 0 \quad \text{and} \quad \psi_s = \psi_{ds}; \tag{9}$$

$$\begin{cases} V_{qs} = \psi_s \omega_s; \\ V_{ds} = 0; \end{cases} \tag{10}$$

$$\begin{cases} I_{qs} = -I_{qr} \dfrac{M}{L_s}; \\ I_{ds} = \dfrac{\psi_s}{L_s} - I_{dr} \dfrac{M}{L_s} \end{cases}. \tag{11}$$

Equation (8) can be written as:

$$\begin{cases} Q_s = -\dfrac{3}{2}\left(-\dfrac{\omega_s \psi_s^{\ 2}}{L_s} + \dfrac{\omega_s \psi_s M}{L_s} I_{dr} \right); \\ P_s = (-1.5) I_{qr} \dfrac{\omega_s \psi_s M}{L_s}. \end{cases} \tag{12}$$

Thus, the torque equation can be written as follows:

$$T_e = -1.5 \frac{M}{L_s} n_p I_{qr} \psi_{ds}. \tag{13}$$

Modified STA controller

A system with a variable structure is a system whose structure changes during its operation. It is characterized by the choice of a function and switching logic, this choice allows the system to switch from one structure to another at any time [29]. Sliding mode control (SMC) is a kind of variable structure system. The objective of the SMC technique is to keep the surface at zero. The major drawback of the SMC technique is the chattering phenomenon [30]. Several methods have been suggested in order to reduce this problem, for example neural algorithm (NA), fuzzy logic (FL), neuro-fuzzy algorithm (NFA), synergetic control (SC), second-order sliding mode (SOSM), and super twisting algorithm.

The super twisting algorithm is a kind of SOSM controller. It is one of the most famous and most widely used controls in the field of AC motor control. STA method reduces more the chattering phenomena compared to the classical SMC controller [31]. For robust and high effectiveness controller, an intelligent STA controller was studied in the literature [32]–[39]. In [40], the authors proposed the use of a direct field-oriented control with traditional STA controllers applied to the six-phase induction motor. The experimental results show the superiority of the proposed technique. Synergetic control and STA controller are combined to control and regulate the power quality of DFIG-based dual-rotor wind power [41]. On the other hand, STA is a simple algorithm, more robust, and easy to apply compared to the traditional SMC method. When using STA, we do not need the mathematical form of the studied system, as it is applied directly and can be used in place of the classic controllers, for example hysteresis comparator and PI controller. Equation (14) represents the form of the STA controller [42]:

$$u(t) = u_1(t) + u_2(t); \tag{14}$$

$$u_1(t) = \lambda_1 \sqrt{|S|}.sign(S); \tag{15}$$

$$u_2(t) = \lambda_2 \int sign(S).dt \tag{16}$$

STA controller can be expressed by the following equation:

$$u(t) = \lambda_1 \sqrt{|S|}.sign(S) + \lambda_2 \int sign(S).dt \tag{17}$$

In this section, a new STA technique was designed to minimize the chattering phenomena. The designed technique named modified STA (MSTA) controller is an effective controller for uncertain systems and it overcomes the main drawbacks of the traditional SMC and STA methods. The MSTA controller is a modified STA controller. The MSTA controller is a simple structure, robust controller, and easy to adjust. The control input of the designed MSTA controller comprises three inputs as (18):

$$w(t) = w_1(t) + w_2(t) + w_3(t); \tag{18}$$

$$w_1(t) = k_1 \sqrt{|S|}.sign(S); \tag{19}$$

$$w_2(t) = k_2 \int sign(S).dt; \tag{20}$$

$$w_3(t) = S. \tag{21}$$

Equation (22) shows the principle of the proposed MSTA controller. This proposed controller is simple structure, robust controller and easy to implement:

$$w(t) = k_1 \sqrt{|S|} sign(S) + k_2 \int sign(S) dt + S. \tag{22}$$

Where k_1 and k_2 are scalar coefficients.

This suggested technique will be used to improve the effectiveness of the DFTC control. On the other hand, Figure 1 shows a block diagram representation of the MSTA controller.

