ЭЛЕКТРОТЕХНИЧЕСКИЕ КОМПЛЕКСЫ И СИСТЕМЫ

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APPLICATION OF FRACTIONAL-ORDER SECOND-ORDER CONTINUOUS SLIDING MODE CONTROLLER IN DIRECT FLUX AND TORQUE CONTROL SYSTEM OF DOUBLY-FED INDUCTION GENERATOR INTEGRATED TO WIND TURBINE: SIMULATION STUDIES

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 new nonlinear controller for direct flux and torque control (DFTC) of a doubly-fed induction generator (DFIG) based on a single-rotor wind turbine (SRWT) using the fractional-order second-order continuous sliding mode (FOSOCSM) controller is presented in this paper. Three different controllers are proposed to control the electromagnetic torque and rotor flux of the doubly-fed induction generator driven by a single-rotor wind turbine. The main goal of the proposed DFTC control structure is to improve the quality of the electromagnetic torque and stator current of the SRWT system by reducing electromagnetic torque undulations, stator current, and rotor flux undulations in the DFIG-SRWT systems. The mathematical model of the DFIG has been described. The descriptions of the modified space vector modulation (MSVM) strategy and the proposed FOSOCSM controller have been presented. The DFTC–MSVM control structure with proposed FOSOCSM controllers has been described. This proposed strategy has been shown to be robust and stable against parametric uncertainties and load electromagnetic torque. The validity, robustness, and effectiveness of the proposed DFTC-FOSOCSM technique are demonstrated through simulation studies in the MATLAB® software environment. Numerical simulation results demonstrate that the proposed DFTC control scheme with proposed FOSOCSM controllers has a faster transient response than traditional DFTC and DFTC with classical SOCSM controllers. Also, it reduces ripples in both electromagnetic torque of stator current, and rotor flux significantly compared to the classic technique and DFTC with traditional SOCSM controllers.

Keywords: single-rotor wind turbine, direct flux and torque control, doubly-fed induction generator, fractional-order second-order continuous sliding mode, modified space vector modulation.

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ПРИМЕНЕНИЕ КОНТРОЛЛЕРА НЕПРЕРЫВНОГО СКОЛЬЗЯЩЕГО РЕЖИМА ВТОРОГО ПОРЯДКА (SMC) В DFTC АСИНХРОННОГО ГЕНЕРАТОРА С ДВОЙНЫМ ПИТАНИЕМ (DFIG), ИНТЕГРИРОВАННОГО В ВЕТРОТУРБИНУ: ИМИТАЦИОННЫЕ ИССЛЕДОВАНИЯ

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 представлен новый нелинейный контроллер для управления прямым потоком и крутящим моментом (DFTC) ветротурбины (SRWT) на базе асинхронного генератора с двойным питанием

(DFIG) с использованием контроллера непрерывного скользящего режима второго порядка (FOSOCSM). Предложены к сравнению три различных контроллера для управления электромагнитным моментом и потоком ротора асинхронного генератора с двойным питанием, приводимого в действие ветроколесом. Основной целью предлагаемой структуры управления DFTC является улучшение качества электромагнитного момента и тока статора системы SRWT за счет уменьшения пульсаций электромагнитного момента, тока статора и пульсаций потока ротора в системах DFIG–SRWT. Описана математическая модель DFIG. Представлены описания модифицированной стратегии пространственной векторной модуляции (MSVM) и предлагаемого контроллера FOSOCSM. Описана структура управления DFTC–MSVM с предлагаемыми контроллерами FOSOCSM. Показано, что предлагаемая стратегия является надежной и стабильной в отношении параметрических неопределенностей и электромагнитного момента нагрузки. Обоснованность, надежность и эффективность данной методики DFTC–FOSOCSM продемонстрированы в ходе имитационных исследований в программной среде MATLAB®. Результаты численного моделирования показывают, что предложенная схема управления DFTC с контроллерами FOSOCSM имеет более быструю переходную характеристику, чем традиционные DFTC и DFTC с классическими контроллерами SOCSM, что значительно уменьшает пульсации как в электромагнитном моменте тока статора, так и в потоке ротора по сравнению с классической техникой и с DFTC с традиционными контроллерами SOCSM.

Ключевые слова: ветроэнергетическая установка, прямое управление потоком, крутящий момент, асинхронный генератор с двойным питанием, непрерывный скользящий режим второго порядка, модифицированная пространственная векторная модуляция.

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Introduction

In recent years, there has been a great deal of demand for the use of renewable energies in generating electric power, especially wind energy, due to its advantages compared to other renewable sources. Among the advantages of wind energy, we mention that it is infinite energy, inexpensive, and can be used easily in contrast to petroleum energy, and the low cost of production of electrical energy from some sources. In [1], the completed wind energy capacity at the end of 2021 reached 800 GW, this large value reflects the increasing demand for this source. This value is constantly increasing over the years. To generate electric power using wind energy we need electric generators, the latter are multiple and many, for example, we mention doubly-fed induction generators (DFIG), synchronous generator (SG), Squirrel cage asynchronous generator (SCAG), coiled rotor asynchronous generator (CRAG). These generators can be used in the case of variable and constant wind speeds. Among the generators used in variable speed wind turbines, we find DFIG the most used compared to other types [2–4]. However, the DFIG gives more efficiency in the case of variable wind speed compared to a synchronous generator. Therefore, different control algorithms have been proposed for DFIGs. Among the most famous and most widely used methods in the field of generator control, we find direct flux and torque control (DFTC) [5], field-oriented control (FOC) [6], fuzzy control [7], sliding mode control (SMC) [8], super twisting algorithm [9], direct active and reactive power control (DARPC) [10], second-order sliding mode control (SOSMC) [11], neural control [12], backstepping control [13] and hybrid control [14–19]. Among these algorithms, the classical DFTC technique offers many advantages include: simplicity in calculations, fast dynamic response, robustness algorithm, easy to implementation and robustness against machine parameter mismatches [20–22]. The DFTC technique presented in [23], imposes some drawbacks such as electromagnetic torque ripple, variable switching frequencies, flux ripple, and harmonic distortion of current. Although several techniques have been designed with fixed switching frequency [24, 25], these techniques require high sampling frequency to show good transient performance and steady-state. In order to take high frequencies, high-speed sensors must be used and they must also be strong against external noise, and this is what makes the cost very high. In [26], the DFTC technique is presented based on the traditional space vector modulation (SVM) strategy, and a neural proportional-integral (NPI) controller is used to minimizes rotor flux and electromagnetic torque undulations. This designed strategy is a simple algorithm, robust control and easy to implement compared to vector control. The NPI controller used in this DFTC strategy makes it necessary for minimizing the harmonic distortion of current and response time. The numerical simulation results show the characteristics of the designed technique. In [27], the authors proposed the use of a twelve sectors DFTC method with a fuzzy controller applied to the DFIG. In this proposed technique, the switching table was replaced by fuzzy logic control. The proposed technique is more robust than traditional DFTC control. However, the harmonic distortion of current is reduced by fuzzy DFTC. In [28], the DFTC technique based on a neural switching table has been proposed. The simulation results show the superiority of the designed method. In [29], a modified DFTC method was proposed based on STA controllers with a constant switching frequency. STA and neural algorithms were combined to improve the performances of the DFTC method [30]. In [31], the electromagnetic torque and rotor flux undulations were reduced when using the DFTC method with fuzzy STA controllers. This proposed technique is more robust than the traditional technique. In addition, the harmonic distortion of current was reduced by DFTC with fuzzy STA controllers. In [32], the second-order continuous sliding mode-based DFTC technique (SOCSM-DFTC) is used to regulate and control the rotor flux and electromagnetic torque of the DFIG-based wind turbines. In addition, this control reduces more the rotor flux and electromagnetic torque undulations compared to the traditional DFTC control scheme. Moreover, it does not take into account the mathematical form of the system and its analytical information. In this method, two SOCSM controllers are used to control the torque and flow together. On the other hand, due to the non-linearity and ease of controlled tuning, it is very easy to improve the performance and efficiency of the DFIG according to this reference.

