https://doi.org/10.3311/PPee.20333

Periodica Polytechnica Electrical Engineering and Computer Science, 67(1), pp. 10–20, 2023

Backstepping Control Based on a Third-order Sliding Mode Controller to Regulate the Torque and Flux of Asynchronous Motor Drive

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Received: 17 April 2022, Accepted: 06 November 2022, Published online: 22 December 2022

Abstract

This work represents a new nonlinear control for the asynchronous motor (AM) drive. The designed nonlinear control is based on the combination between the backstepping control (BC) scheme and third-order sliding mod control (TOSMC). In this proposed nonlinear control, the torque and flux are controlled. Also, the torque, current, and flux ripples are minimized by a proposed BC-TOSMC strategy. The proposed BC-TOSMC strategy is more robust compared to the field-oriented control (FOC). The proposed BC-TOSMC strategy of AM drive has been simulated in MATLAB/Simulink software. The comparisons were made between the proposed BC-TOSMC strategy and the FOC strategy under different operating conditions. The results show that the proposed BC-TOSMC strategy minimized the flux, current, and torque ripples of the AM drive compared to the FOC strategy, with a reduction torque ripples ratio of about 57.14%. Also, the total harmonic distortion (THD) values of stator current using the proposed BC-TOSMC strategy and FOC technique are respectively 1.09% and 3.42%. In this case, utilizing the proposed BC-TOSMC strategy, the performance of the AM has improved from the FOC strategy.

Keywords

asynchronous motor, backstepping control, third-order sliding mod control, field-oriented control, total harmonic distortion

1 Introduction

The asynchronous motor is among the most widely used machines today as a result of its many advantages compared to other motors. This motor has been used in several fields such as wind energy, where this motor is used to generate electric power from wind because of its durability [1]. Moreover, this motor is used as a pump due to its low cost and ease of control [2].

To control this motor, there are several ways to control it, as there are linear and non-linear techniques. Also, artificial intelligence can be used to control asynchronous motors such as neural networks (NNs), genetic algorithm (GA), and fuzzy logic (FL). One of the methods used to control an asynchronous motor is direct torque control (DTC) [3]. This technique is a simple algorithm compared to field-oriented control (FOC). This technique is used to control the torque and flux of the asynchronous motor. Also, this technique is an evolution of the FOC strategy. Controlling using the DTC strategy provides better results in terms of torque and current ripples than the FOC strategy [4]. Among the disadvantages of this technique are large ripples in terms of torque, flux, and electric current. To overcome these shortcomings, several techniques have been combined with the DTC strategies, such as the FL algorithm [5] and NNs controller [6].

Several works have suggested the use of a multi-level inverter to improve the performance and effectiveness of the DTC strategy [7–9]. The results showed the effectiveness of using the multi-level inverter in reducing the torque and flux fluctuations of the asynchronous motor. The use of a multi-level inverter has disadvantages in controlling the asynchronous motor, as it makes the cost of control increase and the complexity of the system and this is undesirable.

Other techniques that have been proposed to control the asynchronous motor are nonlinear techniques such as sliding mode control [10] and backstepping control [11].

Since backstepping control is among the nonlinear techniques that provide better results and improve the perfor-

Cite this article as: Zellouma, D., Benbouhenni, H., Bekakra, Y. "Backstepping Control Based on a Third-order Sliding Mode Controller to Regulate the Torque and Flux of Asynchronous Motor Drive", Periodica Polytechnica Electrical Engineering and Computer Science, 67(1), pp. 10–20, 2023. https://doi.org/10.3311/PPee.20333

mance and efficiency of electrical machines. This technique is different from the SMC technique. This technique was used to control several electrical machines such as the asynchronous generator [12]. On the other hand, durability is among the advantages of this technique. This technique is related to the studied system, which makes it somewhat affected by the change in the parameters of the machine or the studied system.

Toimprove the performance and effectiveness of the backstepping control technique, a new idea is proposed for this technique by combining it with third-order sliding mode control (TOSMC).

In this paper, the backstepping control and TOSMC control are combined to improve the performance and efficiency of the backstepping control technique and on the other hand reduce the torque and flux ripples of the asynchronous motor. Also, underestimate the total harmonic distortion (THD) of stator current.

This new work can be summarized in the following points:

- A new backstepping control scheme based on the TOSMC strategy is designed to control the asynchronous motor drive.
- The proposed backstepping control scheme based on the TOSMC strategy minimizes the torque, current, and flux ripples of the asynchronous motor drive.
- The backstepping control scheme based on the TOSMC strategy minimizes harmonic distortion of the stator current of the asynchronous motor drive.
- A new robust control strategy was presented and compared with the FOC strategy.

The rest of the work is organized as follows: a mathematical model of the TOSMC method is presented in Section 2, with the advantages and disadvantages of this method. Section 3 presents the backstepping control scheme of the asynchronous motor drive. In Section 4 the proposed backstepping control scheme based on the TOSMC method is presented. Section 5 shows the comparative simulation results obtained on an asynchronous motor drive. Finally, Section 6 provides the conclusions.

2 Third-order SMC strategy

TOSMC technique is among the nonlinear techniques that have been proposed for controlling electrical systems. This technique is a kind of nonlinear technique, which is proposed in [13] to improve the performance and effectiveness of the DTC strategy of the asynchronous generator. This technique reduces ripples in both torque and active power compared to classic techniques such as the PI controller [14].

Among the advantages of this technique is that it is not related to the studied system nor the parameters of the studied machine, unlike the traditional technique such as the SMC technique [13, 14].

TOSMC can be used in the case of linear and non-linear systems, as it is characterized by a simple algorithm, which makes it easy to use and apply compared to other techniques such as SMC controller and high-order SMC technique. This technique can be expressed by equation (Eq. (1)). Through this equation, this technique is a development of the super-twisting algorithm. Durability is also among its advantages, as it is not affected by changing parameters of the studied system. On the other hand, Fig. 1 represents the TOSMC technique.

In this paper, this technique is used to improve the performance and effectiveness of the backstepping control of the induction motor:

$$u(t) = u_1(t) + u_2(t) + u_3(t), \tag{1}$$

$$u_1(t) = K_1 \sqrt{|S|}\ \mathrm{Sign}(S), \tag{2}$$

$$u_2(t) = K_2 \int \mathrm{Sign}(S) \cdot dt, \tag{3}$$

$$u_3(t) = K_3\ \mathrm{Sign}(S), \tag{4}$$

where, S is the sliding surface or error ($S = X^* - X$).

K_1, K_2 and K_3 are the positive gains.

