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Third-Order Sliding Mode Control of Five-Phase Permanent Magnet Synchronous Motor Using Direct Torque Control Based on a Modified SVM Algorithm

Fayçal Mehedi [a,1,*], Ismail Bouyakoub [a,2], Abdelkader Yousfi [b,3], Zakaria Reguieg [a,4]

[a] Laboratoire Génie Electrique et Energies Renouvelables (LGEER), Faculty of Technology, Hassiba Benbouali University of Chlef, 02000 Chlef, Algeria
[b] Laboratory LAGC, Faculty of Science and Technology, Djilali Bounaama University, Khemis Miliana, Algeria
[1] f.mehedi@univ-chlef.dz; [2] i.bouyakoub@univ-chlef.dz; [3] a.yousfi@univ-bkm.dz; [4] z.reguieg@univ-chlef.dz
* Corresponding Author

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ABSTRACT

Direct Torque Control (DTC) is a powerful method for multiphase drive systems, offering significant performance and efficiency gains, but its implementation is challenged by complexities like uncertainties and disturbances. This research addresses these issues, particularly the variable switching frequencies of hysteresis controllers with switching table and the limitations of conventional proportional-integral (PI) controllers in the outer loop, to enhance DTC for superior control in multiphase drives. The study proposes an improved DTC technique for a five-phase permanent magnet synchronous motor (5Ph-PMSM). This strategy integrates a robust nonlinear third-order super-twisting sliding mode control (TOSMC) with a modified space vector modulation (MSVM) algorithm. The MSVM is based on calculating the minimum and maximum of the five-phase voltages, contributing to optimized performance. This proposed DTC-TOSMC-MSVM approach significantly outperforms conventional DTC (DTC-Conv). It achieves tighter control, substantially reducing flux and torque ripple, and minimizing response time. Furthermore, it lowers the total harmonic distortion (THD) and improves disturbance rejection. The merits of the proposed strategy of 5Ph-PMSM are demonstrated through various tests. MATLAB simulations confirm these benefits, showing an 88.88% reduction in speed response time compared to DTC-Conv. Additionally, the proposed method reduces flux ripple by 51.85%, torque ripple by 63.15%, and stator current THD by 61.08%. In addition, the proposed method demonstrates robust performance when faced with changes in machine parameters and load disturbances, making it superior to traditional DTC approaches.

1. Introduction

Multiphase systems present several advantages over their three-phase counterparts, including enhanced performance, greater robustness, lower torque fluctuations, the capacity for higher power output, and a more stable speed response [1]-[3]. In [4], the authors provide a thorough review of recent advancements in multiphase machines, covering their advantages, modeling methods, and the latest developments in modulation and control techniques for the multilevel converters that supply them. The publication also explores future technological trends in the field. Multiphase machines have attracted interest in a number of application areas where high dependability is required, such as pump drives, robotics, energy conversion, multi-machine systems, and ship propulsion [5]-[9].

The traditional Direct Torque Control (DTC) technique has been advanced and studied for its potential to supersede the classical Field-Oriented Control (FOC) in AC drives requiring high performance [10], [11]. In [12], the authors used the FOC technique and DTC for synchronous motors. The DTC approach was shown to be superior in achieving maximum torque per ampere, minimal torque ripple, high efficiency, fast response, and a wide speed range.

DTC technique out due to its strong approach, straightforward calculation method, and rapid response in terms of flux and torque. Notably, this method operates without the need for complex modulation techniques, current regulation, and coordinate transformation [13]. This technique has been employed in the analysis of various electric motors, including the permanent magnet synchronous motor (PMSM) [14], [15], induction motor (IM) [16], 6-phase induction motor [17], [18], doubly fed induction generator (DFIG) [19], [20], interior PMSM drive [21], five-phase induction motor (5P-IM) [22]-[24], dual stator induction generator [25].

While the traditional DTC method offers numerous benefits, it also presents certain challenges, including significant fluctuations in rotor flux and torque, the presence of multiple current harmonics, and limitations at low speeds [26]-[29]. A significant drawback of traditional DTC is the substantial torque ripple it produces. This issue primarily arises from the use of hysteresis comparators and either switching tables or proportional-integral (PI) controllers in its implementation, which can have adverse effects on the overall system performance [30], [31]. Due to the inherent drawbacks of PI controllers in electrical systems, much recent research has focused on developing the PI controller. To achieve superior control regulation of complex or turbulent systems, the Fractional-Order Proportional-Integral-Derivative (FOPID) controller is utilized as an alternative [32]-[35]. The FOPID offers increased flexibility through its additional parameters and demonstrates better handling of disturbances, leading to improved adaptability, stability, and control performance, especially in challenging system conditions [36].

Several recent research papers leveraging cutting-edge technological progress have tackled the limitations inherent in traditional technical methodologies. These papers highlight a range of innovative technologies, including: high-order sliding mode control (HOSMC), artificial neural networks (ANNs) [37], adaptive backstepping controller (ABC), sliding mode controller (SMC), fuzzy logic (FL), super-twisting sliding mode control (STSMC), adaptive-network-based fuzzy inference system algorithm (ANFIS), genetic algorithms (GA), Harris Hawks algorithm (HHA) [38], [39] and synergetic control (SC). In [40], the authors discuss a nonlinear adaptive position controller for a PMSM that utilizes a newly developed ABC approach. This innovative method specifically aims to provide robustness when faced with parameter uncertainties and load force disturbances. An optimal controller for a PMSG-based wind turbine (WT) system is developed using the new wild horse optimizer (WHO) method. This approach allows for the effective tuning of PI controller gains, which in turn improves the PMSG's dynamic performance and the overall system response during both normal and abnormal situations [41]. To address this limitation of the traditional DTC method, researchers have proposed various alternative methods [42]-[46]. These strategies involve incorporating modern techniques instead of relying on switching tables and hysteresis comparators, with the goal of preserving the key performance advantages of the DTC method. In [47], the authors introduced a method for controlling a five-phase PMSM (5Ph-PMSM) without sensors, utilizing a 7-level torque hysteresis within the DTC technique. They highlighted that the motor's torque responsiveness and the amount of torque fluctuation are directly influenced by the magnitude and placement of the voltage vectors employed in this hysteresis-based DTC approach. Furthermore, they explained that using torque hysteresis controllers with varying levels allows for the generation of a diverse set of voltage vectors. In [48], the authors explored a technique to improve the DTC for 5Ph-PMSM. Traditional DTC using space vector modulation (SVM) faces issues like stator flux and torque ripples, and higher current total harmonic distortion (THD). It is proposed to replace traditional PI controllers and hysteresis comparators (HC) with artificial neural networks (ANNs) in the DTC-SVM strategy. Dynamic response is improved, torque and flux ripples are reduced, and stator current is reduced in 5Ph-PMSM drive.

Compared to other control methods, SMC has garnered significant attention in recent years. This is largely due to its strong resilience to external disturbances, straightforward nature, ease of application, and minimal susceptibility to variations in system parameters [49], [52]. Utkin first proposed this approach in 1977 [53]. It stands as a nonlinear control technique that employs a discontinuous control signal to alter a system's behavior, compelling it to move along a predefined switching surface. Within the realm of 5Ph-PMSM control, SMC has become a focal point of research and practical use. For instance, reference [54] demonstrates the successful implementation of SMC to regulate the speed of a 5Ph-PMSM. In [55], the authors evaluated the dynamic performance of a 5Ph-PMSM drive, employing both SMC and MRAS observers. Their control approach was notably justified by its ability to implement a nonlinear control law that is robust to system model uncertainties while maintaining the system's simplicity.

Many researchers have concentrated on the issue of the chattering phenomenon, a significant disadvantage of conventional SMC [56], [57]. This chattering effect leads to oscillations in both current and torque, consequently producing unwanted mechanical vibrations. Several approaches have been suggested to address the limitations of the SMC technique [58], [59]. These include the integration of fuzzy logic [60], the synergetic-SMC-backstepping [61], and the development of Integral Sliding Mode algorithms [62], all aimed at enhancing the performance and effectiveness of the conventional SMC method. In [63], a study tackled the position tracking problem in PMSMs, considering parameter uncertainties and load force disturbances. Their proposed solution involved combining adaptive ABC with SMC to manage load force distribution. Simulations on a PMLSM system validated the controller's effectiveness and robustness, showing excellent position tracking performance in diverse transient and steady-state scenarios, including under various load disturbances.