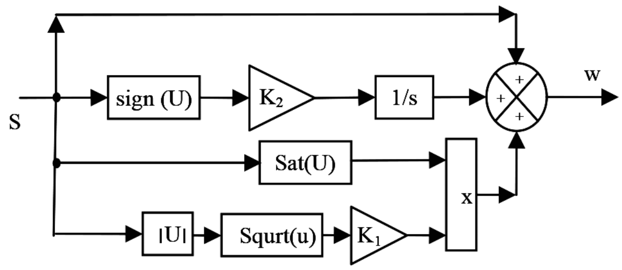


Figure 1. Block diagram of the MSTA controller

This proposed controller is used in this paper for reducing an electromagnetic torque ripple, stator current ripple, rotor flux ripple, and harmonic distortion of stator/rotor currents of the DFIG-based wind turbine system using the DFTC method which the inverter was controlled by the modified SVM strategy.

DFTC with MSTA controllers

This work proposes a novel design of DFTC structure for DFIG-based wind turbine, that replaces the traditional hysteresis controllers and switching table, to enhance the control technique effectiveness such as minimizing the electromagnetic torque and rotor flux undulations, reducing the low THD in the output stator current by controlling the rotor side converter (RSC) of the DFIG.

DFTC–MSTA method with modified SVM technique uses the electromagnetic torque and rotor flux as primary control variables, which are obtained directly from the DFIG measurements. Electromagnetic torque and rotor flux control loops are the two basic loops of the DFTC–MSTA fed DFIG-based wind turbine system and are shown in Figure 2. From Figure 2, the DFTC–MSTA fed DFIG drive mainly consists of rotor flux and electromagnetic torque estimation, DFTC technique, and modified MSVM strategy. Since the DFTC–MSTA control structure is a robust and simple algorithm; it can be used for several AC machines kinds (synchronous, asynchronous…). This proposed DFTC technique ensures excellent electromagnetic torque or speed control without any mechanical information. Moreover, sensitivity to machine parameters is lower for the proposed DFTC technique in comparison with traditional DFTC and field-oriented control techniques.

The DFTC–MSTA objective is to regulate the rotor flux and the electromagnetic torque of the DFIG-based wind turbine. The electromagnetic torque is regulated using the quadrature axis rotor voltage V_{qr}, while the rotor flux is regulated using the direct axis rotor voltage V_{dr}.

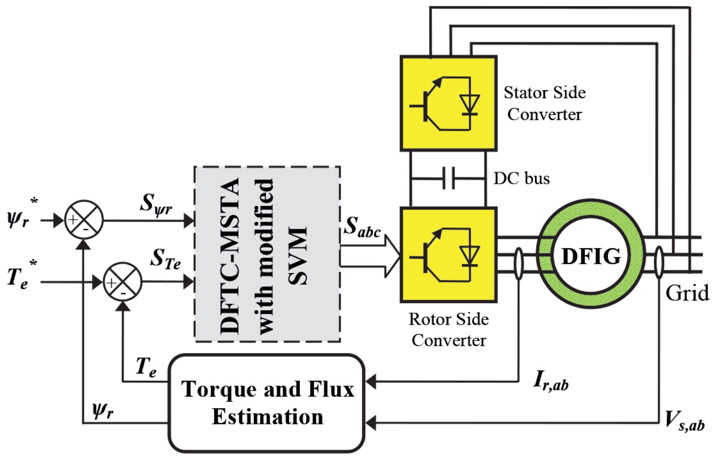


Figure 2. Block diagram of the DFIG with DFTC–MSTA

The phase and amplitude of the rotor flux are estimated by the relation equations (23) to (25):

$$\begin{cases} \psi_{r\beta} = \int_0^t (-R_r i_{r\beta} + V_{r\beta}) dt; \\ \psi_{r\alpha} = \int_0^t (-R_r i_{r\alpha} + V_{r\alpha}) dt. \end{cases} \tag{23}$$

The magnitude and phase of rotor flux are described as follows:

$$\psi_r = \sqrt{\psi_{r\alpha}^2 + \psi_{r\beta}^2}; \tag{24}$$

$$\theta_r = \operatorname{arctg}\left(\frac{\psi_{r\beta}}{\psi_{r\alpha}}\right). \tag{25}$$

With

$$\left|\overline{\psi_r}\right| = \frac{\left|\overline{V_r}\right|}{w_r}. \tag{26}$$

Consequently, the estimation of the rotor flux is based on the parameter of the rotor resistance. The rotor voltage and rotor current are measurable quantities. While the electromagnetic torque can be estimated from the measurement of the rotor current and the estimation of the rotor flux.