In order to adjust the performance of the TOSMC strategy response, the values of K_1, K_2 and K_3 are changed. Fig. 1 shows the internal structure of the TOSMC strategy [15].

3 Backstepping control

Traditionally, backstepping control is among the most robust nonlinear techniques, and this technique has been used to control several electric machines [16–18]. But among its disadvantages is that it depends on the mathematical form

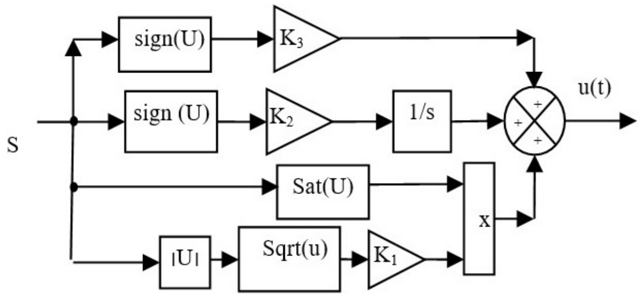

Fig. 1 The TOSMC strategy

of the studied system, which makes there are disadvantages at the level of this technique, such as ripples at the level of torque, flux, and current in the case of an asynchronous motor. Moreover, this technique is relatively complicated compared to both direct control of torque and direct control of power, where the cost of implementation is rather large. On the other hand, the backstepping technique is a form of nonlinear control design that is systematic and recursive [19]. The nonlinear system's stability may be greatly improved using this technique. It is a highly strong tool for testing and determining necessary conditions for the stability of various dynamic systems and their performances based on Lyapunov control functions [20]. The backstepping control in this work is based on the idea of rotor field-oriented control, where the direct and quadrature components of the rotor flux:

$$\begin{cases} \psi_{qr} = 0 \\ \psi_{dr} = \psi_r \end{cases}. \tag{5}$$

3.1 Step 1 (speed and flux loop)

The model of the induction motor on the axis "d" can be described in a reference connected to the rotating field by Eqs. (6) and (7):

$$\begin{cases} \dot{i}_{ds} = N_1 \cdot i_{ds} + N_2 \cdot \psi_{ds} + \delta \cdot V_{ds} \\ \dot{i}_{qs} = N_1 \cdot i_{qs} - w_s \cdot i_{ds} + N_3 \cdot w \cdot \psi_{dr} + \delta \cdot V_{ds} \end{cases}, \tag{6}$$

$$\begin{cases} \dot{\psi}_{dr} = \dfrac{M}{T_r} \cdot i_{ds} + \dfrac{1}{T_r} \cdot \psi_{ds} \\ \Omega = \dfrac{3 \cdot p \cdot M}{J \cdot L_r} \left(i_{qs} \cdot \dot{\psi}_{dr} \right) - \dfrac{T_L}{J} - \dfrac{f \cdot \Omega}{J} \end{cases}, \tag{7}$$

with:

$$\begin{cases} N_1 = -\left(\dfrac{1}{\sigma T_s} + \dfrac{M^2}{\delta \cdot L_r \cdot T_r} \right) \\ N_2 = \dfrac{M}{\delta \cdot L_r \cdot T_r} \\ N_3 = \dfrac{M}{\delta \cdot T_r} \end{cases} \text{and} \begin{cases} \sigma = \dfrac{M}{L_s \cdot L_r} \\ T_s = \dfrac{L_s}{R_s} \\ T_r = \dfrac{L_r}{R_r} \\ \delta = \dfrac{1}{\sigma \cdot L_s} \end{cases}.$$

The starting point of the backstepping control is to determine the speed error and flux error:

$$\begin{cases} e_\Omega = \Omega_{ref} - \Omega \\ e_\psi = \psi_{ref} - \psi_{dr} \end{cases}. \tag{8}$$

By deriving Eq. (7) we obtain:

$$\begin{cases} \dot{e}_\Omega = \dot{\Omega}_{ref} - \dot{\Omega} \Rightarrow \dot{\Omega}_{ref} - \dfrac{3}{2} \dfrac{P \cdot M}{J \cdot L_r} \psi_{dr} i_{qs} - \dfrac{T_L}{J} \\ \dot{e}_\psi = \dot{\psi}_{ref} - \dot{\psi}_{rd} \Rightarrow \dot{\psi}_{ref} - \dfrac{M}{T_r} i_{ds} + \dfrac{1}{T_r} \psi_{dr} \end{cases}. \tag{9}$$

The first Lyapunov can did ate V is chosen as [21]:

$$\begin{cases} V = \dfrac{1}{2} e_\Omega^2 + \dfrac{1}{2} e_\psi^2 \Rightarrow V = e_\Omega \dot{e}_\Omega + e_\psi \dot{e}_\psi \\ \dot{V} = e_\Omega \left(\dot{\Omega}_{ref} - \dfrac{3}{2} \dfrac{pM}{JL_r} \psi_{dr} i_{qs} - \dfrac{T_L}{J} \right) \\ + e_\psi \left(\dot{\psi}_{ref} - \dfrac{M}{T_r} i_{ds} + \dfrac{1}{T_r} \dot{\psi}_{dr} \right) \end{cases}. \tag{10}$$

So, the control i_{qsref} and i_{dsref} is asymptotically stabilizing:

$$\begin{cases} i_{qs_{ref}} = \dfrac{2}{3} \dfrac{J \cdot L_r}{P \cdot M \cdot \psi_{dr}} \left(\dot{\Omega}_{ref} + \dfrac{T_L}{J} + K_\Omega e_\Omega \right) \\ i_{ds_{ref}} = \dfrac{T_r}{M} \left(\dot{\psi}_{ref} + \dfrac{1}{T_r} \psi_{dr} + K_\psi e_\psi \right) \end{cases}. \tag{11}$$

3.2 Step 2 (currents loop)

The final step in the Backstepping control is to compute the load current direct component (i_d) and load current quadrature component (i_q) may be described in (d-q), reference frame as follows:

$$\begin{cases} e_{i_{qs}} = i_{qs_{ref}} - i_{qs} \\ e_{i_{ds}} = i_{ds_{ref}} - i_{ds} \end{cases}. \tag{12}$$

By deriving Eq. (6) we obtain:

$$\begin{cases} \dot{e}_{i_{qs}} = \dot{i}_{qs_{ref}} - \dot{i}_{qs} \Rightarrow \dot{i}_{qs_{ref}} + N_1 \cdot i_{qs} \\ + \omega_s \cdot i_{qs} + N_3 \cdot \omega \cdot \psi_{dr} - \delta \cdot V_{qs} \\ \dot{e}_{i_{ds}} = \dot{i}_{ds_{ref}} - \dot{i}_{ds} \Rightarrow \dot{i}_{ds_{ref}} + N_1 \cdot i_{ds} \\ - \omega_s \cdot i_{qs} - N_2 \cdot \psi_{dr} - \delta \cdot V_{ds} \end{cases}. \tag{13}$$