To mitigate the chattering effect commonly associated with classical SMC, HOSMC presents itself as a compelling alternative. Unlike traditional SMC, which applies the discontinuous control action directly to the sliding surface, HOSMC techniques, considered advanced forms of SMC, apply this discontinuous element to the derivatives of the sliding surface. This indirect application significantly diminishes the chattering phenomenon. Within the existing literature, second-order sliding mode control methods, including twisting, super-twisting, and sub-optimal algorithms, are frequently employed as replacements for conventional SMC across various applications [64]-[67]. In [68], the authors introduced a control method that leverages a second-order SMC approach to enhance the performance of a 5P-IM. This technique is particularly effective because it applies a robust nonlinear control law that addresses system uncertainties without compromising the simplicity of the overall system. In contrast to second-order approaches, Third-Order SMC (TOSMC) involves a greater number of adjustable parameters. This increased parameterization enhances its adaptability, allowing for simultaneous improvements in several performance aspects such as precision, robustness, and the reduction of controlled variable oscillations.

The space vector modulation (SVM) technique, initially proposed by Der Broek and all in 1988, operates on the principle of angle and sector calculations. In recent years, space vector modulation (SVM) techniques have become increasingly significant due to their enhanced modulation features and rapid response capabilities. Notably, SVM has demonstrated a reduction in voltage and current THD and ripples when compared to traditional PWM and other modulation approaches [69]-[71]. Compared to PWM, this method has been shown to decrease voltage and current THD and enhance voltage output by 15%. However, implementing SVM is more complex than PWM, particularly in multilevel inverter systems. The direct application of traditional SVM presents significant cost and experimental challenges. Consequently, researchers have focused on refining the conventional SVM approach and exploring alternative modulation strategies.

In Ref [72], a novel SVM approach determines switching actions based on the minimum and maximum values of the 3-phase voltages. This method, termed the simplified SVM technique, has demonstrated its effectiveness in controlling three-phase inverters. A simplified SVM of 3-phase inverters method offers straightforward control of three phase multilevel inverters [73]. Unlike conventional SVM, this approach avoids intricate computations. Furthermore, employing this modified SVM in multilevel inverters lowers implementation expenses and simplifies practical setup. It's well-established that the chosen control method significantly impacts cost-effectiveness, performance enhancement, and quicker response times, making this technique a valuable asset for inverter control.

This work proposes a DTC strategy for a 5Ph-PMSM drive that incorporates new nonlinear controllers TOSMC. The primary contribution lies in developing this TOSMC-DTC technique for multiphase motors, which aims to improve electromagnetic torque and stator flux regulation, as well as speed control. While standard SMC is effective against system uncertainties and disturbances, it often produces undesirable chattering that can cause mechanical degradation. In contrast, TOSMC improves system stability and provides smoother control by reducing or eliminating chattering through the use of higher-order derivatives. The suggested approach employs three TOSMC units to govern a 5Ph-PMSM drive. To ensure high efficiency and performance, a refined modified space vector modulation (MSVM) technique is also put forth to generate the required inverter switching pulses based on the reference voltages from the TOSMC controllers. The TOSMC-DTC-MSVM algorithm offers numerous benefits, including its simplicity, ease of implementation, strong robustness, and remarkable capability to improve the precision of flux and torque control. The following points summarize the contributions of this work:

- The proposed DTC-TOSMC-MSVM method offers a more efficient and reliable approach in the field of DTC technique compared to the DTC-Conv method.
- Reducing the THD value of the stator current of 5Ph-PMSM compared to conventional technique;
- The proposed control technique effectively minimizes flux and torque ripples in the 5Ph-PMSM.
- Improving the performance of the control multiphase drives systems, reducing the rotor speed tracking error, quickening response times, and a significant enhancement in its robustness against variations in machine parameters.

This paper is structured into five main sections. Section 2 details the fundamentals of the DTC method and presents the mathematical model of the 5Ph-PMSM. Section 3, titled “Proposed Technique,” introduces the TOSMC approach and MSMC strategy developed in this research for controlling the 5Ph-PMSM. Section 4 “Results and Discussion,” showcases simulation outcomes and provides comparisons with conventional technique. Finally, Section 5, “Conclusions,” summarizes the findings derived from the simulations.

2. DTC Approach of 5Ph-PMSM

Although conventional DTC delivers a highly sensitive and efficient method for controlling motors, its need for exact switching frequency management and real-time computation can present implementation hurdles [75]. Utilizing DTC with an 5Ph-PMSM, however, yields benefits like enhanced fault tolerance and reduced torque fluctuations, largely due to the presence of extra phases. The following is the equation for the stator voltage of a 5Ph-PMSM in a d-q-x-y rotating frame [48].

Where, R_s stator resistance, v_{ds}, v_{qs}, v_{xs} and v_{ys} design, respectively, the stator voltage components in the (d, q, x, y) axis, w_r denote angular speed of the 5Ph-PMSM, L_{ls}, L_d, and L_q are the leakage, direct, and quadrature stator inductances, ϕ_f is magnetic flux, and i_{ds}, i_{qs}, i_{xs} and i_{ys} design, respectively, the stator current components in the (d, q, x, y) axis. The electromagnetic torque T_{em} of the 5Ph-PMSM is given by:

$$\begin{cases} v_{ds} = R_s i_{ds} + \frac{d}{dt}(L_d i_{ds} + \emptyset_f) - w_r L_q i_{qs} \\ v_{qs} = R_s i_{qs} + \frac{d}{dt} L_q i_{qs} + w_r(L_d i_{ds} + \emptyset_f) \\ v_{xs} = R_s i_{xs} + \frac{d}{dt} L_{ls} i_{xs} \\ v_{ys} = R_s i_{ys} + \frac{d}{dt} L_{ls} i_{ys} \end{cases} \quad (1)$$

$$T_{em} = \frac{5}{2} P((L_d - L_q) i_{ds} i_{qs} + \emptyset_f i_{qs}) \quad (2)$$

The 5Ph-PMSM used in this study ($L_d = L_q$), so the machine torque is as follows:

$$T_{em} = \frac{5}{2} P\, \emptyset_f i_{qs} \quad (3)$$

The equation for dynamics w_r is:

$$J_m \frac{dw_r}{dt} = PT_{em} - PT_r - f_m w_r \quad (4)$$

Where, J_m is the inertia, T_r is the load torque, P is number of pairs poles, f_m is the viscous damping.

The DTC controls the the on/off states of the VSI switches by directly determining the control sequence that is applied to these switches [54].

The diagram in Fig. 1 illustrates a DTC strategy for a 5Ph-PMSM drive. This method employs a PI controller to establish the desired torque level based on the motor's speed. Furthermore, the technique depends on the estimation of stator flux, sector, and torque. An inverter uses a switching table, which has five inputs and five outputs, to create the required switching signals, which in turn control the five phases of the 5Ph-PMSM drive [54]. Switch table for Conv-DTC in Table 1.

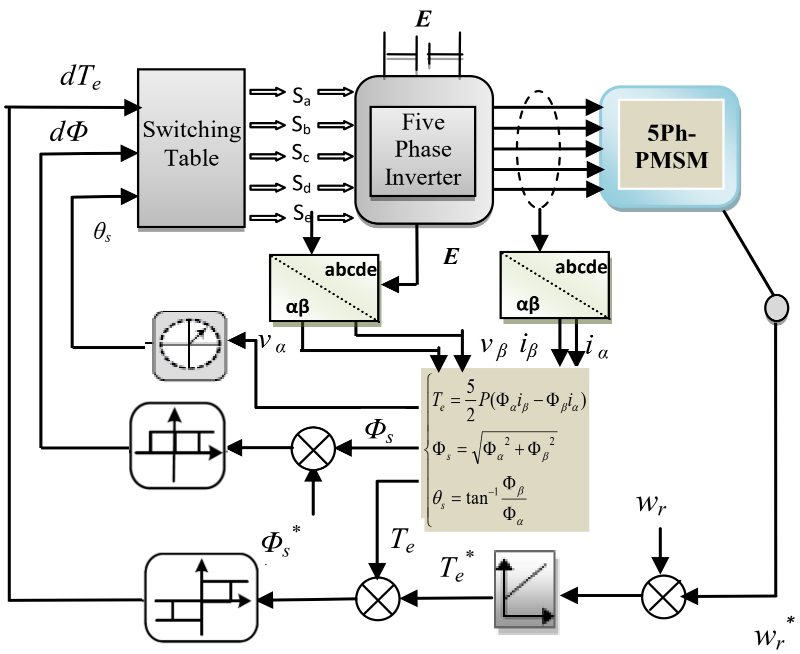

Fig. 1. Designed DTC approach of 5Ph-PMSM

In terms of flux and current stator, the electromagnetic torque of the 5Ph-PMSM is expressed as:

$$T_{em} = \frac{5}{2} P(\varphi_\alpha i_\beta - \varphi_\beta i_\alpha) \tag{5}$$

The torque errors and flux determines the inverter's switching states, as shown in equation (5):

$$\begin{cases} \Delta\varphi_s = \varphi_s{}^* - \varphi_s \\ \Delta T_{em} = T_{em}{}^* - T_{em} \end{cases} \tag{6}$$

Where,

$\Phi_s{}^*$: Reference flux.

$T_{em}{}^*$: Reference torque.