$$T_e = \frac{3}{2}\frac{M}{L_s} n_p (-\psi_{ds} I_{qr} + \psi_{qs} I_{dr}) \tag{27}$$

Electromagnetic torque and rotor flux MSTA controllers are used to influence respectively the two rotor voltage components as in (28) and (29):

$$V_{qr}^* = k_1 \sqrt{|S_{Te}|} \operatorname{sign}(S_{Te}) + k_2 \int \operatorname{sign}(S_{Te}) dt + S_{Te}; \tag{28}$$

$$V_{dr}^* = k_3 \sqrt{|S_{\psi_r}|} \operatorname{sign}(S_{\psi_r}) + k_4 \int \operatorname{sign}(S_{\psi_r}) dt + S_{\psi_r}. \tag{29}$$

Where the sliding mode variables are the rotor flux magnitude error $S_{\psi r} = \psi_r^{*}-\psi_r$ and the electromagnetic torque error $S_{Te} = T_e^{*} - T_e$, and the control gains k_3, k_4, k_1 and k_2 should check the stability conditions.

Results and Discussion

The designed DFTC methods is simulated with the MATLAB software by considering a 1.5 MW doubly-fed induction generator. The parameters of DFIG used for the numerical simulation studies are specified in Table 1. The three DFTC control methods; DFTC-PI, DFTC-STA and DFTC–MSTA are simulated and compared in terms of stator current harmonics distortion, electromagnetic torque ripple, rotor flux ripple, reference tracking, time response, and robustness against generator parameter variations.

Table 1

The DFIG parameters [23, 27]

Parameters	Rated Value	Unity
Number of pairs poles	2	
Nominal power	1,5	MW
Stator resistance	0,012	Ω
Stator frequency	50	Hz
Stator voltage	398	V
Stator inductance	0,0137	H
Rotor resistance	0,021	Ω
Mutual inductance	0,0135	H
Rotor inductance	0,0136	H
Viscous friction	0,0024	Nm/s
Inertia	1000	Kg m^2

First test

In this case, the effectiveness of the designed strategies (DFTC-PI, DFTC-STA, and DFTC–MSTA) is tested under reference electromagnetic torque and rotor flux variation. The reference values of electromagnetic torque and rotor flux are set at 0 *N.m* and 1.6 *wb*, respectively. Figures 3–5 show the obtained simulation results from this test. The waveforms are taken from the 0 to 1.4 sec for better illustrations. It is shown that the MSTA controller has high effectiveness compared to PI and STA controllers. From Figures 3a and 3b, we notice that the electromagnetic torque and rotor flux follow the references precisely.

Figure 3c represents the current signal for designed techniques. Starting from Figure 3c, we notice that the stator current is related to the system, as well as the reference values of electromagnetic torque and rotor flux.

From Figure 4, we notice that the DFTC control with the proposed MSTA controller greatly reduced the ripples of both electromagnetic torque, rotor flux, and stator current of the DFIG compared to DFTC-PI and DFTC-STA control techniques. The DFTC–MSTA control scheme reduces more the ripples in torque, rotor flux and current compared to DFTC-PI and DFTC-STA methods (see Figure 4). On the other hand, Figure 5a, Figure 5, *b*, and 5, *c* show the THD of one phase stator current of the DFIG obtained using Fast Fourier Transform method for the designed DFTC techniques (DFTC-PI, DFTC-STA, and DFTC–MSTA). It can be observed through these figures that the THD value is more minimized for the DFTC–MSTA (0.20 %) when compared to the DFTC-PI (0,53 %) and DFTC-STA (0,31 %). Based on the obtained results, it can be said that DFTC–MSTA has proven effective in reducing the value of ripples both in electromagnetic torque and stator current.