The second Lyapunov can did ate V_e is chosen as:

$$\begin{cases} V_e = \dfrac{1}{2} \left(e_\Omega^2 + e_{i_{qs}}^2 + e_\psi^2 + e_{i_{ds}}^2 \right) \\ \dot{V}_e = e_\Omega \dot{e}_\Omega + e_{i_{qs}} \dot{e}_{i_{qs}} + e_\psi \dot{e}_\psi + e_{i_{ds}} \dot{e}_{i_{ds}} \\ \dot{V}_e = \dot{V} + e_{i_{qs}} \dot{e}_{i_{qs}} + e_{i_{ds}} \dot{e}_{i_{ds}} \end{cases}. \tag{14}$$

Therefore, Eq. (13) can be rewritten as:

$$\dot{V}_e < 0 \Leftrightarrow \dot{e}_{i_{qs}} = -K_{i_{qs}} \cdot e_{i_{qs}} \text{ and } \dot{e}_{i_{ds}} = -K_{i_{ds}} \cdot e_{i_{ds}}$$

$$\begin{cases} V_{qs} = \delta \left(\dot{i}_{qs_{ref}} + N_1 i_{qs} + \omega_s i_{ds} - N_3 \omega \psi_{dr} + K_{i_{qs}} e_{i_{qs}} \right) \\ V_{ds} = \delta \left(\dot{i}_{ds_{ref}} + N_1 i_{ds} - \omega_s i_{qs} - N_2 \psi_{dr} + K_{i_{ds}} e_{i_{ds}} \right) \end{cases}. \tag{15}$$

Fig. 2 shows the backstepping control of the asynchronous motor drive, where the inverter was controlled by the traditional PWM strategy. The backstepping control is more robust compared to the traditional FOC strategy and DTC technique [16].

Backstepping control, despite its robustness, gives ripples in the torque, current, and flux levels of the asynchronous motor drive. These drawbacks make this method undesirable. To overcome these shortcomings, a new idea is presented in the next part.

4 Backstepping control based on TOSMC controller

In Section 4, a new nonlinear control strategy is proposed to control the asynchronous motor drive. This proposed nonlinear control strategy was based on backstepping control and TOSMC strategy to obtain a more strategy and minimized the torque, stator current, and flux ripples of the asynchronous motor drive. The advantages of the backstepping control and TOSMC controller are combined to improve the efficiency and performance of the asynchronous motor. The proposed technique is among the most robust techniques and is not affected by the change in parameters of the studied machine. This proposed BC-TOSMC technique is used to control the torque and flux of the asynchronous motor. Fig. 3 represents the proposed BC-TOSMC technique for controlling the asynchronous motor, where we need to measure current and voltage. The proposed backstepping control technique is a modification of the classical backstepping control technique, whereby a TOSMC controller is used in the position