The amplitude of the stator flux is expressed in terms of its concordia quantities:

$$\varphi_s = \sqrt{\varphi_\alpha{}^2 + \varphi_\beta{}^2} \tag{7}$$

The position θ_s of the stator flux is:

$$\theta_s = \tan^{-1}\frac{\varphi_\beta}{\varphi_\alpha} \tag{8}$$

Table 1. Switch table for Conv-DTC

dΦ	dT	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
	-1	V7	V3	V19	V17	V25	V24	V28	V12	V14	V6
0	1	V14	V6	V7	V3	V19	V17	V25	V24	V28	V12
	0	V31	V0	V31	V0	V31	V0	V31	V0	V31	V0
	-1	V17	V25	V24	V28	V12	V14	V6	V7	V3	V19
1	1	V24	V28	V12	V14	V6	V7	V3	V19	V17	V25
	0	V0	V31	V0	V31	V0	V31	V0	V31	V0	V31

3. Proposed Method

3.1. Five-Phase SVM Strategy

Conventional SVM techniques have relied on space vectors. This is because directly determining the sector and angle from the reference voltage presents a complex calculation. Instead, these calculations are executed in the stationary (α, β) frame using the Clarke transformation applied to the three-phase reference voltages. This classic control technique has been successfully applied to various electrical machines, including asynchronous and synchronous motors [69], [70]. Recent research has seen widespread use in DTC schemes [31], [46]. Furthermore, its implementation in multiphase systems has yielded favorable outcomes [54]. Despite these advantages, implementing SVM is more challenging than conventional pulse width modulation (PWM). However, a drawback associated with this approach is the high cost of implementing an electrical control system, primarily stemming from of the traditional SVM method. In [74], a new simplified SVM algorithm is proposed that avoids complex sector and angle calculations found in traditional methods. This SVM strategy, based on three-phase voltage minimum and maximum values, offers ease of implementation and reduced THD in 2-level inverters. MATLAB/Simulink simulations and dSPACE implementation validate its effectiveness.

This paper puts forth a basic five-phase MSVM strategy. This method identifies the necessary switching configurations by computing the minimum and maximum of the five voltages (V_a, V_b, V_c, V_d, and V_e). The MSVM technique was selected due to its uncomplicated nature and ease of implementation. Furthermore, it is expected to offer improved performance of the systems compared to PWM technique and traditional SVM methods. Fig. 2 illustrates the fundamental concept behind the five-phase MSVM technique for a two-level inverter.

The presented five-phase MSVM method involves a four-stage process. First, it identifies the lowest value among five voltage inputs (V_a, V_b, V_c, V_d, and V_e). Second, it pinpoints the highest value among the same five voltages. Third, it calculates the sum of these minimum and maximum voltage values. Finally, it generates the pulse sequences for S_a, S_b, S_c, S_d, and S_e.

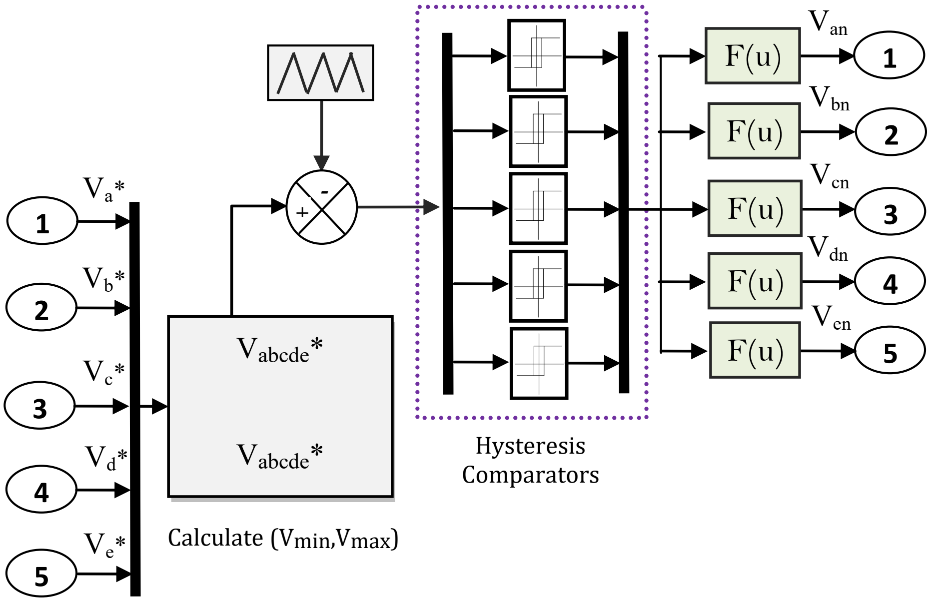

Fig. 2. Five-phase MSVM strategy

3.2. TOSMC-DTC Strategy Based MSVM of the 5Ph-PMSM

The traditional DTC approach for multi-phase PMSM commonly employs hysteresis comparators alongside switching tables and the PI controller for speed regulation. This methodology can compromise the system's reliability by contributing to increased torque and flux fluctuations [48], [54]. There are various SMC techniques in the literature, all developed to reduce chattering phenomena [73], [76]. Despite these advancements, their application in multiphase systems still presents considerable hurdles.

In this section, a new DTC control system for the 5Ph-PMSM is presented, utilizing TOSMC techniques to achieve improved performance over the traditional DTC. This design incorporates two TOSMC controllers in place of the usual hysteresis comparators and employs a modified SVM strategy instead of the standard switching table. Furthermore, as for the external control loop, the speed control unit has been replaced by a proposed TOSMC controller. The methodology for estimating electromagnetic torque and stator flux is retained from conventional DTC.

This suggested TOSMC-DTC-MSVM approach employs two novel TOSMC regulators to manage both the stator flux and torque. Instead of a traditional switching table, it utilizes the MSVM algorithm. This TOSMC-DTC-MSVM strategy aims to combine the strengths of vector control and conventional DTC to mitigate the torque and flux oscillations commonly seen in 5Ph-PMSM drive. The integration of TOSMC controllers and MSVM Algorithm is intended to achieve a consistent switching frequency and reduce pulsations in both stator flux and torque.

While various methods exist to control and lessen torque fluctuations in AC motors, the STSMC stands out as a distinctive higher-order SMC approach that needs knowledge solely about the sliding surface [64], [65]. To overcome the limitations of traditional SMC, a TOSMC has been developed [77], [78]. This technique demonstrates effectiveness in systems where uncertainties exist, providing a robust control alternative and solution to both nonlinear and linear control approach. Instead of using the first derivative of the sliding surface like standard SMC, the TOSMC strategy, similar to the STSMC approach, utilizes the command input on the second-order derivative. The control input for TOSMC is constructed from the sum of three distinct components, detailed in equation (9).

$$u(t) = u_1(t) + u_2(t) + u_3(t) \tag{9}$$

Therefore, equation (9) is presented as:

$$\begin{cases} u_1(t) = \lambda_1.\sqrt{|S|)}sign(S) \\ u_2(t) = \lambda_2.\int sign(S)dt \\ u_3(t) = \lambda_3.sign(S) \end{cases} \tag{10}$$

Here, S indicates the switching surface.

The constants λ_1, λ_2, and λ_3 indicate the positive gains that have changed.

The following is the selection of the sliding surfaces based on (4) and (6):

$$\begin{cases} S(w_r) = w_r^* - w_r \\ S(T_{em}) = T_{em}^* - T_{em} \\ S(\varphi_s) = \varphi_s^* - \varphi_s \end{cases} \tag{11}$$

The errors identified in Equations (11) served as the input for the TOSMC controllers. Specifically, the TOSMC regulators for speed, electromagnetic torque T_{em}, and stator flux were employed to manipulate the reference values T_{em}*, and the stator voltage components in the x and y axes (V_x* and V_y*) respectively. Fig. 3 illustrates the internal architecture of a TOSMC strategy designed to regulate the speed, flux, and torque of a 5Ph-PMSM drive.

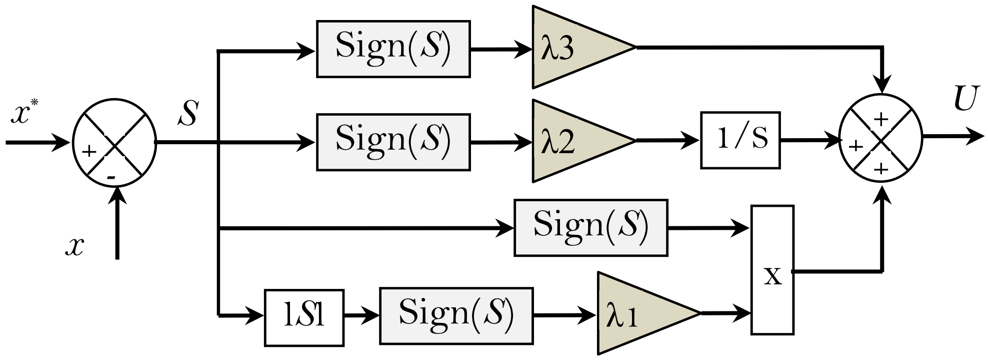

Fig. 3. Architecture of the TOSMC approach

The bloc diagram for proposed TOSMC-DTC-MSVM approach, illustrated in Fig. 4. The suggested control approach demonstrates a greater potential for minimizing flux and torque ripple compared to DTC-Conv and other existing control strategies. To govern the flux and torque of a 5Ph-PMSM drive, a control principle termed TOSMC-DTC-MSVM approach is introduced. Within this framework, the y axis voltage (V_y∗) is employed to regulate the torque, while the x axis voltage (V_x∗) manages the stator flux.