In this work, a new DFTC method for DFIG in wind power conversion systems is proposed. The designed technique is a fractional-order SOCSM-based DFTC control scheme (FOSOCSM-DFTC). The objective of improving the performance of the SOCSM controller by fractional calculus is to reduce the electromagnetic torque and rotor flux error of the rotor DFIG in the event of changing machine parameters (Rs, Rr, Ls, and Lr). The stability of the fractional-order SOCSM controller is proven using the Lyapunov stability technique. On the other hand, the proposed fractional-order SOCSM controller is robust, easy to implement, simple algorithm, and easy to adjust.

The main contributions of this paper are as follows:

– a new robust control theory is proposed for the DFIG-based single-rotor wind turbine system.

– the proposed DFTC control scheme with fractional-order SOCSM controller (FOSOCSM) is robust compared to the classical DFTC control technique with PI and SOCSM controllers.

– the DFTC control scheme with fractional-order SOCSM controllers improved the dynamic performances of the DFIG-based single-rotor wind turbine system.

– the proposed control scheme reduced electromagnetic torque and rotor flux ripples.

– the proposed method is simple and easy to implement compared to field-oriented control.

This research work is presented in the following section; in section 2, the DFIG mathematical model is presented. The modified SVM technique is presented in section 3. The proposed fractional-order SOCSM controller is detailed in section 4. Section 5 describes the DFTC control scheme of DFIG based on a modified SVM technique and two PI controllers. The designed DFTC control structure is evaluated and the simulated results are analyzed in Section 6. Finally, concluding remarks are given in the last section.

Methods and Materials

DFIG model. In order to give the mathematical model of an electric machine, the Park transform is the most commonly used. The Park transformation is an uncomplicated mathematical method used to give a mathematical concept to electric machines. The rotor and stator voltage are given, respectively, as follows [33], [34]:

$$\begin{cases} V_{dr} = R_r I_{dr} - \omega_r \psi_{qr} + \dfrac{d}{dt}\psi_{dr}; \\ V_{qr} = R_r I_{qr} + \omega_r \psi_{dr} + \dfrac{d}{dt}\psi_{qr}; \\ V_{ds} = R_s I_{ds} - \omega_s \psi_{qs} + \dfrac{d}{dt}\psi_{ds}; \\ V_{qs} = R_s I_{qs} + \omega_s \psi_{ds} + \dfrac{d}{dt}\psi_{qs}, \end{cases} \tag{1}$$

where ω_r and ω_s — are respectively the rotor and stator electrical pulsations, while ω is the mechanical one.

The rotor and stator pulsations and rotor speed are interconnected by the following equation: $\omega_s = \omega_r + \omega$.

Equation (2) represents the stator and rotor flux of the three-phase DFIG.

$$\begin{cases} \psi_{dr} = MI_{ds} + L_r I_{dr}; \\ \psi_{qr} = MI_{qs} + L_r I_{qr}; \\ \psi_{ds} = MI_{dr} + L_s I_{ds}; \\ \psi_{qs} = MI_{qr} + L_s I_{qs} \end{cases} \tag{2}$$

(V_{dr}, V_{qr}, V_{ds}, V_{qs}), (ψ_{dr}, ψ_{qr}, ψ_{ds}, ψ_{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 electric machine contains two parts, the electrical part and the mechanical part, the electrical part is represented in the equations of voltages, and flux, and the mechanical part is represented by the following equation:

$$T_e = T_r + J\frac{d\Omega}{dt} + F_r\Omega. \tag{3}$$

The torque of the machine is related to the flux and current, and its expression is given by the following equation:

$$T_e = \frac{3}{2}\frac{M}{L_s} n_p(-\psi_{ds} I_{qr} + \psi_{qs} I_{dr}). \tag{4}$$

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 stator active and reactive powers of the stator side are defined as:

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

In order to develop a decoupled control of the stator's active and reactive powers, we use a Park reference frame linked to the stator flux. By supposing that the d-axis oriented along with the stator flux position and based on equation (6) with neglecting R_s we can write [30]:

$$\psi_{qs} = 0 \quad \text{and } \psi_s = \psi_{ds}; \tag{6}$$

$$\begin{cases} V_{ds} = \psi_s \omega_s; \\ V_{qs} = 0; \end{cases} \tag{7}$$

$$\begin{cases} I_{qs} = -I_{qr}\dfrac{M}{L_s}; \\ I_{ds} = \dfrac{\psi_s}{L_s} - I_{dr}\dfrac{M}{L_s} \end{cases}. \tag{8}$$

Equation (8) can be written as:

$$\begin{cases} Q_s = -\dfrac{3}{2}\left(-\dfrac{\omega_s \psi_s{}^2}{L_s} + \dfrac{\omega_s \psi_s M}{L_s} I_{dr}\right); \\ P_s = (-1.5) I_{qr} \dfrac{\omega_s \psi_s M}{L_s}. \end{cases} \tag{9}$$

Thus, the torque equation can be written as follows:

$$T_e = -1.5\frac{M}{L_s} n_p I_{qr} \psi_{ds}. \tag{10}$$

Modified SVM technique. Currently, most AC machine control uses the traditional SVM technique. This is due to many advantages such as reduce the harmonic distortion of current, and robust modulation technique compared to traditional pulse width modulation (PWM). The SVM technique is an algorithm for the control of PWM. This technique is used to obtain alternating current and to control the speed of AC motors. But this technique is difficult to implement compared to the traditional PWM technique, especially with the multi-level inverters. In [35], an experimental result of the SVM technique with a neural algorithm has been presented. The obtained results showed the effectiveness of the proposed method. In [36], a simplified SVM technique was proposed to control the three-phase five-level cascaded H-bridge inverter. The proposed method used in [36] significantly minimizes calculation time and efforts without reducing the fundamental output voltage of the inverter. In [37, 38], a new SVM algorithm is proposed to control the traditional inverter. This new technique is based on the calculated maximum and minimum of three-phase voltages. This technique was used to control the five-phase inverter [39, 40]. A schematic diagram of this modified SVM technique of a two-level inverter is shown in Figure 1. Through Figure 1, we find that this method is very simple, easy, and it can be easily applied to multilevel inverters compared to the traditional SVM technique.