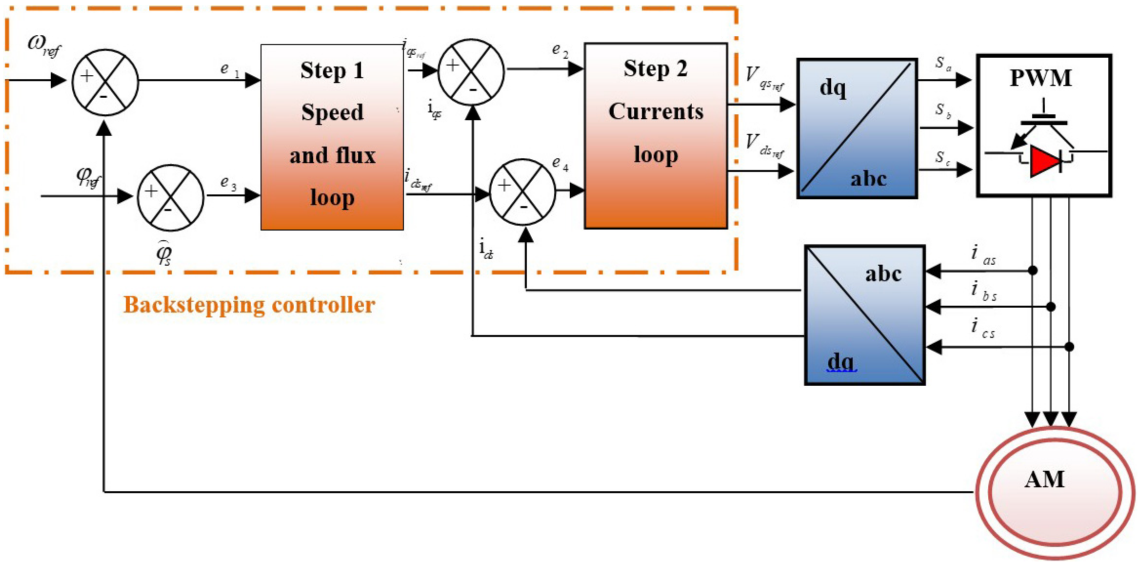

Fig. 2 Block diagram of backstepping control scheme for IM

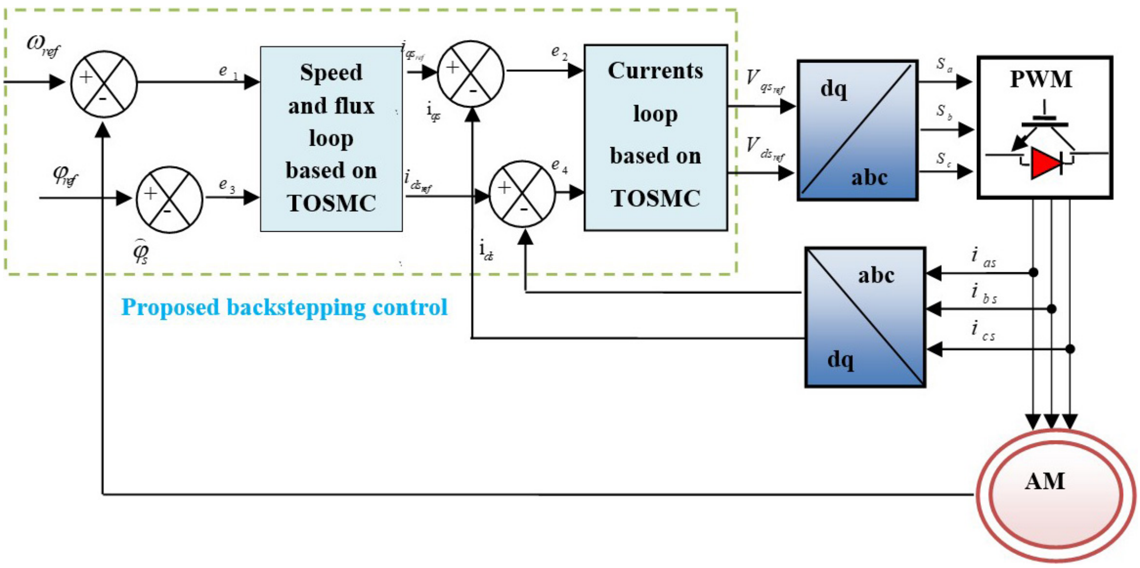

Fig. 3 The structure of the BC-TOSMC of the asynchronous motor

of the gain in order to reduce the fluctuations in the torque, current and flux level of the asynchronous motor. Also to reduce the THD value of the electric current.

5 Results

In Section 5, simulations are studied with an asynchronous machine operated as motor that used in this work is a 1.5 kW. The parameters are cited and presented in the Appendix. On the other hand, the MATLAB/Simulink software was used to verify the proposed backstepping control technique.

The proposed backstepping control schemes will be tested and compared in different configurations such as the tracking and robustness tests. The results obtained were compared with those obtained using the FOC technique.

5.1 First test

This test consists in tracing the behavior of the proposed BC-TOSMC technique in the case of constant speed with the change of torque from 0 N m to 3 N m and this is in a time of 2 seconds. The obtained results are shown in Fig. 4. By Fig. 4, torque and speed perfectly follow the references of both the proposed BC-TOSMC technique and the classical FOC-PI technique with preference to the proposed BC-TOSMC technique in dynamic response (see Figs. 4(a) and (b)). Also, the proposed BC-TOSMC technique reduced torque ripples compared with the classical FOC-PI technique (see Fig. 5(b)). Moreover, in the case of the proposed BC-TOSMC technique, there is no overshooting of the reference speed compared to the classical FOC-PI technique (see Fig. 5(a)).

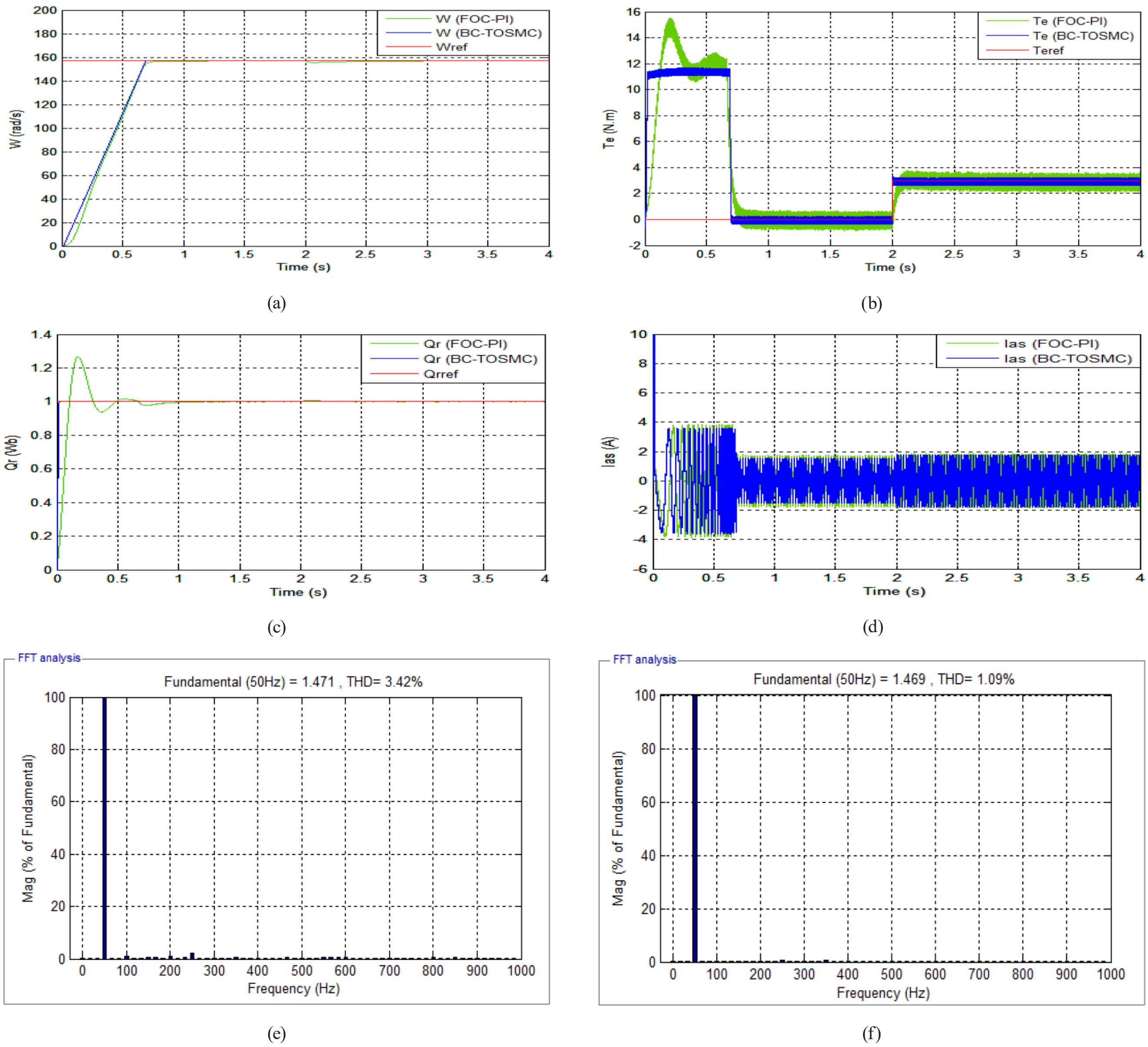

Fig. 4 The results of the first test; (a) Rotor speed; (b) Torque; (c) Flux; (d) Current; (e) THD of current *Ias* (FOC-PI); (f) THD of current *Ias* (BC-TOSMC)