4. Results and Discussion

Using a MATLAB/Simulink model, we performed simulations to evaluate the efficacy and efficiency of the created DTC system, which employs a TOSMC approach based on the modified SVM algorithm of the 5Ph-PMSM. With results in terms of torque ripples, THD of stator current, response time, and flux ripples, compared to the traditional method. Consequently, two tests are suggested to examine the contrast between DTC-Conv and the DTC-TOSMC-MSVM strategy, tracking performance test under the influence of load torque T_r variation and robustness test. Table 2 lists the values of the 5Ph-PMSM parameters [43].

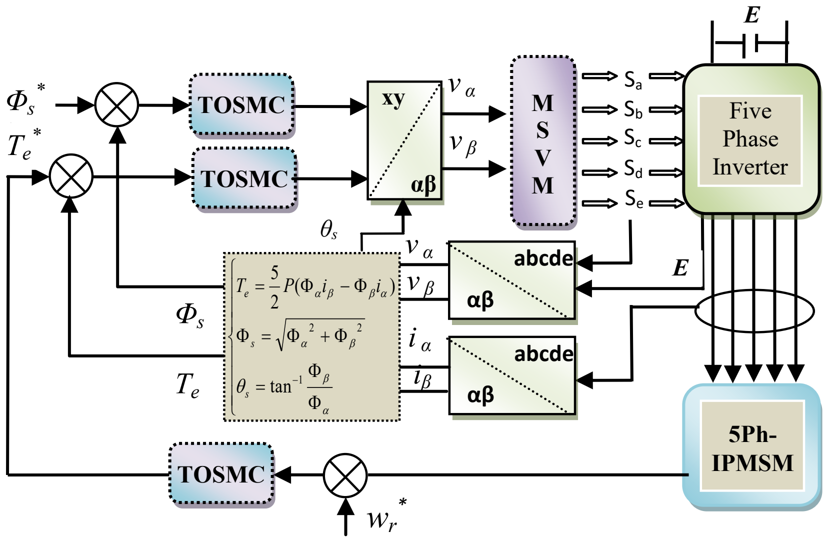

Fig. 4. Structure of the proposed TOSMC-DTC-MSVM approach of the 5Ph-IPMSM

Table 2. The 5Ph-PMSM parameters

Parameter	P	φ_f	R_s	L_q	L_q	f	J_m
Values	2	0.2 web	0.67 Ω	0.0085 H	0.0085 H	50 Hz	0.004 Kg/m^2

4.1. The First Test Case

The suggested DTC-TOSMC-MSVM approach for 5P-PMSM is evaluated in a tracking performance scenario, and the traits of both methods are examined with regard to their sensitivity to the T_r variation. Under no load, the 5Ph-PMSM operates at 100 rad/s, ramping up to 150 rad/s at t = 0.2s. A nominal T_r = 10 Nm was applied at t = [0.4, 0.6s], followed by a consign inversion (-50 rad/s) at t = 0.8s. The 5Ph-PMSM speed is shown in Fig. 5 for the DTC-Conv and DTC-TOSMC-MSVM approach used in this investigation. As illustrated in Fig. 9, the traditional method exhibited a speed reduction from 150 rad/s to 137 rad/s when torque T_r was applied at t = 0.4 s. This performance contrasts with the DTC-TOSMC-MSVM approach, which effectively sustained its reference speed. The rejection rate of speed disturbance was estimated at about 2% using the suggested approach, compared to the traditional technique, which reached 9%. The suggested control method significantly reduces response time compared to the DTC-Conv technique. Specifically, its speed response time is estimated at 0.01 s, a notable improvement over the traditional method's 0.09 s response. As presented in Table 3, the response time is cut by approximately 88.88%. Both methods avoid overshooting the reference value.

As shown in Fig. 6, the simulation results for torque (T_{em}) indicate that the DTC-TOSMC-MSVM method delivers superior performance compared to the conventional technique. Fig. 10 shows the zoom of torque T_{em}. Employing the DTC-TOSMC-MSVM strategy significantly reduces torque oscillations compared to the conventional DTC method. The suggested approach achieves a torque ripple of only 2.8 Nm, a substantial improvement over the 7.6 Nm ripple observed with the conventional approach. This results in a torque ripple decrease of almost 63.15% as shown in Table 3.

The stator flux for both control strategies is displayed in Fig. 7, where it takes a constant value and closely resembles the reference value despite variations. When compared to the traditional DTC approach, the DTC-TOSMC-MSVM strategy shows extremely reduced ripples. Fig. 11 illustrates

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that the proposed method significantly reduces stator flux ripples to a mere 0.0065 Wb, which is considerably less than the 0.0135 Wb ripple produced by the traditional approach. A reduction of approximately 51.85% is observed in the flux ripple (See Table 3). The stator flux component trajectories, $\Phi_{\alpha s}$ and $\Phi_{\beta s}$, are depicted in Fig. 8 for both control strategies. The paths are circular for both, maintaining a diameter of 0.8 Wb. However, the DTC-TOSMC-MSVM strategy demonstrates a clear benefit in terms of reduced ripples in the flux when compared to the traditional technique.

The stator current's THD values for both methods are presented in Fig. 12 and Fig. 13. The Fig. 13 clearly shows that the proposed DTC-TOSMC-MSVM technique achieved a THD of 10.87%, significantly outperforming the classical control technique's 27.93% (Fig. 12). This indicates that the proposed method substantially improves current quality, reducing the THD by approximately 61.08%. The THD of current values are shown in Table 3.

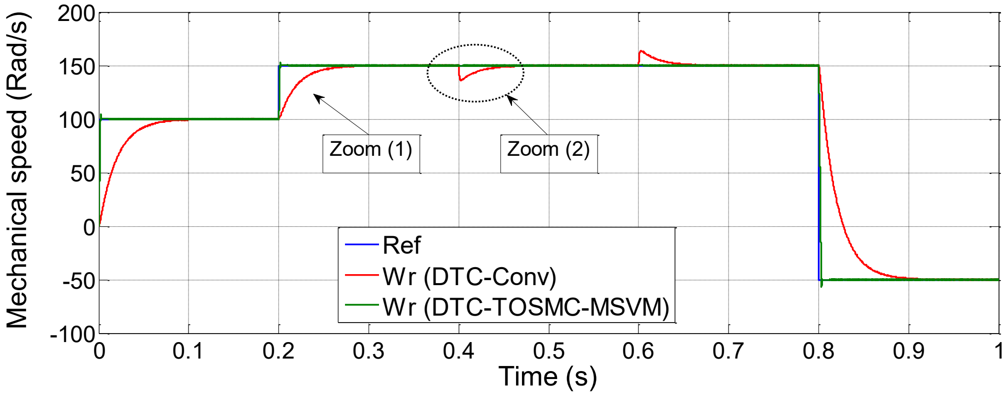

Fig. 5. Rotation speed (Test 1)

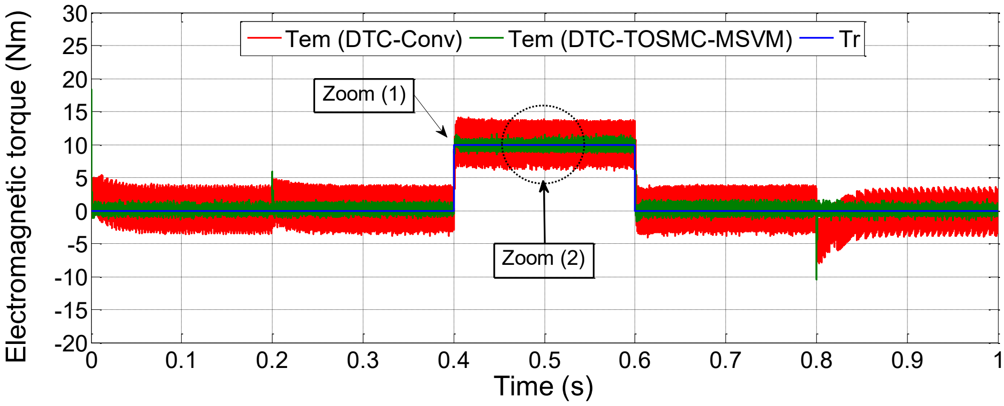

Fig. 6. Electromagnetic torque (Test 1)