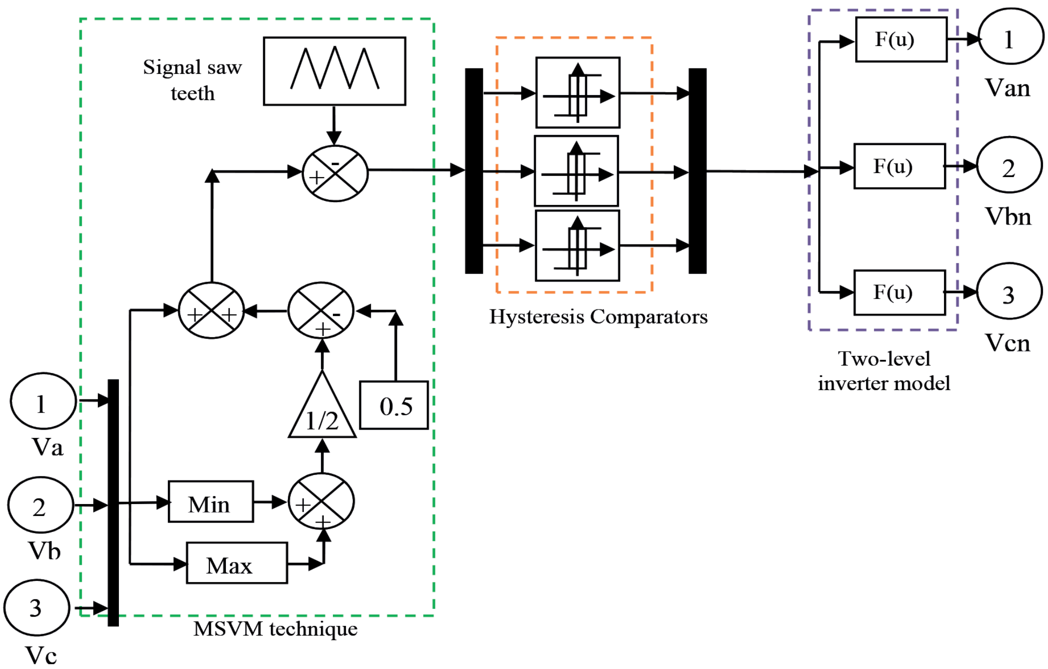


Figure 1. Block diagram of the modified SVM technique [41]

DFTC control with modified SVM technique. The classical DFTC methods have tremendous applications in AC machines superior effectiveness drives. The classical DFTC method have significant advantages over traditional field-oriented control. These advantages include minimized harmonic content in output voltage, fast response dynamic, a simple algorithm, robust method, easy to apply, low cost, and so on [32]. These multiple features and characteristics made this method the most widely used in the field of controlling electrical machines, and in particular in the field of electric power generation. This method depends on directly controlling the electromagnetic torque of the machine without using the inner rings and PWM technique. This method uses a switching table and two hysteresis controllers to control the electromagnetic torque and flux. In [41, 42], seven-level DFTC control was proposed to control the permanent magnet synchronous motor (PMSM) and the induction motor (IM), respectively. In [43], DFTC control with synergetic control was proposed to regulate the torque of the double star induction motor (DSIM). The simulation results show the superiority of the proposed technique. In [44], four-level DFTC control was proposed to control the IM drives. A Five-level DFTC method was proposed in [45], this proposed technique was used to control the IM. In [46], 24-sectors DFTC control was proposed to control the IM drives. In [47], four-level DFTC control was proposed to control the PMSM drives. In [48], a modified DFTC technique was proposed based on traditional SVM, where four PI controllers were used to control the torque and flux of DSIM drives.

In this section, we use the DFTC control scheme with modified SVM (MSVM) and PI controllers to regulate the electromagnetic torque and rotor flux of DFIG-based wind turbines. This designed DFTC control is shown in Figure 2. Through Figure 2, we find that this DFTC technique is a very simple, robust method, easy, and it can be easily applied to other machines compared to field-oriented control (FOC).

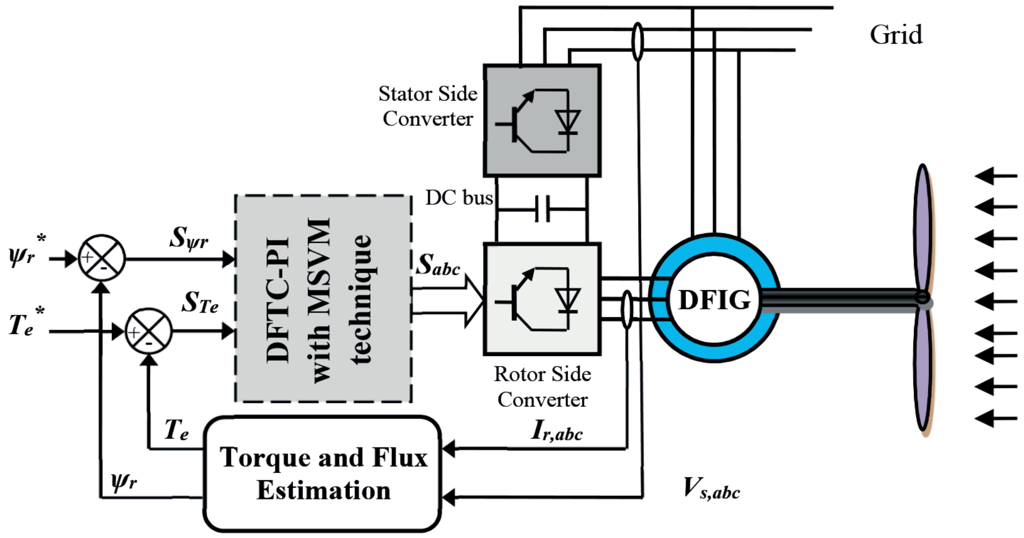


Figure 2. Block diagram of the DFIG with DFTC–MSVM

This method needs to estimation the rotor flux and electromagnetic torque of DFIG. To estimate the rotor flux and electromagnetic torque, we need to measure both voltage and stator current. On the other hand, the estimate of the stator flux is based on the parameter of the stator resistance.

The phase and amplitude of the stator flux are estimated by the relation equations (11) to (12):

$$\begin{cases} \Psi_{s\beta} = \int_0^t (-R_S \cdot I_{s\beta} + V_{s\beta})dt; \\ \Psi_{s\alpha} = \int_0^t (-R_S \cdot I_{s\alpha} + V_{s\alpha})dt. \end{cases} \quad (11)$$

Equation (12) represents the magnitude of stator flux:

$$\psi_s = \sqrt{\psi_{s\alpha}^2 + \psi_{s\beta}^2}; \tag{12}$$

$$\theta_s = \operatorname{arctg}\left(\frac{\psi_{s\beta}}{\psi_{s\alpha}}\right), \tag{13}$$

where θ_s — is the phase of stator flux.