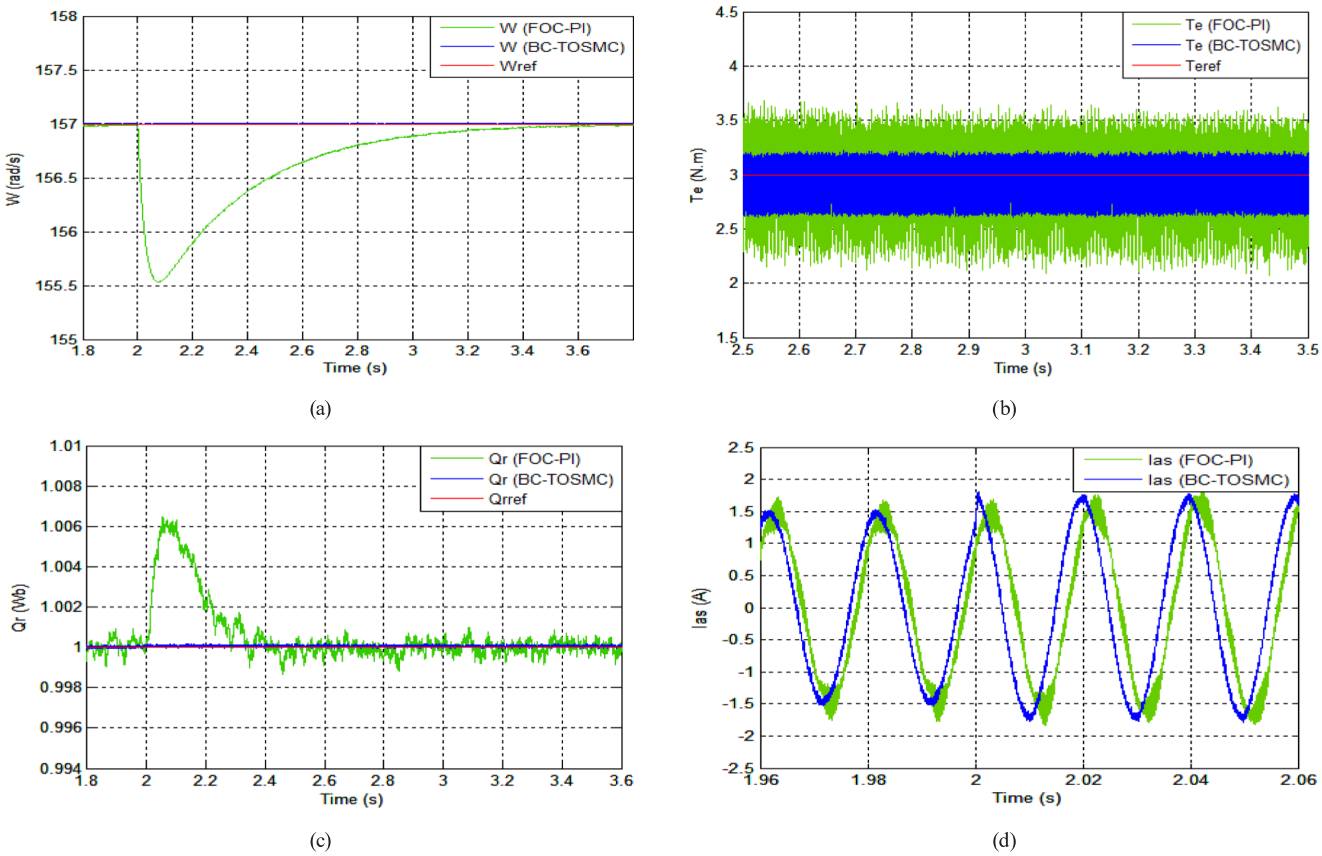

Fig. 5 Zoom in the results of the first test; (a) Rotor speed; (b) Torque; (c) Flux; (d) Current

The flux is shown in Fig. 4(c), where we note that the proposed BC-TOSMC technique provided satisfactory results in terms of reference tracking and not exceeding the reference value compared to the classical FOC-PI technique (see Fig. 5(c)). Moreover, the proposed BC-TOSMC technique gave less ripples to the flux compared to the classical FOC-PI technique.

The electric current of an asynchronous motor is shown in Fig. 4(d), the shape of which is related to torque. The higher the torque value, the higher the current value. Also, the current is sinusoidal with larger ripples in the case of the classical FOC-PI technique (see Fig. 5(d)). The quality of the current is good in the case of the proposed BC-TOSMC technique.

The proposed BC-TOSMC technique reduced the THD value of the electric current, as its value was 1.09% for the proposed BC-TOSMC technique and 3.42% for the classical FOC-PI technique. So the proposed BC-TOSMC technique reduced the THD value by about 68.12% compared to the classical FOC-PI technique.

In Table 1, most of the results obtained from the first test are summarized, as it is noted that the proposed BC-TOSMC technique improved most of the parameters such as steady-state error, transient performance of the speed, and torque response.

Table 1 Comparison between the FOC-PI and BC-TOSMC strategy

Performance criteria	FOC-PI	BC-TOSMC
THD (%)	3.42	1.09
Transient performance of the speed	Relatively fast with medium settling time	Low settling time
Steady state error %	> 3	Negligible
Improvement of transient performance	Good	Very good
Minimization of torque ripple	Medium	Very good
Simplicity of implementation	simple	More simple
Torque response	Medium	Very fast
Robustness to parameters variation	+	++

5.2 Robustness tests

The robustness of the two strategies (FOC-PI and BC-TOSMC) resulting from the parameters is tested following the specifications below:

- Test B1: robustness variation of the reference speed;
- Test B2: robustness variation stator resistance.

5.2.1 Test B1: variation of the reference speed

Fig. 6 illustrates the rotor speed, the electromagnetic torque, rotor flux, THD value of stator current, and stator current (*Ias*) of both strategies. In this test, the speed is changed from 150 rad/s to 0 rad/s at the moment 2 seconds. Torque and speed follow the references well, with a preference for the proposed BC-TOSMC technique in dynamic response compared to the classical FOC-PI method (see Figs. 6(a) and (b)). Moreover, the proposed BC-TOSMC technique has reduced torque ripples compared to the classical FOC-PI method (see Fig. 7(b)). Also, the proposed BC-TOSMC minimized the speed response compared to the traditional FOC-PI strategy (see Fig. 7(a)). The flux of the proposed BC-TOSMC methods is represented in Fig. 6(c), where an overshoot of the reference value is observed for the classical FOC-PI technique with an advantage of the proposed BC-TOSMC technique in the dynamic response to the flux compared to the classical FOC-PI technique. Moreover, the proposed BC-TOSMC technique has reduced flux ripples compared to the classical FOC-PI technique.