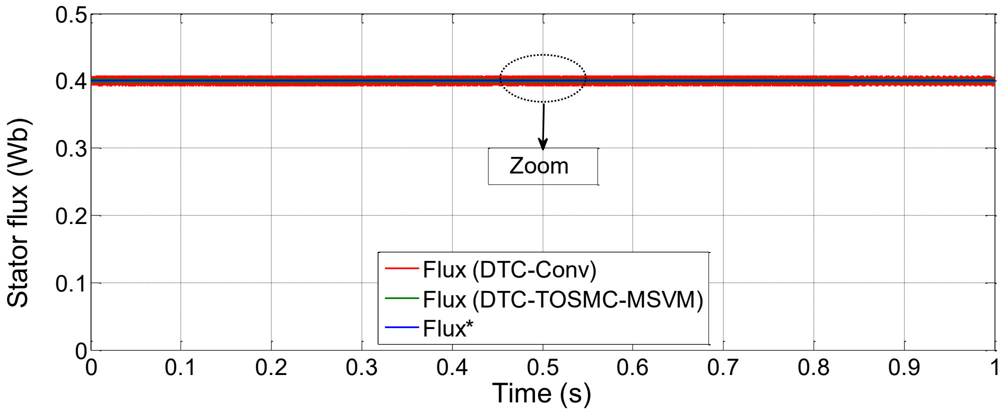

Fig. 7. Stator flux (Test 1)

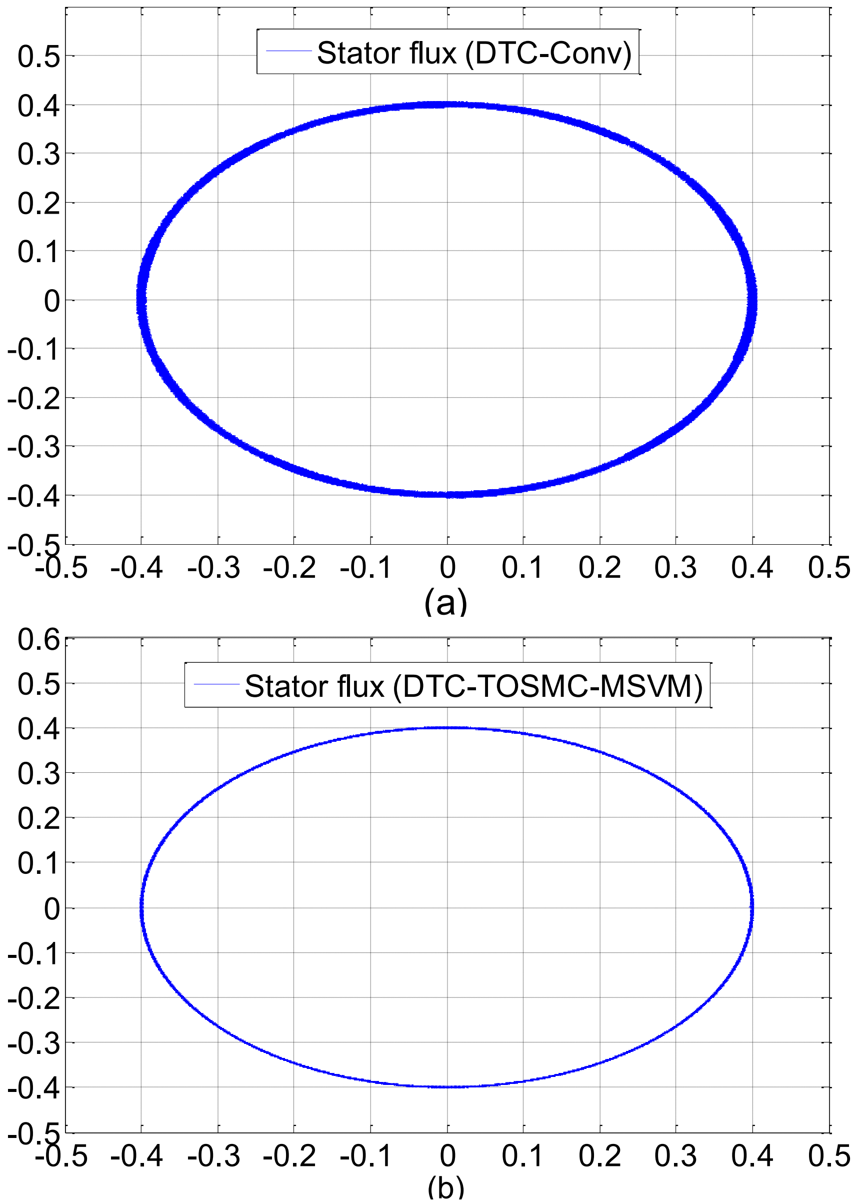

Fig. 8. Stator flux vector α-β axis trajectories (test 1), when: (a) DTC-Conv, (b) TOSMC-DTC-SVM

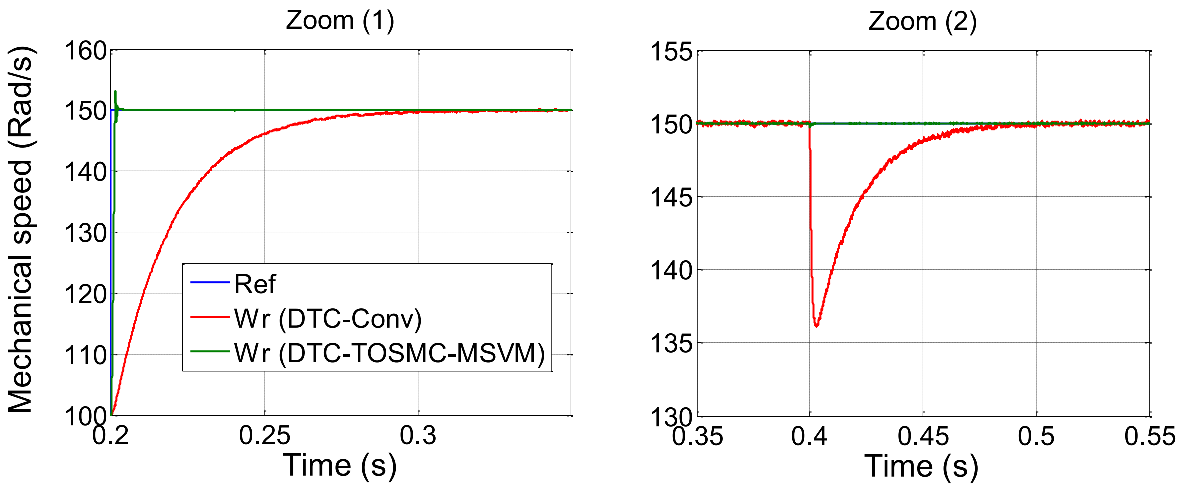

Fig. 9. Zoom in the rotation speed (test 1)

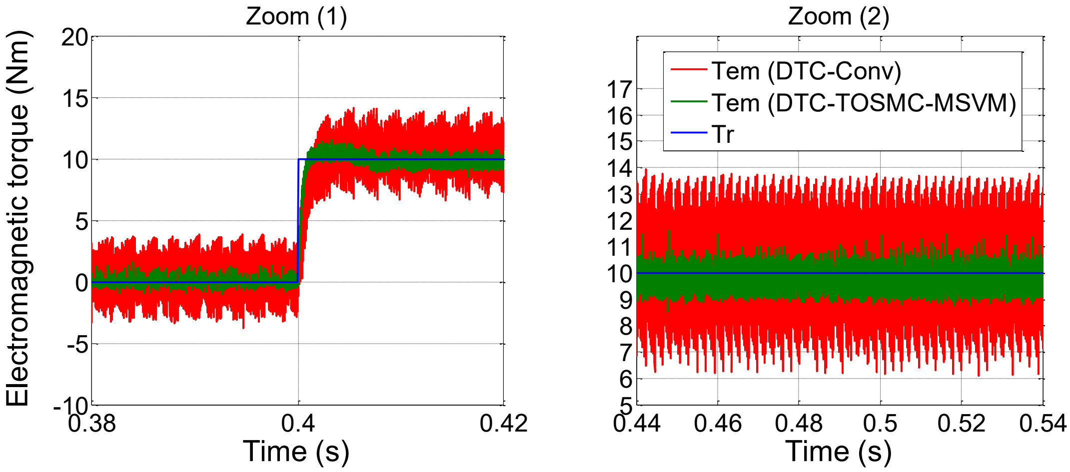

Fig. 10. Zoom in the electromagnetic torque (test 1)