The estimation of the electromagnetic torque is based on the rotor current and stator flux. Equation (14) represents how to estimation the electromagnetic torque from rotor current and stator flux.

$$T_e = \frac{3}{2}\frac{M}{L_s} n_p (-\psi_{ds} I_{qr} + \psi_{qs} I_{dr}). \tag{14}$$

Despite the advantages of this designed DFTC method in this section, it has several disadvantages similar to the classical method. This method does not eliminate the electromagnetic torque and rotor flux undulations of the DFIG (see [32]). Also, the THD level remains somewhat high.

In order to reduce electromagnetic torque and rotor flux undulations, we propose in the next part a new nonlinear method. This new method relies on the combination of two different methods in principle, to obtain a more robust nonlinear method. And thus reduce electromagnetic torque and rotor flux undulations of DFIG-based wind turbines.

Fractional order second-order continuous sliding mode. In this section, a new nonlinear control was proposed. This the proposed method is named fractional-order second-order continuous sliding mode (FOSOCSM) control. This proposed method is based on fractional calculus and the SOCSM approach. It can be said that the new nonlinear method, is only an improvement in the performance and effectiveness of the SOCSM controller. We used the fractional calculus feature to improve and develop the performance of the SOCSM controller. The proposed FOSCSM controller is a very simple structure, more robust, easy to adjust, and easy to implement. On the other hand, the FOSOCSM controller reducing more the chattering phenomenon compared to the traditional SOCSM controller. This new nonlinear method offers better and better performance than the classic SOCSM method, and this is what we will explain in the rest of the article. Equation (15) represents the proposed FOSOCSM controller. By K_1 and K_2 the stability of the FOSOCSM controller can be controlled. On the other hand, λ represents fractional calculus. It can take positive or negative values, depending on the system used.

$$w = (-K_1 |S|^{a_1} \operatorname{sign}(S) - k_2 \cdot \operatorname{sign}|S|^{1/2} + \int \alpha \cdot \operatorname{sign}(S)\, dt)^{\lambda}. \tag{15}$$

Where K_1 and K_2 — is the constant gains.

DFTC with FOSOCSM controllers. The FOSOCSM-DFTC control structure used in this work significantly minimizes the electromagnetic torque and rotor flux undulations of DFIG-based wind turbines. This proposed control method is a modification of the proposed method in [32] to reduce electromagnetic torque and rotor flux ripples. The proposed DFTC control technique is verified through MATLAB software. Results are compared with traditional SOCSM and PI controllers to prove the feasibility of the proposed FOSOCSM controllers. The proposed FOSOCSM-DFTC method, which is designed to control rotor flux and electromagnetic torque of the DFIG-based wind turbines is shown in Figure 3. Through Figure 3, we notice that this method is simple and uncomplicated and has almost kept the same shape as the proposed method in [32], and the difference lies in the use of the proposed FOSOCSM controller and modified SVM technique in this paper. On the other hand, in this proposed method we used the same block to estimate the electromagnetic torque and rotor flux used in the case of the traditional DFTC method with PI controllers.

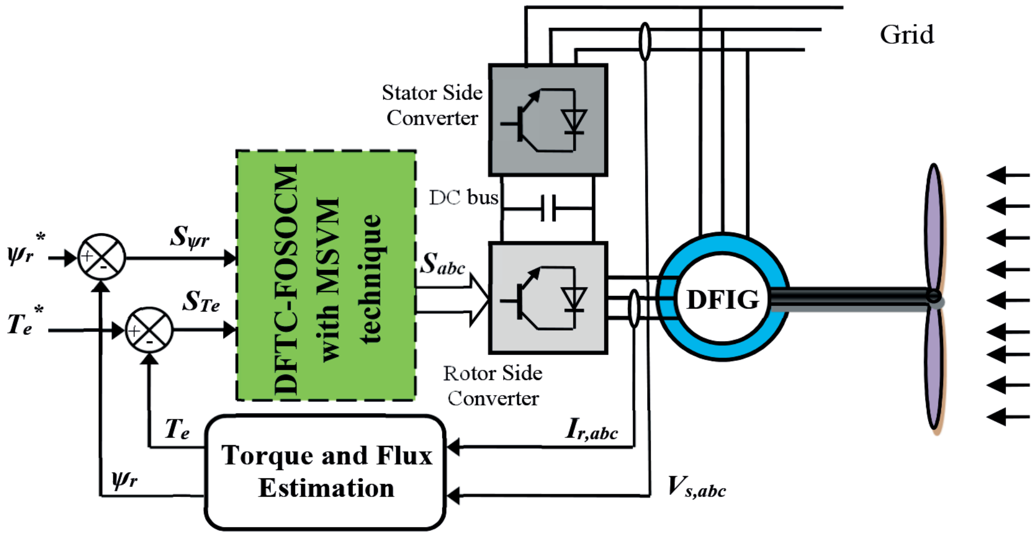


Figure 3. Block diagram of the DFIG with DFTC-FOSOCSM

Electromagnetic torque and rotor flux FOSOCSM controllers are used to influence respectively on the two rotor voltage components as in (16) and (17).

$$V_{dr}^* = (-l_1 \left|S_{\psi r}\right|^{a_1} \operatorname{sign}\left(S_{\psi r}\right) - k_1 \cdot \operatorname{sign}\left|S_{\psi r}\right|^{1/2} + \int \alpha \cdot \operatorname{sign}\left(S_{\psi r}\right) dt)^{\lambda}; \tag{16}$$

$$V_{qr}^* = (-l_2 \left|S_{Te}\right|^{a_1} \operatorname{sign}\left(S_{Te}\right) - k_2 \cdot \operatorname{sign}\left|S_{Te}\right|^{1/2} + \int \alpha \cdot \operatorname{sign}\left(S_{Te}\right) dt)^{\lambda}, \tag{17}$$

where the electromagnetic torque error $S_{Te} = T_e^* — T_e$ and the rotor flux magnitude error $S_{\psi r} = \psi_r^* - \psi_r$ are the sliding variables, and the constant gains k_1 and k_2 must check the stability conditions, λ is the fractional order ($0 < \lambda < 1$).

Results and Discussion

In this section, numerical simulations are carried out with a 1,5 MW DFIG attached to a 398 V/50 *Hz* grid, by using the environment of MATLAB software. The proposed control techniques are simulated and compared regarding stator current harmonics distortion, rotor flux ripple, reference tracking, electromagnetic torque ripples, and robustness against DFIG parameter variations.

The DFIG used in our work has the following parameters: P_n = 1,5 MW, p = 2, R_s = 0,012 Ω, 50 Hz, 380/696 *V*, R_r = 0.021 Ω, L_s = 0.0137 *H*, J = 1000 kg·m², f_r = 0.0024 Nm/s, L_r = 0,0136 *H* and L_m = 0,0135 H [32], [33].