The electric current of the motor is represented in Fig. 6(d), where it takes the form of a sinusoid and its value is related to the torque, where the higher the torque, the higher the value of the electric current (see Fig. 6(d)).

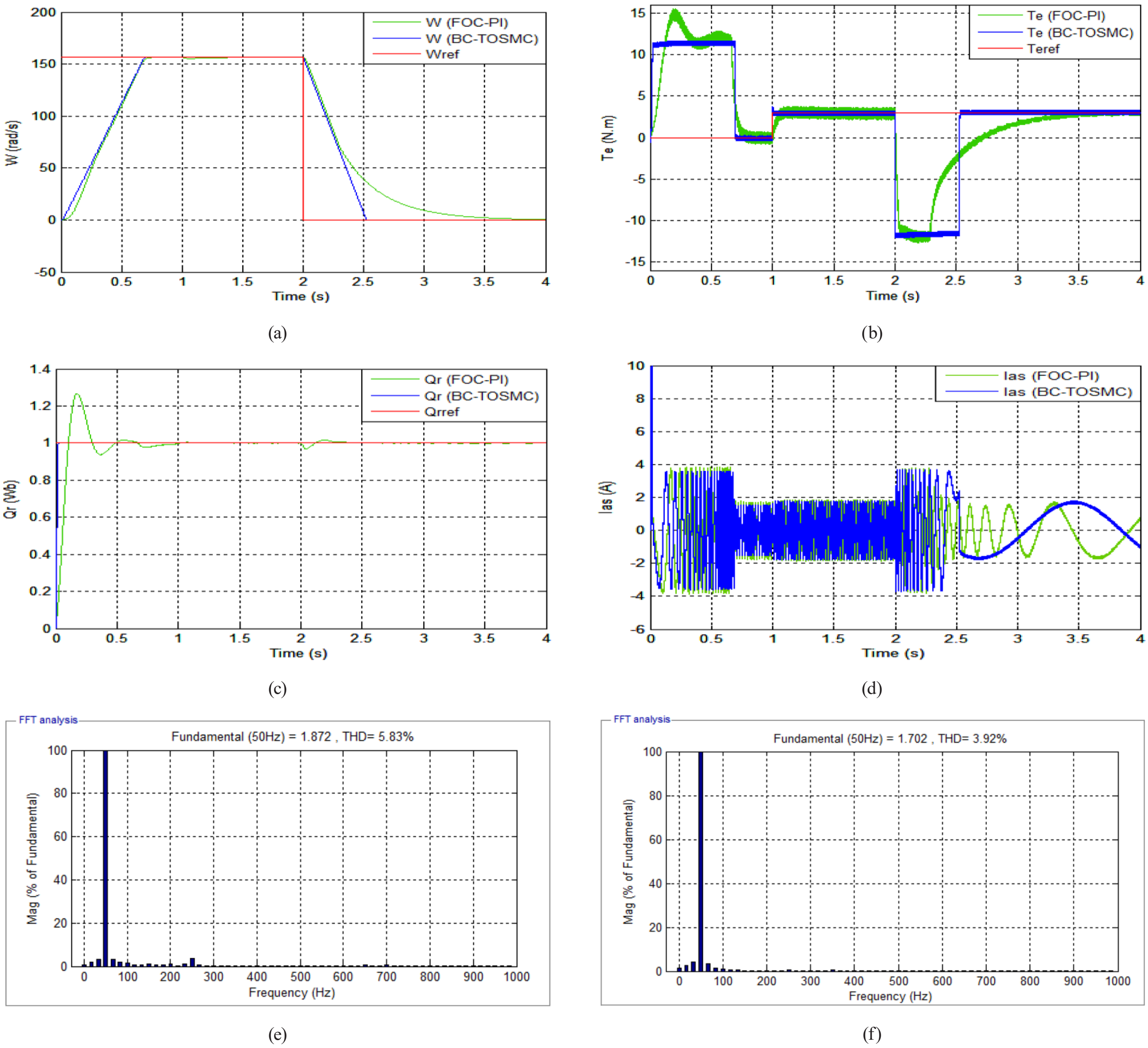

Fig. 6 The results of the variation of the reference speed test; (a) Rotor speed; (b) Torque; (c) Flux; (d) Current; (e) THD of current *Ias* (FOC-PI); (f) THD of current *Ias* (BC-TOSMC)