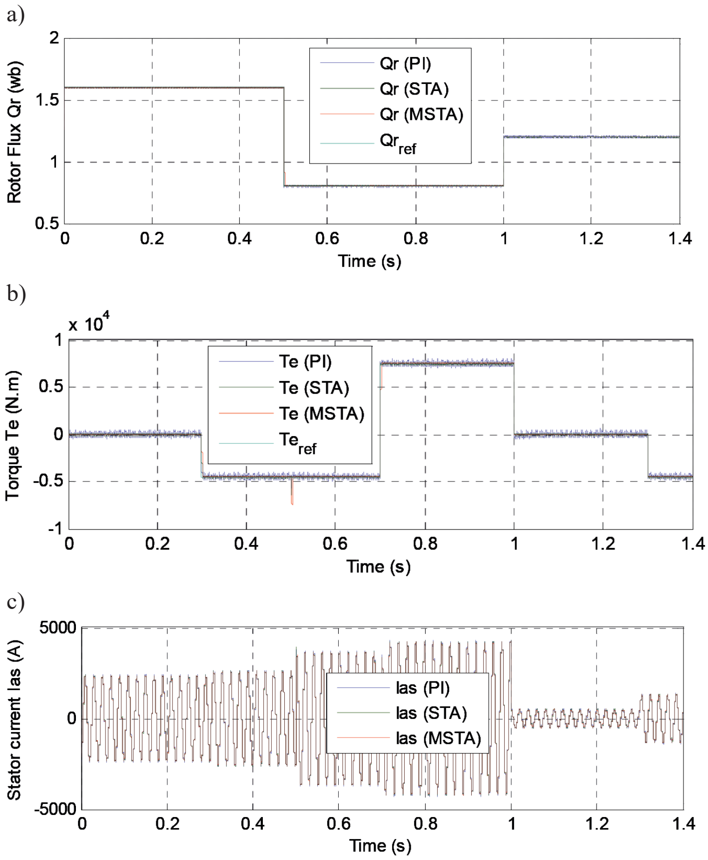


Figure 3: *a* —Flux; *b* — Torque; *c* — Current

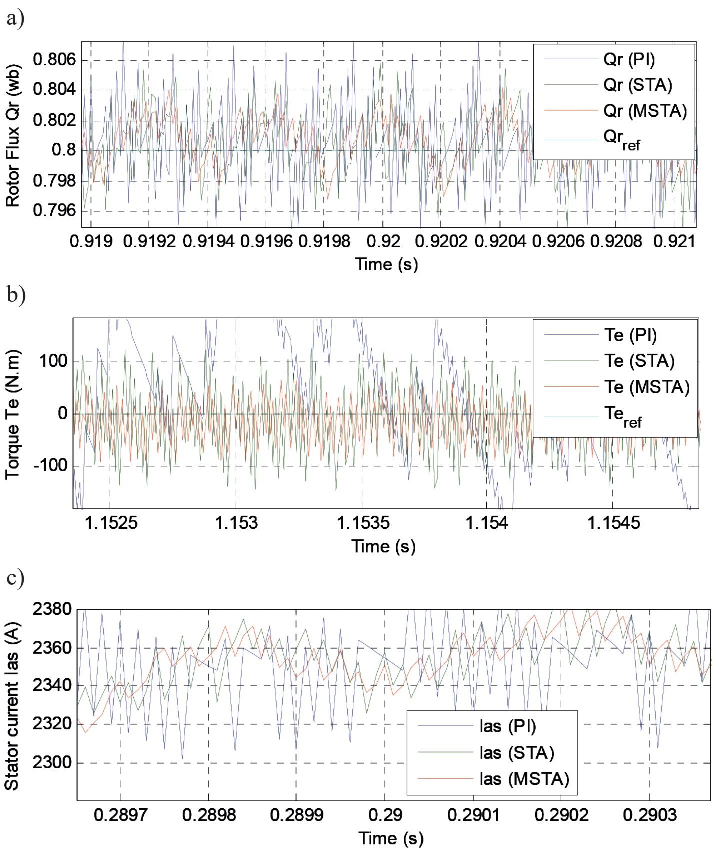
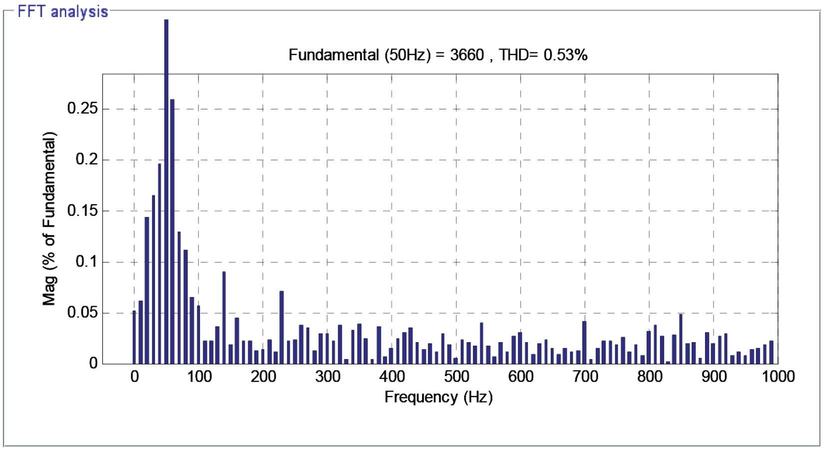
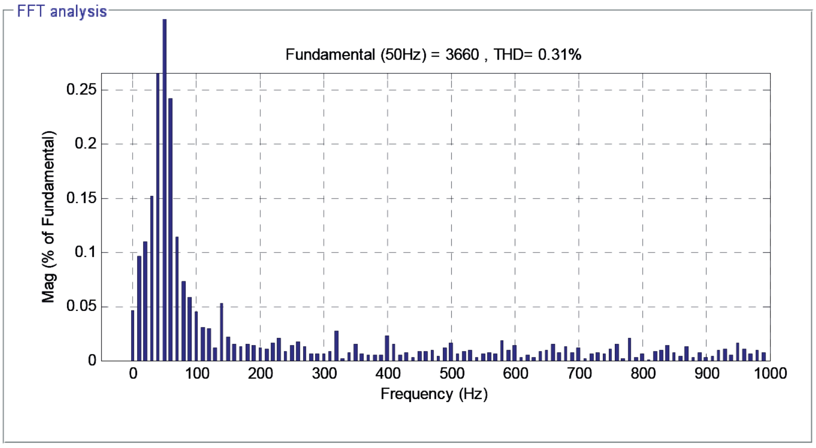