First test. This test represents the reference tracking test. This test aims to study the behavior of the proposed methods of control by taking the generated speed as constant and equal to the nominal value. As well as knowing which method provides the best results and reduces electromagnetic torque and rotor flux ripples together. The results obtained are shown in Figures 4–6. Figure 4a represents the stator current signal of the machine. From this figure, the shape of the stator current is sinusoidal, and on the other hand, its value is related to the reference value of the electromagnetic torque and the system itself. Figure 4, *b* and 4, *c* represents the rotor flux and electromagnetic torque of the designed DFTC methods, respectively. We note through these figures that the electromagnetic torque and rotor flux tracks almost perfectly their references values for all the proposed methods. By looking at Figures 5, *a*, 5, *b* and 5, *c*, we notice that the DFTC-FOSOSMC method reduces more ripples in stator current, electromagnetic torque, and rotor flux compared with DFTC-SOSMC and DFTC-PI methods. On the other hand, Figures 6, *a*, 6, *b* and 6, *c* show the THD value of stator current (I_{as}) for both DFTC techniques. It can be observed that the THD value is minimized for DFTC-FOSOCSM (0,14 %) when compared to DFTC-PI (0,73 %) and DFTC-SOCSM (0,23 %).

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

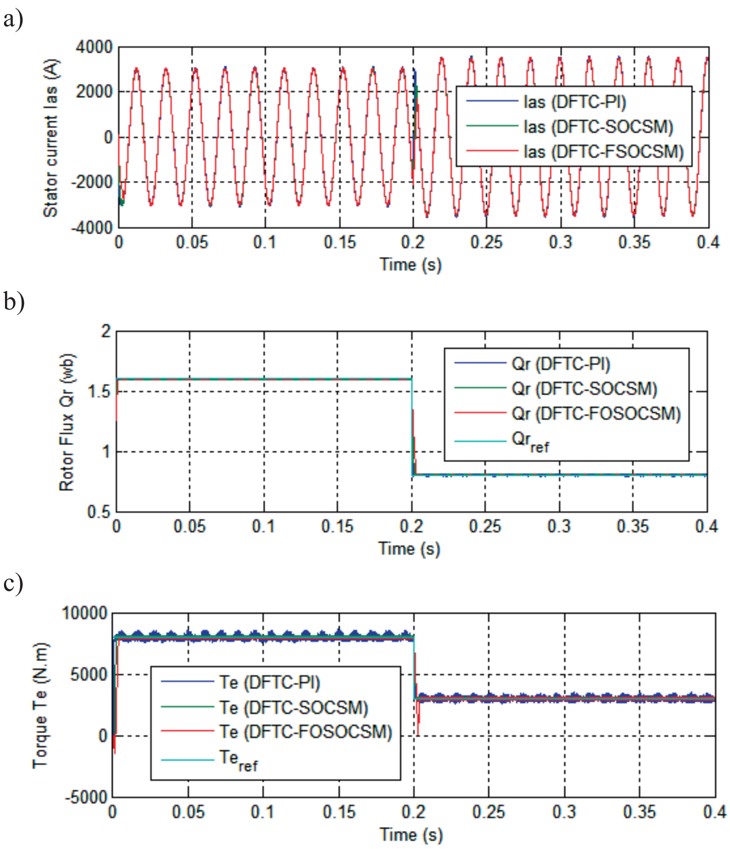


Figure 4. The results obtained:
a — Current *Ias*; *b* — Rotor flux; *c* — Electromagnetic torque *Te*

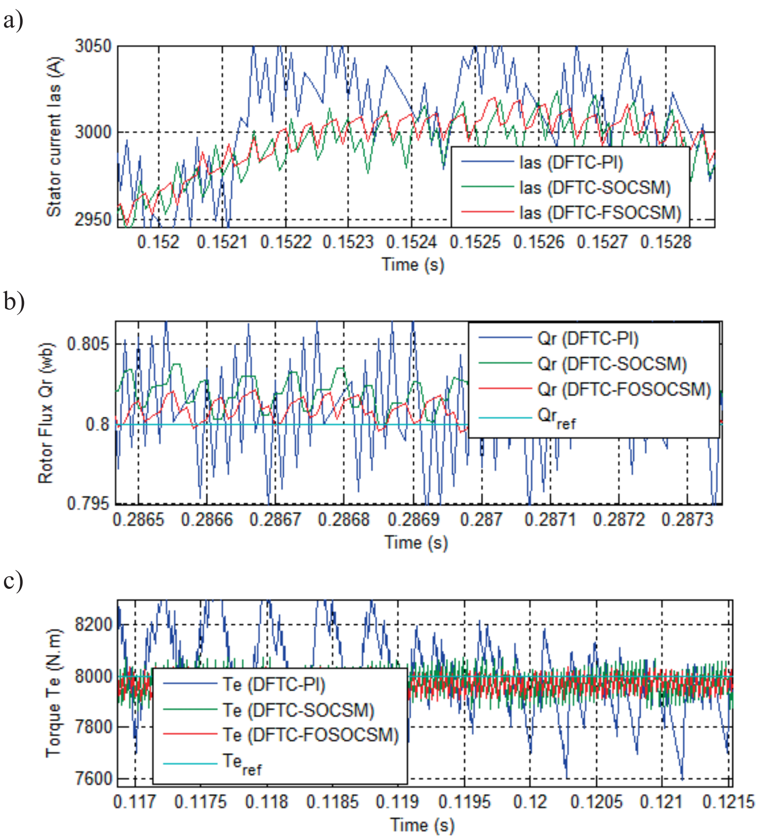
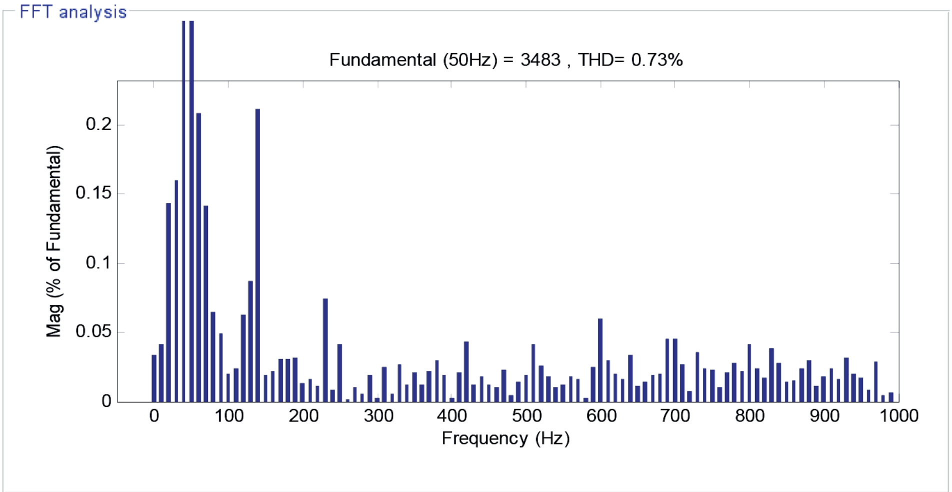
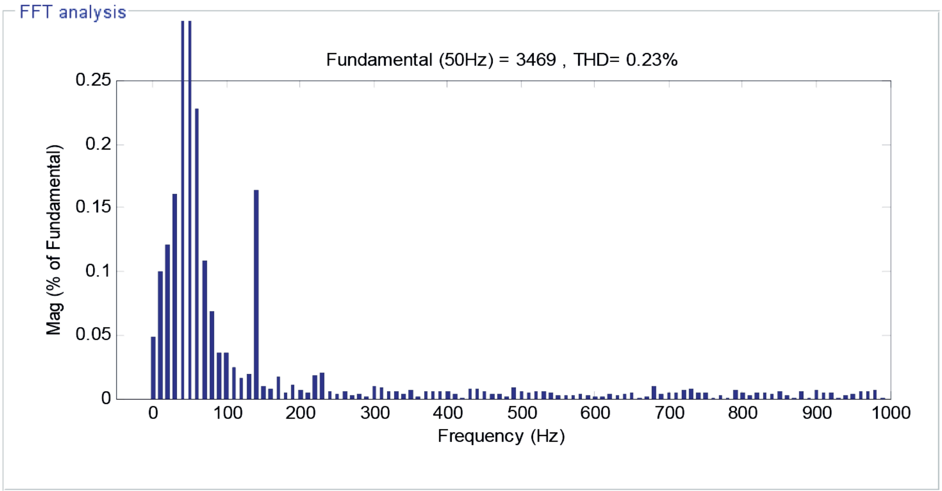