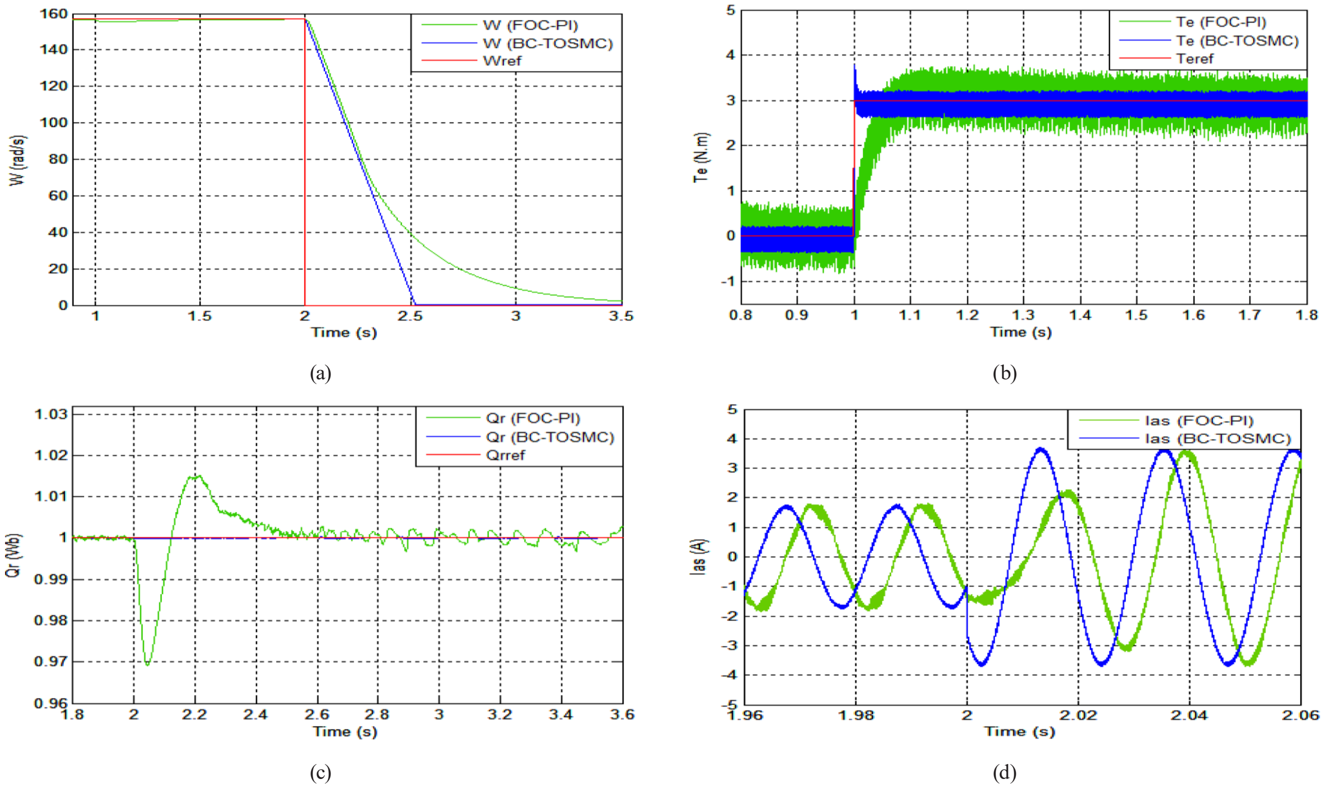

Fig. 7 Zoom in the results of the variation of the reference speed test; (a) Rotor speed; (b) Torque; (c) Flux; (d) Current

In addition, the quality of the current is better in the case of the proposed BC-TOSMC technique compared to the classical FOC-PI technique (see Fig. 7(d)).

The THD value of the electric current is represented in Figs. 6(e) and (f), where the THD value is small in the case of the proposed BC-TOSMC technique (3.92%) compared to the classical FOC-PI technique (5.83%). Also, the proposed BC-TOSMC technique reduced the THD value by about 32.76% compared to the classical FOC-PI technique.

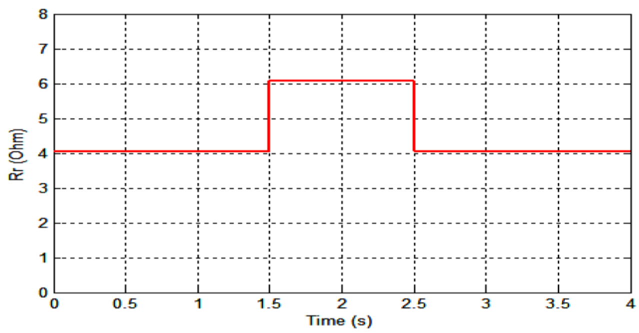

Fig. 8 Variation rotor resistance

5.2.2 Test B2: robustness variation rotor resistance

In this test, the behavior of the proposed BC-TOSMC technique in case of a change in the rotor resistance (R_r) value is studied. The rotor resistance is changed as per Fig. 8.

Changing the rotor resistance value greatly affects the classical FOC-PI technique compared to the proposed BC-TOSMC technique (see Fig. 9(a) to (f)), where we notice large ripples at the level of torque (see Fig. 10(b)), current (see Fig. 10(d)) and flux (see Fig. 10(c)). Moreover, there is a large reference overflow for speed (see Fig. 10(a)), and flux (see Fig. 10(c)) in the case of the classical FOC-PI technique. From Figs. 9 and 10, the proposed BC-TOSMC technique was not affected by a change in the resistance value which indicates that it is more robust than the classical FOC-PI technique. In this test, torque, speed, and flux remain satisfactorily following the references with an advantage of the proposed BC-TOSMC technique of tracking and dynamic response compared to the classical FOC-PI technique (see Figs. 9(a) to (c)).

The THD value of the stator current (*Ias*) is represented in Figs. 9(e) and (f), where the THD value is small in the case of the designed BC-TOSMC technique (4.53%) compared to the traditional FOC-PI strategy (5.42%). Also, the designed BC-TOSMC strategy minimized the THD value by about 16.42% compared to the traditional FOC-PI strategy.