Figure 4: *a* — Zoom (Flux);
b — Zoom (Torque); *c* — Zoom (Current)

a)



b)



c)

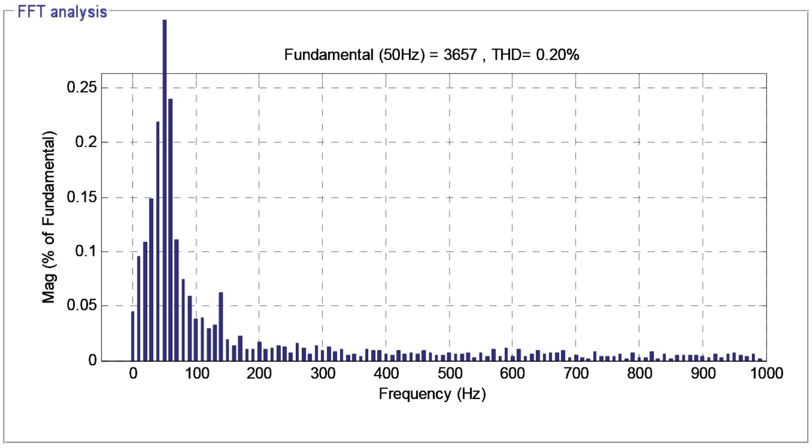


Figure 5: *a* — THD (DFTC-PI);
b — THD (DFTC-STA); *c* — THD (DFTC–MSTA)

Second test

In this test, the effectiveness of the DFTC–MSTA technique is tested under machine parameters and electromagnetic torque/flux variation. The DFIG is running at its nominal speed. The rotor and stator resistance of the DFIG is doubled and the values of inductances L_s, L_r and M are divided by 2. Figures 6 to 8 show the simulation results of the STA, MSTA, and PI controllers under described conditions. As shown by these figures, we notice that parameter variations of the DFIG increase slightly the time-response of the DFTC-PI technique compared to DFTC-STA and DFTC–MSTA methods. Electromagnetic torque and rotor flux also remain very well referenced for all the proposed controls (see Figure 6). On the other hand, these results show that these variations present a clear effect on the electromagnetic torque, stator current and rotor flux curves and that the effect appears more important for the DFTC-PI and DFTC-STA techniques than that with the DFTC–MSTA control method (see Figure 7). The THD current of the DFTC-PI and DFTC–MSTA is shown in Figures 8, *a,* 8, *b* and 8, *c*, respectively. From these figures, it may observe that the current THD is marginally less with the MSTA controller when compared with traditional PI controller and STA controller fed DFTC-based DFIG. Thus, it can be concluded that the designed DFTC–MSTA control method and in addition to its efficiency in minimizing THD current has kept the most important advantage of the DFTC-PI and DFTC-STA witch is simplicity.