Figure 5. The results obtained: *a* — Zoom (Current *Ias*).;
b — Zoom (Rotor flux); c — Zoom (Electromagnetic torque *Te*)

a)



b)



c)

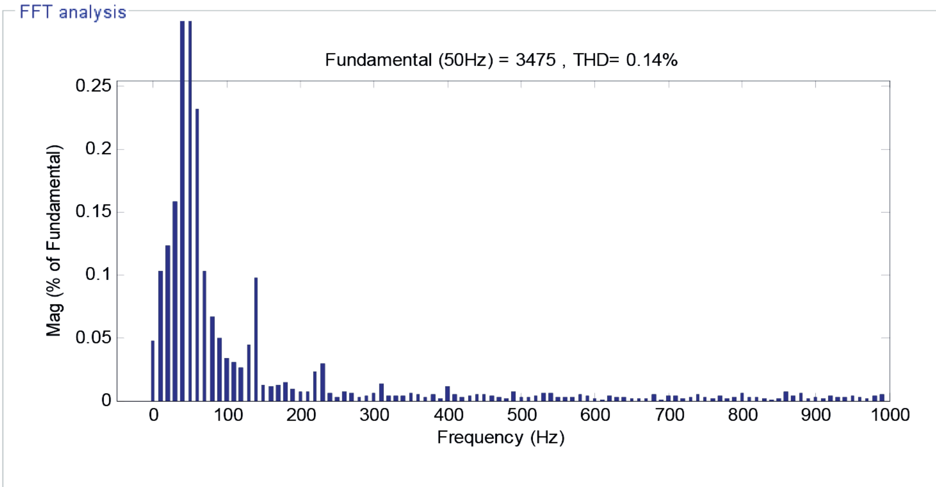


Figure 6. (THD) values obtained: *a* — THD (DFTC-PI);
b — THD (DFTC-SOCSM); *c* — THD (DFTC-FOSOCSM)

Second test. The principal objective of this test is to examine the influence of a machine parameters variation on the rotor flux, stator current, and electromagnetic torque and behavior for designed DFTC techniques. The simulation results are shown in Figures 7 to 9. These figures show that the electromagnetic torque and rotor flux follow the references with high accuracy for all the proposed methods (see Figure 7, *b* and 7, *c*). However, the stator current remains sinusoidal (see Figure 7, *a*) and is related to the system and the reference value of the electromagnetic torque and rotor flux. On the other hand, we notice by looking at Figures 8a, 8b and 8c that the DFTC-FOSOCSM method significantly reduced the ripples of stator current, electromagnetic torque, and rotor flux compared to both DFTC-PI and DFTC-SOCSM methods.

Figures 9, *a*–*c* show the THD value of stator current (I_{as}) for three proposed DFTC methods. It can be observed that the THD value is reduced for DFTC-FOSOCSM (0.18 %) when compared to DFTC-PI (0,85 %) and DFTC-SOCSM (0,27 %). This result is attractive for wind turbine applications to guarantee the quality and stability of the generated power when the machine parameters are changing. Thus, it can be said that the proposed FOSOCSM controller provided better performance than both PI and SOCSM, and this is what we observed through two tests, as well as the THD ratio and the value of electromagnetic torque and rotor flux ripples.

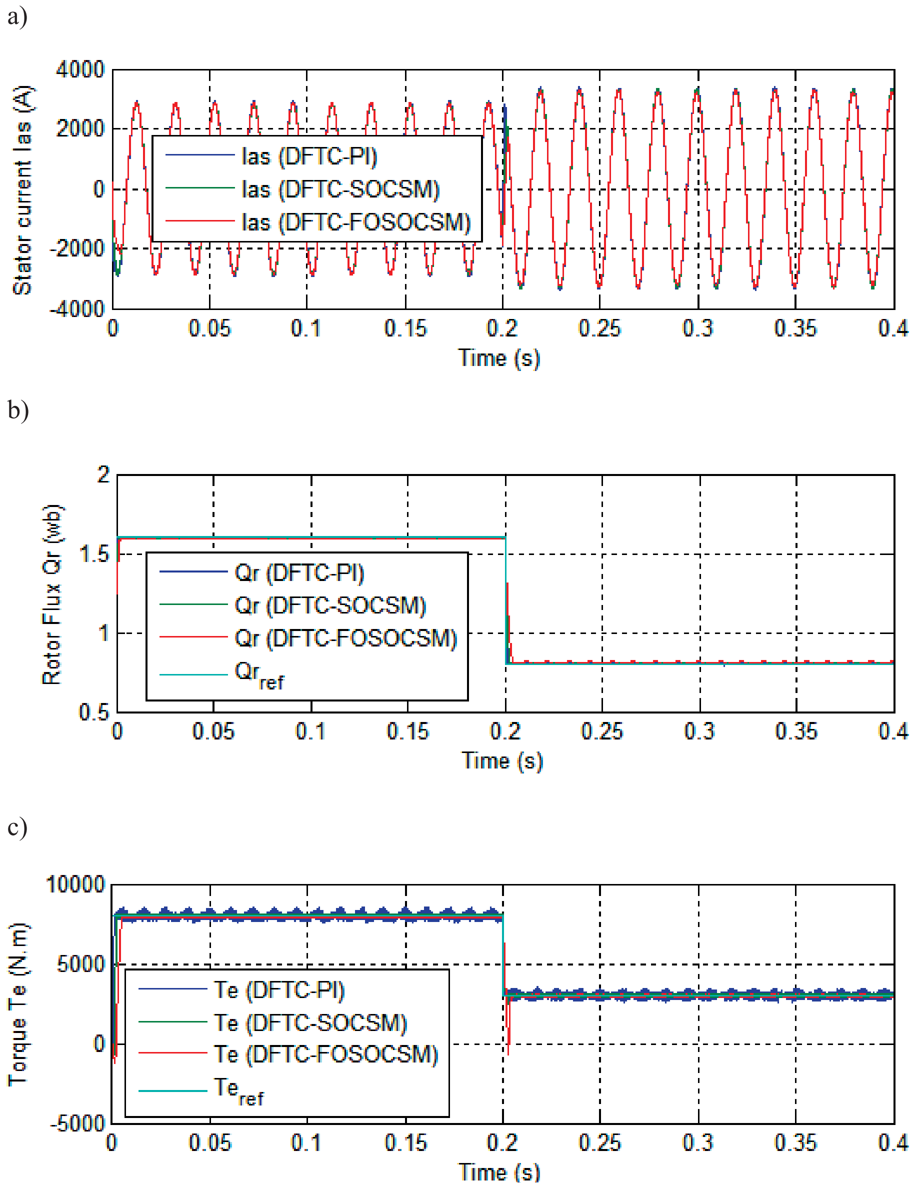
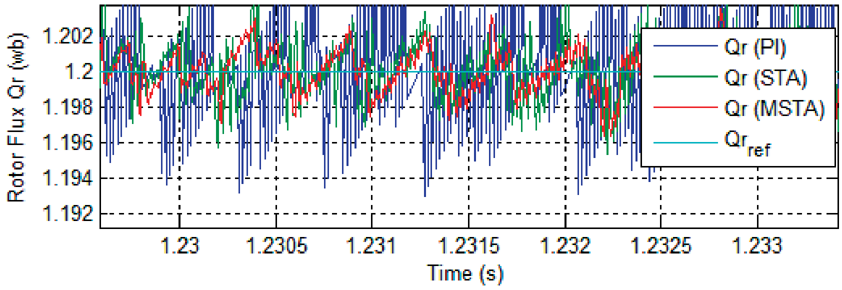
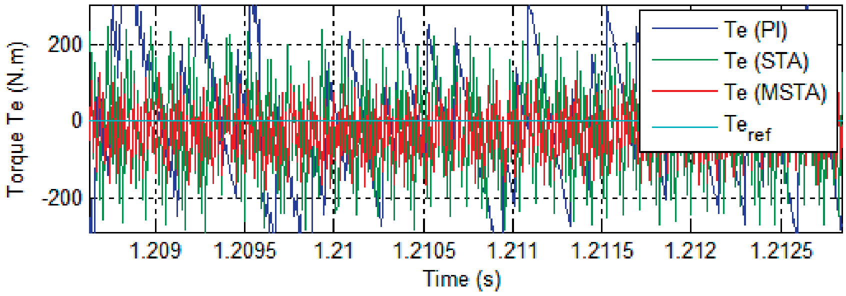