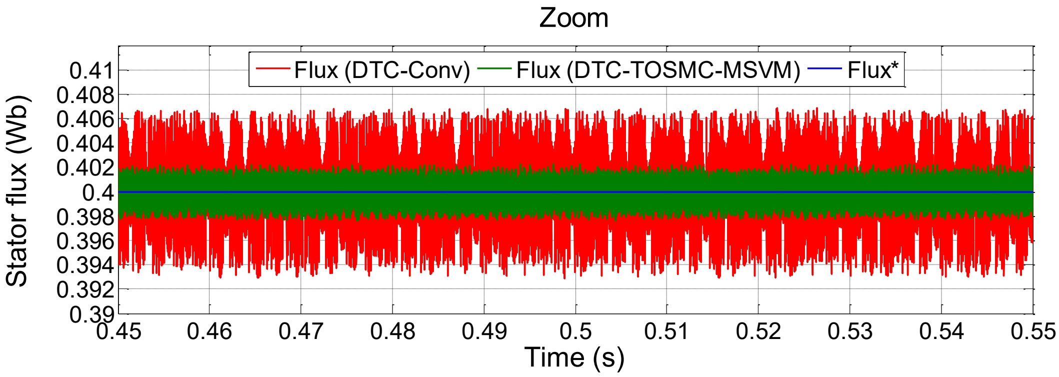

Fig. 11. Zoom in the stator flux (test 1)

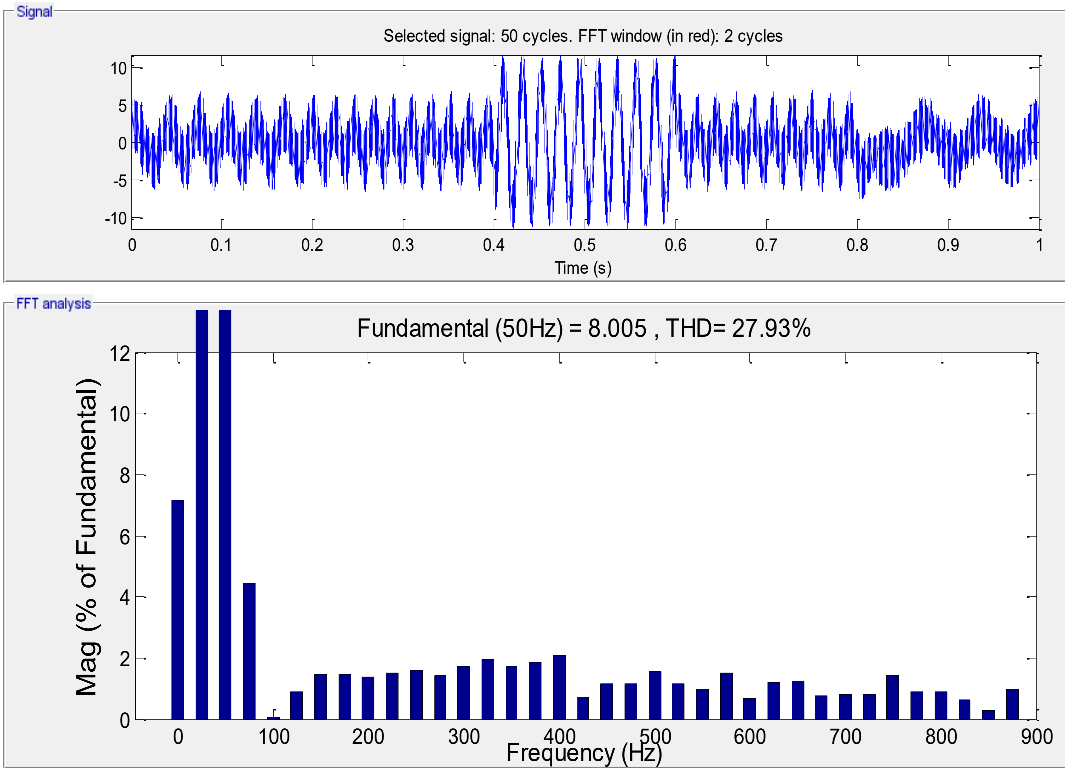

Fig. 12. THD of phase current I_{as} (DTC-Conv)

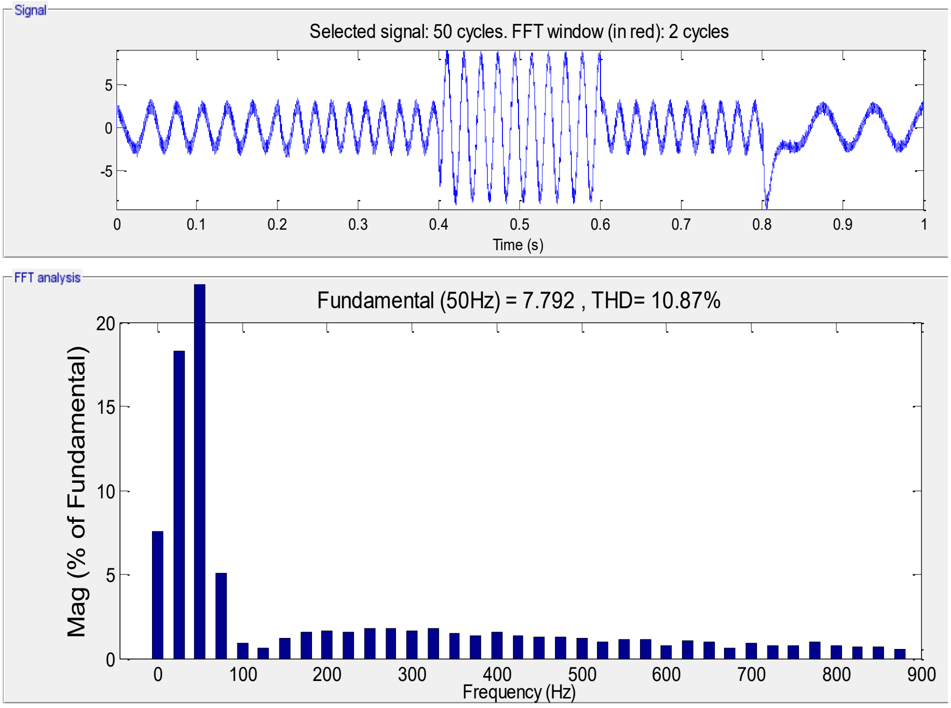

Fig. 13. THD of phase current I_{as} (DTC-TOSMC-MSVM)

Table 3. Comparative performance of DTC-Conv and DTC-TOSMC-MSVM technique

	DTC-Conv	DTC-TOSMC-MSVM	Ratios (%)
Response Time [s]	0.09	0.01	88.88
Torque Ripples [N.m]	[6.2 – 13.8] 7.6	[8.7 – 11.5] 2.8	63.15
Flux Ripples [Wb]	[0.393 – 0.4065] 0.0135	[0.3970 – 0.4035] 0.0065	51.85
Current THD [%]	27.93	10.87	61.08

4.2. The Second Test Case

A robustness test was conducted to determine how effectively the proposed DTC-TOSMC-MSVM method handles parameter variations in a 5Ph-PMSM. The control system's robustness was assessed under three main parameter changes: a 20% reduction in nominal stator inductances L_d and L_q, and a 100% increase in both the inertia moment J_m and stator resistance R_s. Table 4 provides the new parameter values for this test.

Table 4. New values for the 5Ph-IPMSM parameters

	R_s	L_q	L_q	J_m
Old values	0.67 Ω	0.0085 H	0.0085 H	0.004 Kg/m^2
New values	1.34 Ω	0.0068 H	0.0068 H	0.008 Kg/m^2

Fig. 14, Fig. 15, Fig. 16, Fig. 17, Fig. 18, Fig. 19 display the test's findings. The stator flux, stator current, torque, and speed response for the 5Ph-PMSM drive of each technique are all affected differently by these variations. Fig. 14, illustrates the 5Ph-PMSM speed for both the DTC technique. The response speed is known to be closely related to the architecture of the control system and the particular values of its parameters. Compared to the DTC-TOSMC-MSVM technique for the 5Ph-PMSM drive, the DTC-Conv speed responses are more affected by machine parameter changes, according to the data displayed in Fig. 17. The overshoots of speed w_r were 111 Rad/s and 103 rad/s for the DTC-Conv approach and the DTC-TOSMC-MSVM approach, respectively. The speed response time using the proposed technique was estimated to be 0.01 s, compared to the traditional

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technique, which took approximately 0.1s. As a result, the DTC-TOSMC-MSVM strategy greatly decreased speed response time, which was calculated to be 83%. This suggests that the suggested approach performs exceptionally well.