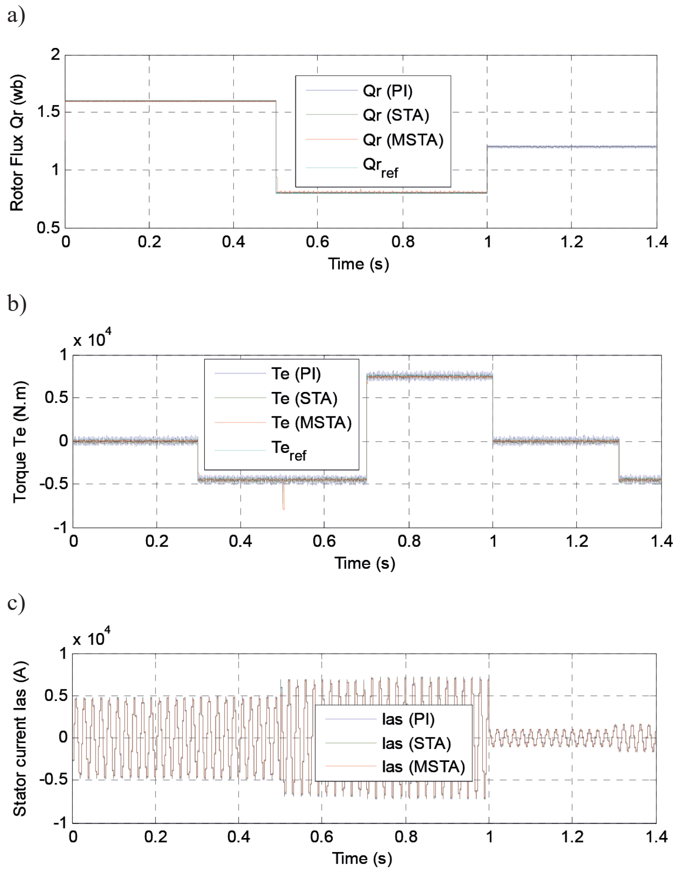
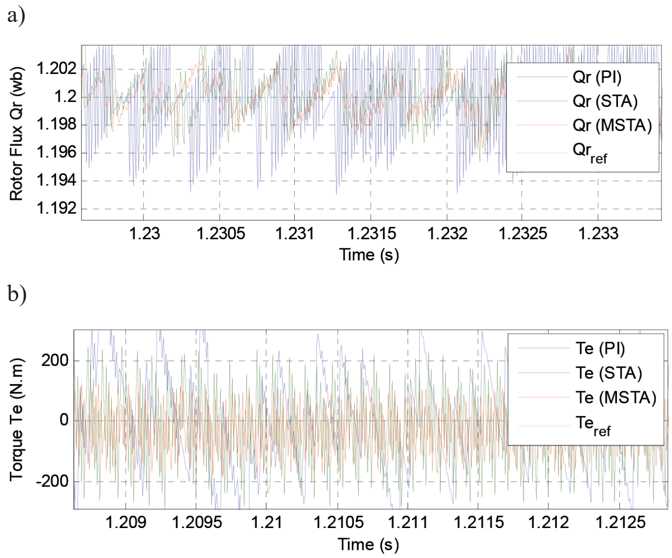


Figure 6: *a* —Flux; *b* — Torque; *c* — Current



c)