Figure 7. The results obtained:
a — Current *Ias*; *b* — Rotor flux; *c* — Electromagnetic torque *Te*

a)



b)



c)

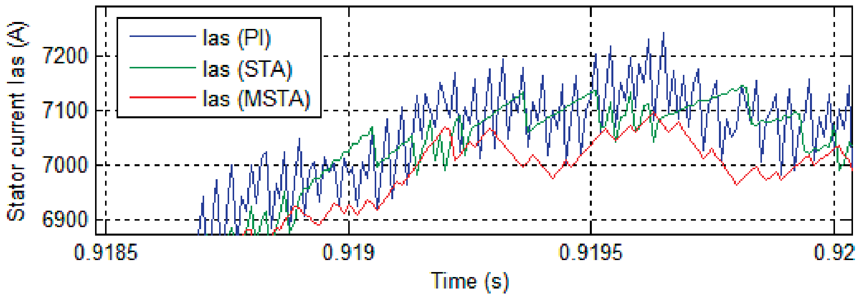
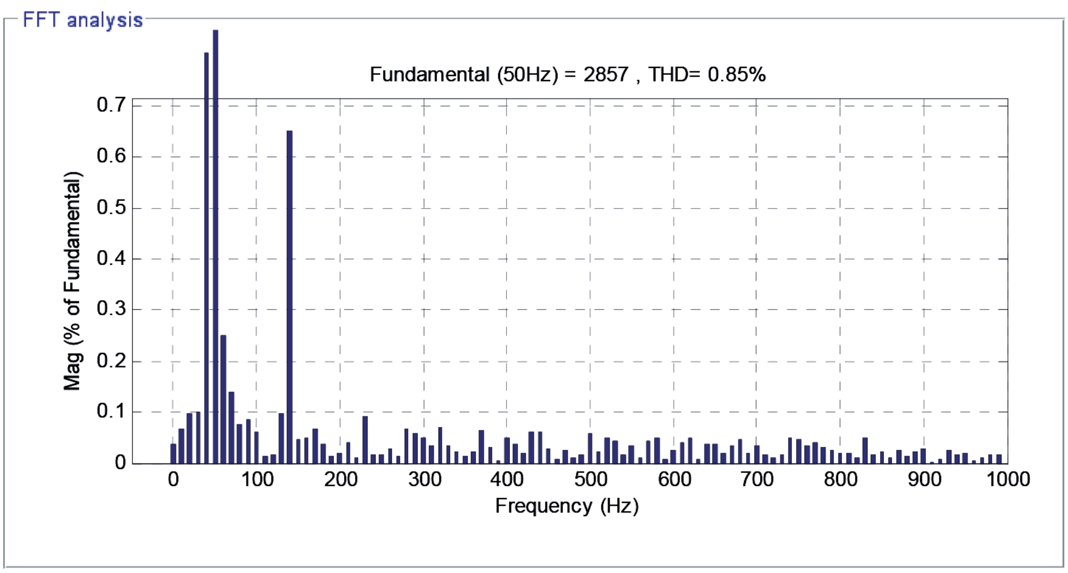
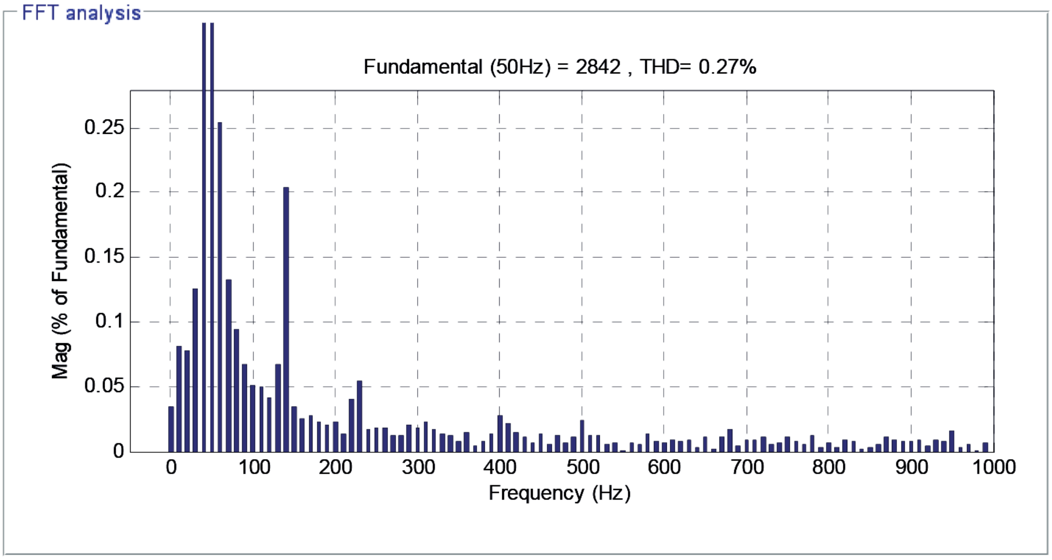