As illustrated in Fig. 15, the DTC-TOSMC-MSVM strategy results in lower torque pulsations compared to the traditional DTC method when applied to a 5Ph-PMSM drive. This indicates that the DTC-TOSMC-MSVM technique enhances the quality of the torque even when the parameters of the 5Ph-PMSM drive change. This improvement highlights the superiority and significant potential of this strategy over the conventional DTC approach. Fig. 18 shows the zoom of torque T_{em}. The DTC-TOSMC-MSVM technique significantly decreased torque ripples, achieving values of 3.1 N.m compared to 11.3 N.m with the DTC-Conv method. This represents an approximate 72.56% reduction in torque ripples using the proposed DTC-TOSMC-MSVM strategy over the conventional DTC approach.

Fig. 16 shows the stator flux value change pattern of the two techniques according to the given flux reference value. Fig. 19 shows the zoom of stator flux. The proposed method offers a distinct advantage over DTC-Conv by maintaining a stable stator flux with a ripple of just 0.0075 Wb, even when machine parameters fluctuate. Conversely, DTC-Conv exhibits a higher flux ripple of 0.0205 Wb under the same conditions, indicating its susceptibility to such changes.

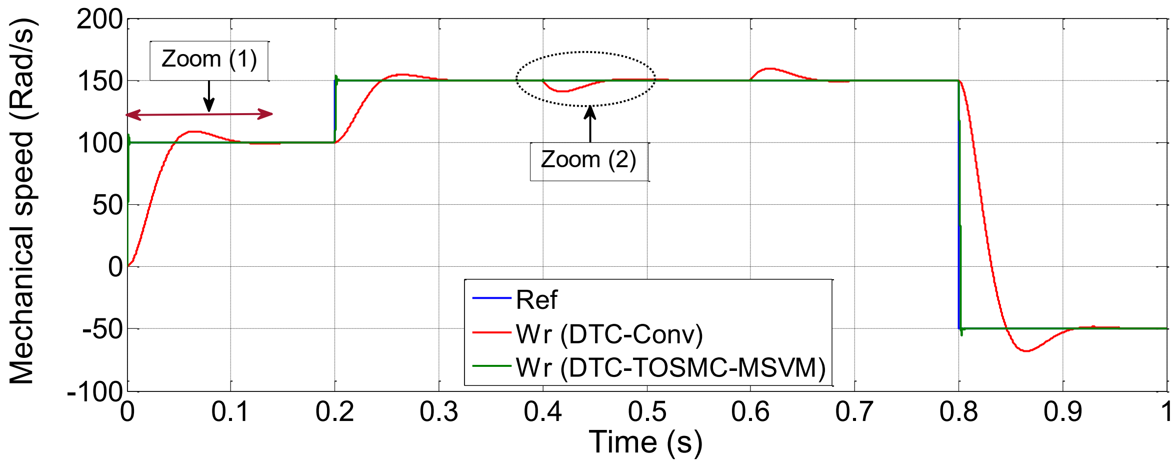

Fig. 14. Rotation speed (second test)

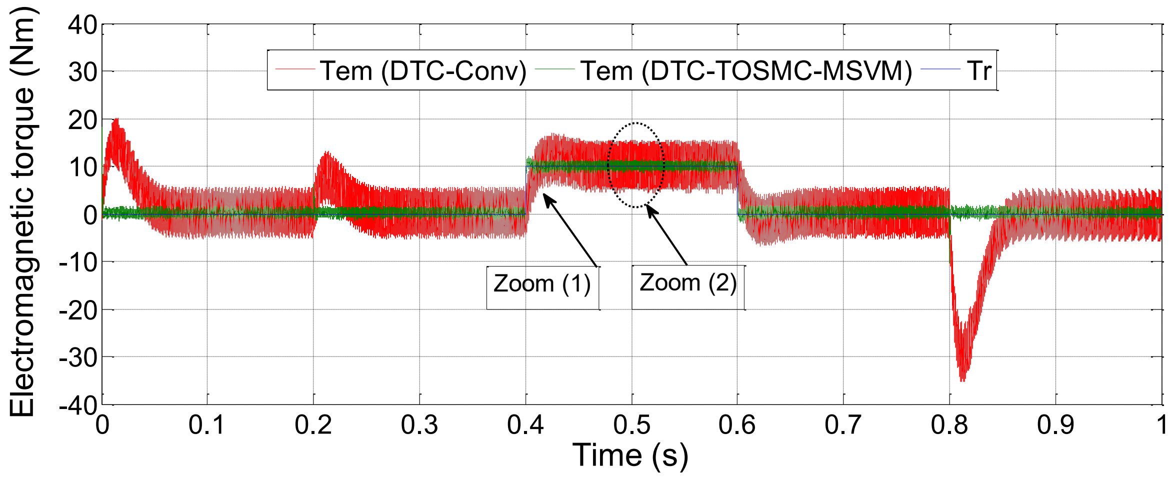

Fig. 15. Electromagnetic torque (second test)

As illustrated in Fig. 20 and Fig. 21, which present the stator current's THD, the proposed DTC-TOSMC-MSVM technique exhibits superior performance. Its THD of 11.95%, clearly visible in Fig. 21, is a marked improvement over the 37.01% recorded by the classical control approach, as shown in Fig. 20. This indicates that the proposed method effectively boosts current quality, cutting the THD by roughly 67.71%. The outcomes unequivocally confirm that the DTC-TOSMC-MSVM strategy is superior in improving system robustness and dynamic accuracy for applications that need high reliability in the face of parametric uncertainties and external disturbances.

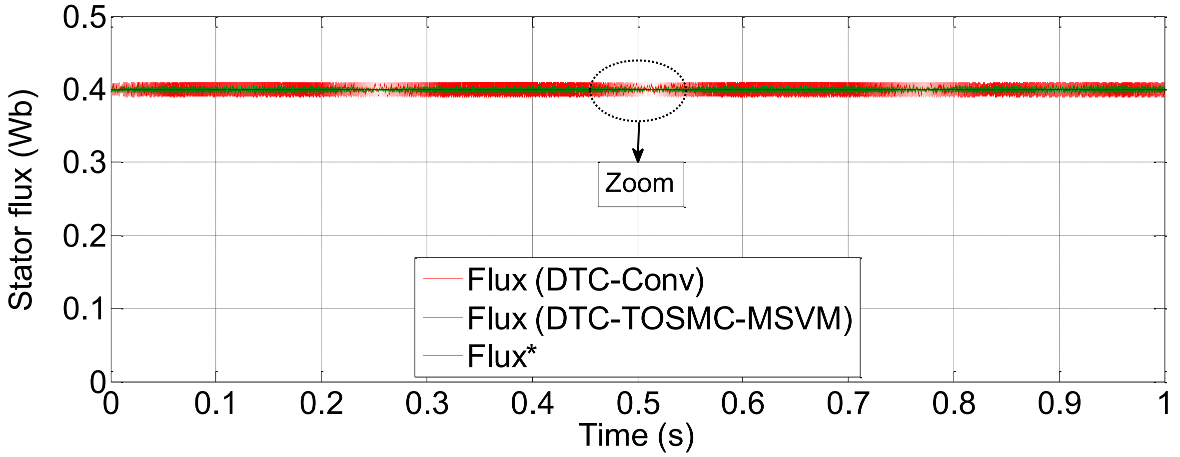

Fig. 16. Stator flux (second test)

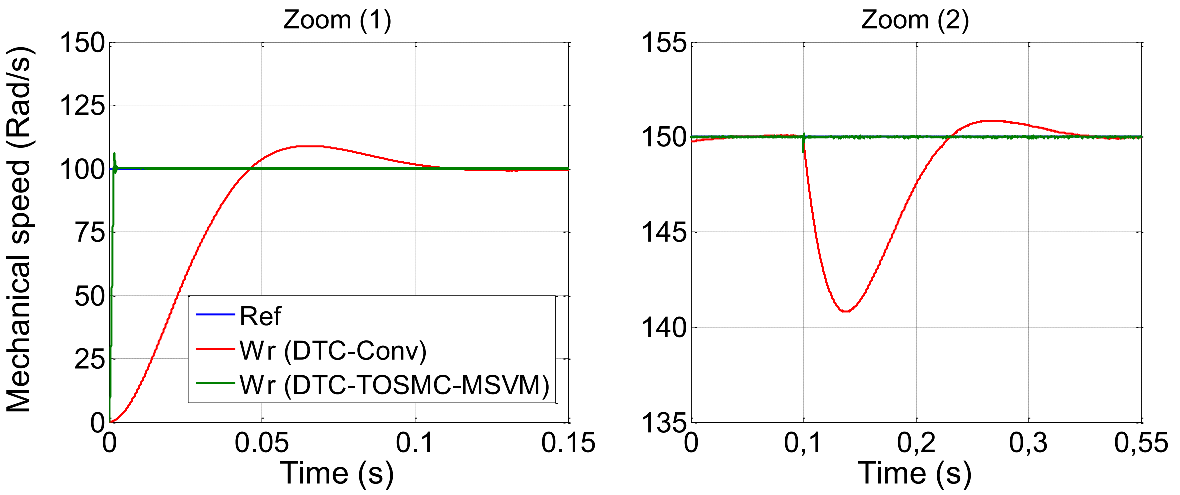

Fig. 17. Zoom in the rotation speed (second test)