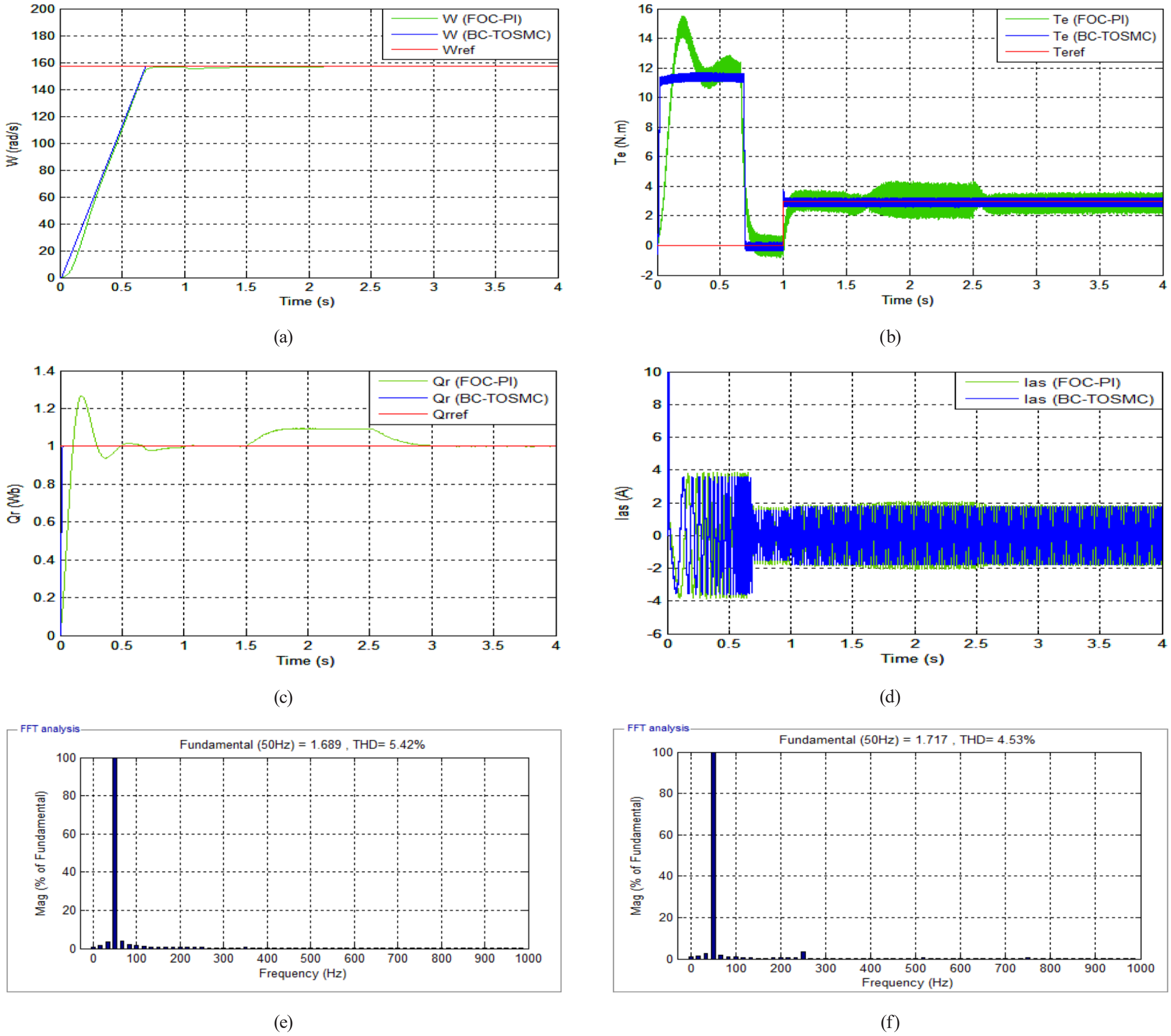

Fig. 9 The results of the variation of the rotor resistance test; (a) Rotor speed; (b) Torque; (c) Flux; (d) Current; (e) THD of current *Ias* (FOC-PI); (f) THD of current *Ias* (BC-TOSMC)

6 Conclusions

The numerical results and the nonlinear control strategy of the asynchronous motor drive fed by the PWM inverter have been presented in this paper. Our objective was the application of the proposed BC-TOSMC strategy to control the asynchronous motor drive, reduce the torque, current, and flux ripples, and make the asynchronous motor drive insensible with the parametric variation and the external disturbance. However, the proposed BC-TOSMC strategy is robust compared to the traditional FOC strategy. This proposed BC-TOSMC strategy gives a minimum THD value of the stator current and improves the response dynamics of the speed, stator flux, and torque of the asynchronous motor. Also, the various numerical results obtained show the designed BC-TOSMC strategy's robustness to the asynchronous motor and load parameters disturbances. In addition, the numerical results obtained with this proposed BC-TOSMC strategy are very interesting compared to the traditional FOC with PI controller in minimizing the flux ripple, current ripple, and torque of the asynchronous motor. The proposed BC-TOSMC strategy is characterized by being robust and can be applied to any system, which will be effective in improving the performance and efficiency of electrical machines in the future.

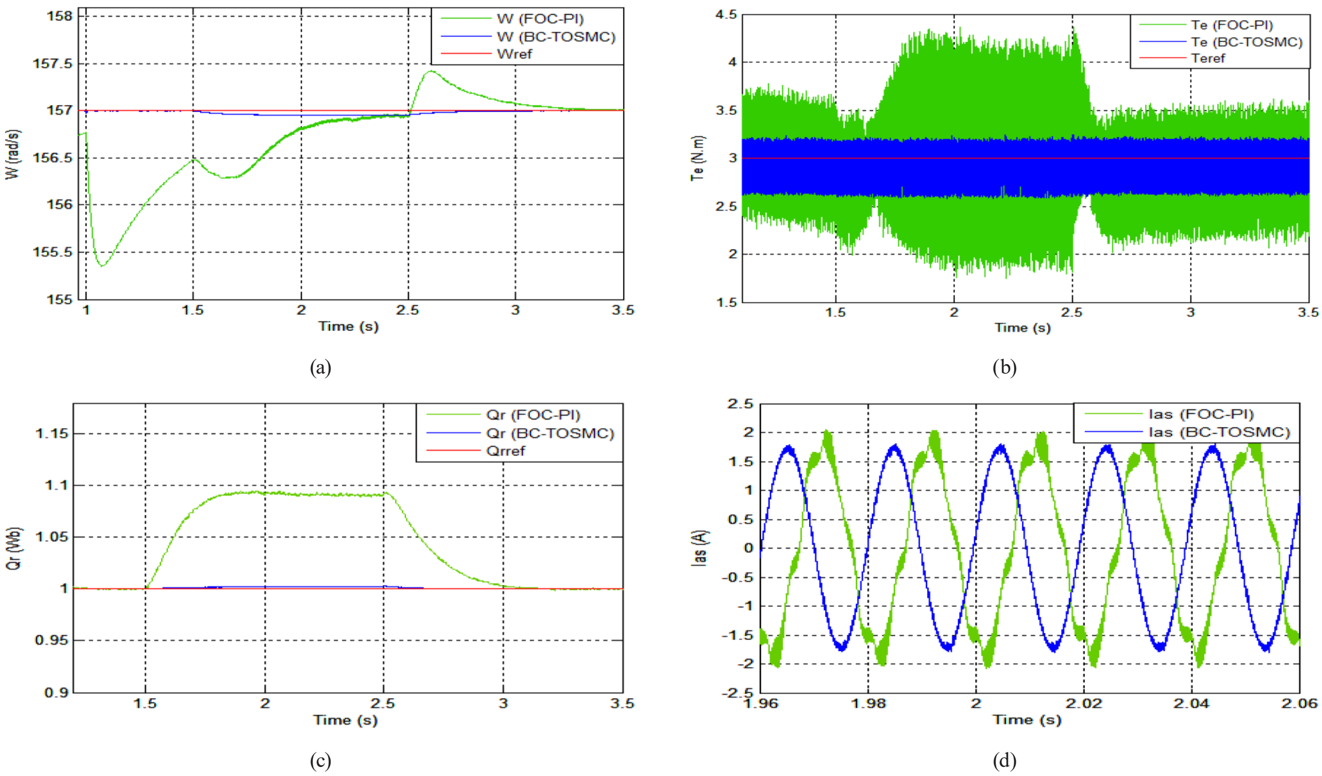

Fig. 10 Zoom in the results of the variation of the rotor resistance test; (a) Rotor speed; (b) Torque; (c) Flux; (d) Current

Nomenclature

AM	Asynchronous motor
PWM	Pulse width modulation
FOC	Flux oriented control
BC	Backstepping control
TOSMC	Third-order-sliding mode control
THD	Total distortion harmonic
DTC	Direct torque control
SMC	Sliding mode control
PI	Proportional integral

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Appendix

The parameters of the asynchronous motor, in SI units are: 1.5 kW, p = 2, F = 50 Hz, R_s = 5.35 Ω, R_r = 4.05 Ω, $L_s = L_r$ = 0.5763 H, M = 0.556 H, J = 0.498 kg m^2, f_r = 0 N m s/rad.

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