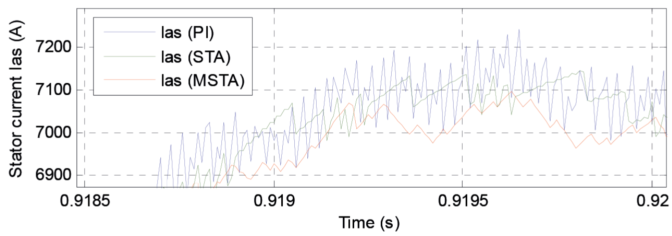
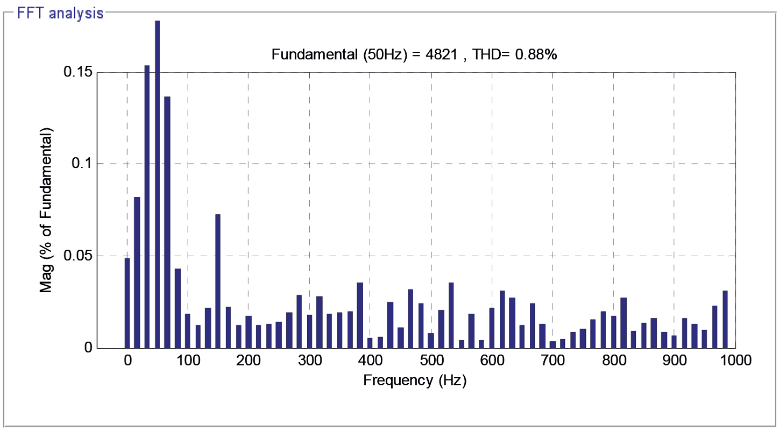
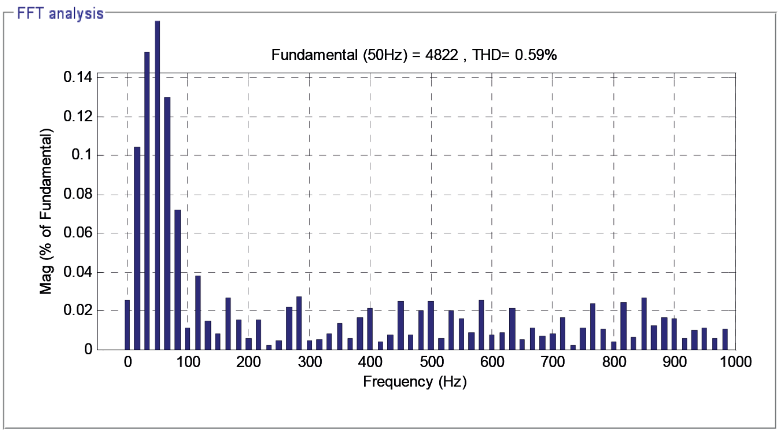


Figure 7: *a* — Zoom (Flux);
b — Zoom (Torque); *c* — Zoom (Current)

a)



b)



c)

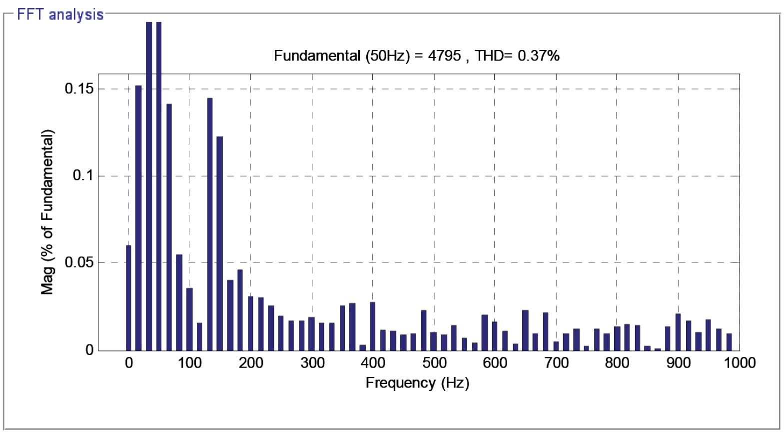


Figure 8: *a* — THD (DFTC–PI);
b — THD (DFTC–STA); *c* — THD (DFTC–MSTA)

In the end, we will compare the proposed DFTC method in this work with some scientific works, and this is according to the THD value of stator current. The values are shown in Table 2.

Table 2

Compare THD current with other control techniques

		THD,%
Ref.[22]	Classical DTC	2,57
	SOCSM-DTC	0,98
Ref.[23]		1,15
Ref. [27]	FOC	3,7
Ref. [43]	DPC	2,56
Ref. [28]		1,14
Proposed techniques	DFTC-PI	0,53
	DFTC-STA	0,31
	DFTC-MSTA	0,20

Where, DPC is the direct power control, and FOC is the field-oriented control. Through this table, we note that the proposed DFTC with proposed MSTA controller gives a lower THD value compared to the rest of the methods implemented in various scientific works. Accordingly, it can be concluded that the DFTC with proposed MSTA controller is solid and robust compared to some controls. This is due to the use of proposed MSTA controllers.