Figure 8. The results obtained: *a* — Zoom (Current *Ias*);
b — Zoom (Rotor flux); *c* — Zoom (Electromagnetic torque *Te*)

a)



b)



c)

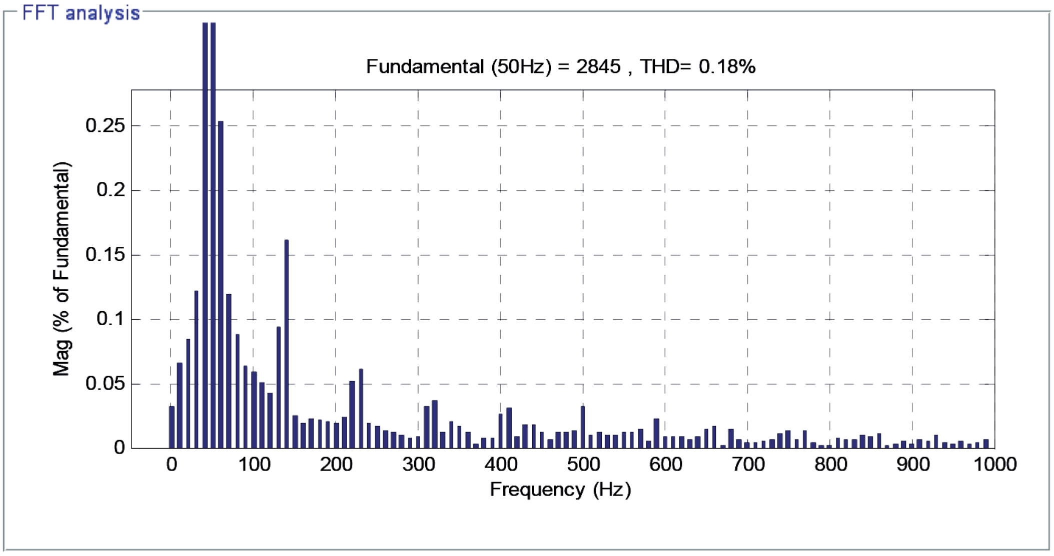


Figure 9. (THD) values obtained:
a — THD (DFTC-PI); *b* — THD (DFTC-SOCSM); *c* — THD (DFTC-FOSOCSM)

A comparative study between the methods proposed in this work is necessary and imperative to identify the strengths and weaknesses of each method. Table 1 represents a comparative study between the various proposed methods. It is clear that the proposed DFTC-FOSOCSM technique is more robust than the DFTC-PI and DFTC-SOSCSM methods. The proposed method provided better results in both dynamic responses, THD, rise time, overshoot, settling time compared to DFTC-PI and DFTC-SOSCSM methods. On the other hand, the proposed method gave a very good quality of the output current of the generator, as well as less flux and torque fluctuations.

Finally, a comparative study of the obtained value of THD of the stator current with some publications. This is in order to know the efficacy of the proposed method with other works and methods that exist on the ground. Table 2 represents the comparison between the proposed method and some published works. Through this table, we find that the DFTC-FOSOCSM method gives a much better value than several methods implemented in various scientific works, and this is because of the use of the proposed FOSOCSM controller. Accordingly, it can be concluded that the DFTC method with the proposed FOSOCSM controller is very robust compared to some controls.

Table 1

Compare the results obtained from the designed methods with the DFTC-PI

Criteria	Techniques		
	DFTC-PI	DFTC-SOCSMC	DFTC-FOSOCSMC
Dynamic response (s)	Medium	Fast	Fast
THD (%)	0,73	0,23	0,14
Reduce torque and flux ripples	Acceptable	Good	Excellent
Simplicity of calculations	Simple	Complicated	Complicated
Settling time (ms)	High	Medium	Medium
Overshoot (%)	Remarkable ≈ 22 %	Remarkable ≈ 10 %	Neglected near ≈ 1,5 %
Torque and flux tracking	Good	Very good	Excellent
Simplicity of converter and filter design	Simple	Simple	Simple
Sensitivity to parameter change	High	Medium	Medium
Rise Time (s)	High	Medium	Medium
Torque: ripple (N.m)	Around 700	Around 260	Around 130
Improvement of transient performance	Good	Very good	Excellent
Quality of stator current	Acceptable	Very good	Excellent
Rotor flux: ripple (wb)	Around 0,015	Around 0,005	Around 0,001

Table 2

Compare THD current with other control strategies

Techniques		THD, %
Ref. [32]	Classical DTC	2,57
	SOCSM-DTC	0,98
Ref. [49]		1,14
Ref. [50]	FOC	3,7
Ref. [51]	DPC	2,56
Ref. [17]		1,15
Proposed methods	DFTC-PI	0,73
	DFTC-SOCSM	0,23
	DFTC-FOSOCSM	0,14

Conclusion

This work presents a new DFTC technique for DFIG based on fractional-order second-order continuous sliding mode controllers. The proposed DFTC technique is robust and a modified SVM strategy is used. The rotor/stator current is nearly sinusoidal and there is a significant minimization in rotor flux and electromagnetic torque undulations. The same DFTC technique is explored to control DFIG under unbalanced grid voltage conditions. A direct and quadrature rotor voltage based on fractional-order second-order continuous sliding mode controllers is proposed. Without using the rotating reference frame and sequential decomposition, the proposed DFTC method with fractional-order second-order continuous sliding mode controllers minimizes the undulations in the rotor flux and electromagnetic torque. The proposed DFTC-FOSOCSM strategy has improved the robustness of the DFTC technique, increasing its characteristics in transient and dynamic conditions in terms of efficiency, overshoot, rapidity, rise time, and stability. Simulation results show the performances of the designed nonlinear controller.

Indeed, this designed DFTC strategy deserves attention because they solve the drawbacks of high undulations of the electromagnetic torque and flux for wind power systems. On the other hand, this research work in this paper is limited given that the wind speed is constant. In order to further enhance the robustness of the DFIG-SRWP system under previous concerns in future papers this is through interactions between DFIGs with different strategies, such as neural algorithm, fractional-order PI, genetic algorithm, neuro-fuzzy control, and type 2 fuzzy logic control.

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

– a simple nonlinear controller was designed.

– minimizes the electromagnetic torque and rotor flux ripples.

– minimization of the THD of stator current by 80,82 %, 39,13 % of both DFTC-PI and DFTC-SOCSM, respectively.

– a new DFTC technique was presented and confirmed with numerical simulation.

The work can be extended with neuro-FOSOCSM controller (NFOSOCSM) or terminal FOSOCSM to obtain more minimum electromagnetic torque ripple, zero settling time, and zero steady-state error. Direct vector control-based FOSOCSM methods can also be taken up as an extension of this work.

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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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