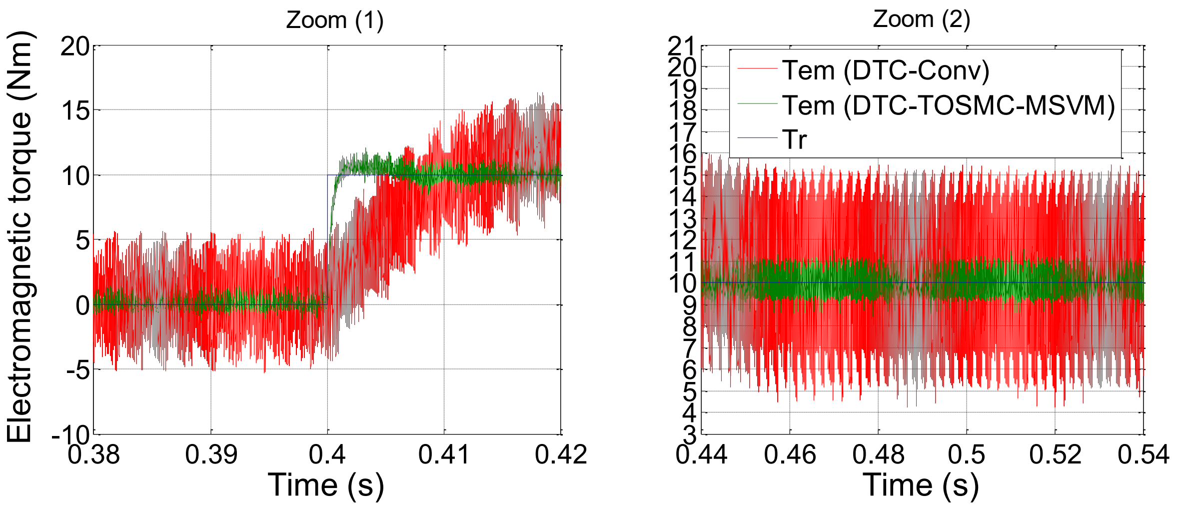

Fig. 18. Zoom in the electromagnetic torque (second test)

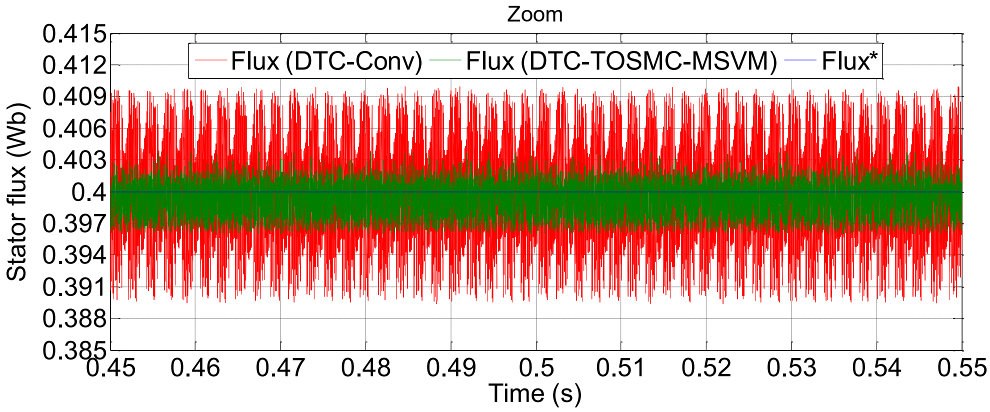

Fig. 19. Zoom in the stator flux (second test)

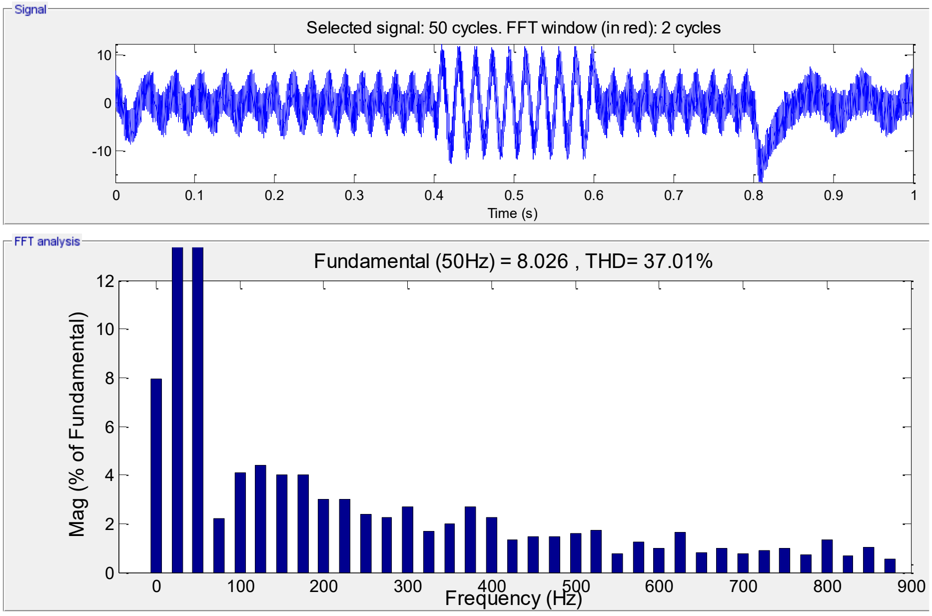

Fig. 20. THD of phase current I_{as} (DTC-Conv)

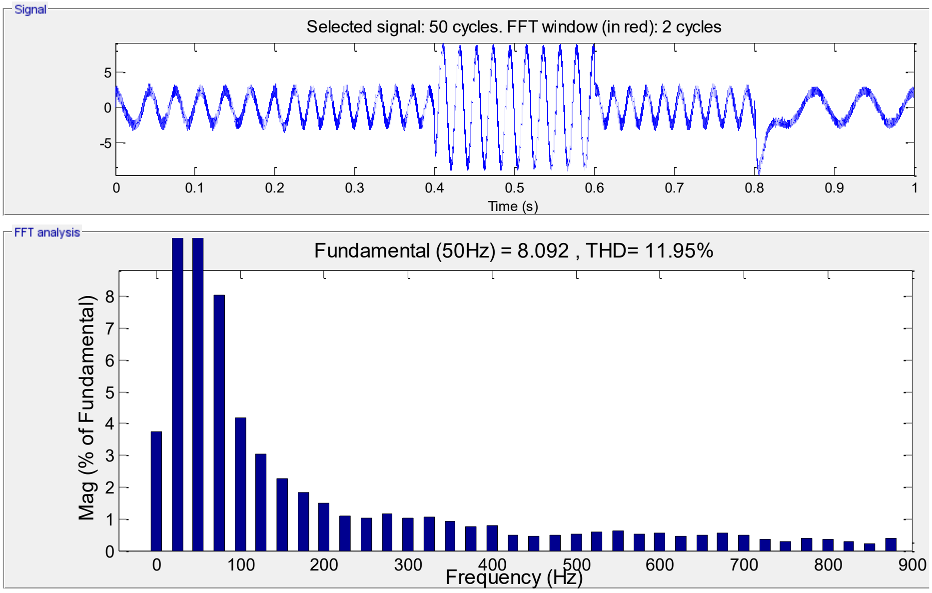

Fig. 21. THD of phase current I_{as} (DTC-TOSMC-MSVM)

5. Conclusion

This research introduces an advanced control approach for a 5Ph-PMSM drive. By integrating a TOSMC strategy with a MSVM algorithm, the proposed method significantly enhances the performance of DTC technique. Our MATLAB simulations under various operating conditions demonstrate that the proposed DTC-TOSMC-MSVM method outperforms conventional DTC, proving its effectiveness and potential for improved drive system performance. The effectiveness of the presented technique was investigated based on several key performance indicators: Current THD, reference tracking, response time, robustness, and ripple reduction in flux and torque. The effectiveness of the presented technique was investigated based on several key performance indicators: Current THD, reference tracking, response time, robustness, and ripple reduction in flux and torque. Furthermore, the DTC-TOSMC-MSVM approach significantly reduced the ripple content in both stator flux and torque, achieving reduction rates of 51.85% and 63.15%, respectively, when compared to the DTC-Conv method. The use of the designed technique is estimated to enhance THD quality by 61.08% when compared to the DTC-Conv method. Also, this proposed approach improved the response time of machine speed by an estimated 88.88% compared to the DTC approach.

Future research is expected to propose innovative and highly effective approaches, such as combining hybrid nonlinear algorithms with artificial intelligence. This will involve experimental validation and comparison with simulated results.

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