Conclusion

In this paper, a modified STA controller was proposed to regulate and control the electromagnetic torque and rotor flux of the doubly-fed induction generator based on the wind turbine. The proposed nonlinear control leads to improve the control effectiveness of the control structure that is based on modified STA controller by reducing electromagnetic torque and rotor flux undulations under variable load torque and flux references. The modified STA controller was used to define the attractive control part of the traditional STA technique and PI controller.

The proposed modified STA controller was compared with the traditional PI controller and traditional STA method. The obtained results illustrated the performances of the proposed modified STA controller even in the presence of time-varying reference trajectory, load torque changing, and DFIG parameter variations. In addition, electromagnetic torque and rotor flux undulations were largely reduced and response time was improved using the proposed modified STA controller. Moreover, robustness, stability, and high decoupling between the control axes were ensured. Finally, the robustness, suggested a good solution to improve the DFTC method characteristics applied for wind power systems, which helps to ensure high quality of electromagnetic torque and rotor flux.

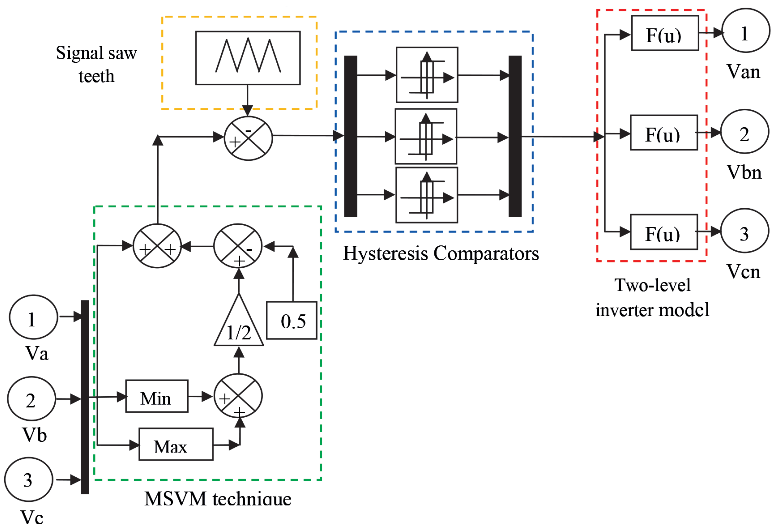


Figure 9. Block diagram of the modified SVM technique

Appendix

The modified SVM technique is a new modulation structure. It has several advantages, including simplicity and ease of implementation, unlike the traditional method.

Depends on the calculation of the maximum and minimum values of three-phase voltages. This technique was used in this paper to control the inverter of the DFIG. This technique is detailed in [16], [23]. The block diagram of the modified SVM technique is shown in Figure 9.

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ИНФОРМАЦИЯ ОБ АВТОРАХ

Алмакки Али Надхим Джбарах — аспирант
Научный руководитель:
Мазалов Андрей Андреевич
ФГБОУ ВО «Казанский национальный исследовательский технический университет им. А. Н. Туполева–КАИ»
420111, Российская Федерация, г. Казань, ул. К. Маркса 10
e-mail: *alinadhimj@gmail.com*
Мазалов Андрей Андреевич —
кандидат технических наук, доцент
ФГБОУ ВО «Казанский национальный исследовательский технический университет им. А. Н. Туполева–КАИ»
420111, Российская Федерация, г. Казань, ул. К. Маркса, 10
ФГБОУ ВО «Южный федеральный университет»
344006, Российская Федерация, г. Ростов-на-Дону, ул. Б. Садовая 105/42.
e-mail: *anmaz8@list.ru*

INFORMATION ABOUT THE AUTHORS

Almakki, Ali Nadhim Jbarah — Postgraduate
Supervisor:
Mazalov, Andrey A.
Kazan National Research Technical University named after A. N. Tupolev — KAI
10 Karla Marksa Str., Kazan, 420111, Russian Federation
e-mail: *alinadhimj@gmail.com*
Mazalov, Andrey A. —
PhD, associate professor
Kazan National Research Technical University named after A. N. Tupolev—KAI
10 Karla Marksa Str., Kazan, 420111, Russian Federation
Southern Federal University
105/42 Bolshaya Sadovaya Str., Rostov-on-Don, 344006, Russian Federation
e-mail: *anmaz8@list.ru*

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