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Improve of the direct torque control strategy applied to a multi-phase interior permanent magnet synchronous motor using a super twisting sliding mode algorithm

Introduction. *Conventional direct torque control (DTC) is a superior control strategy for managing the torque of a five-phase interior permanent magnet synchronous motor (FP-IPMSM). Nevertheless, the DTC's switching frequency results in large flux and torque ripples, which produce acoustic noise and impair control performance. On the other hand, the DTC scheme's performance when using conventional PI controllers results in high flux and torque ripples, which decreases the system's robustness.* ***Goal.*** *This work aims to use a modern variable structure control of the DTC scheme based on a super twisting algorithm in order to ensure efficient control of multiphase machine, reduce flux and torque ripples, minimize tracking error, and increase robustness against possible disturbances.* ***Scientific novelty.*** *We propose to use super-twisting sliding mode control (STSMC) methods of the DTC based on the space vector modulation (SVM) algorithm of the multiphase motor.* ***Methodology.*** *In order to achieve a decoupled control with higher performance and to ensure stability while handling parameter changes and external disturbances, a STSMC algorithm on the DTC technique incorporating the SVM algorithm was implemented in place of the switch table and PI controller.* ***Results.*** *The suggested STSMC-DTC based SVM approach outperforms the conventional DTC methods in achieving the finest performance in controlling the FP-IPMSM drive.* ***Practical value.*** *The merits of the proposed DTC technique of FP-IPMSM are demonstrated through various tests. The suggested STSMC-DTC approach reduces flux and torque ripples by roughly 50 % and 60 %, respectively, in comparison to the conventional DTC strategy. Furthermore, the proposed technique of FP-IPMSM control method is made to provide robust performance even when machine parameters change.* References 24, table 2, figures 8.

Key words: **direct torque control, flux and torque ripples, robustness, multi-phase interior permanent magnet synchronous motor, super twisting sliding mode algorithm.**

Вступ. *Традиційне пряме управління моментом (DTC) є чудовою стратегією управління крутним моментом п'ятифазного синхронного двигуна з внутрішніми постійними магнітами (FP-IPMSM). Однак, частота перемикання при DTC призводить до великих пульсацій потоку та моменту, які створюють акустичний шум та погіршують характеристики керування. З іншого боку, ефективність схеми DTC при використанні традиційних ПІ-регуляторів призводить до великих пульсацій потоку та моменту, що знижує надійність системи.* ***Мета***. *Робота спрямована на використання сучасного управління змінною структурою схеми DTC, заснованої на алгоритмі суперскручування, для забезпечення ефективного управління багатофазною машиною, зменшення пульсацій потоку та моменту, мінімізації помилки стеження та підвищення стійкості до можливих перешкод.* ***Наукова новизна***. *Запропоновано використовувати методи керування ковзним режимом суперскручування (STSMC) з DTC, засновані на алгоритмі просторово-векторної модуляції (SVM) багатофазного двигуна.* ***Методологія***. *Для досягнення розв'язаного управління з більш високою продуктивністю та забезпечення стабільності при обробці змін параметрів та зовнішніх збурень, було реалізовано алгоритм STSMC на основі DTC, що включає алгоритм SVM, замість таблиці перемикання та ПІ-регулятора.* ***Результати***. *Запропонований STSMC-DTC підхід на основі SVM перевершує традиційні DTC методи у досягненні найкращої продуктивності при керуванні приводом FP-IPMSM.* ***Практична цінність***. *Переваги запропонованого DTC методу для FP-IPMSM продемонстровані в ході різних випробувань. Запропонований підхід STSMC-DTC знижує пульсації потоку і крутного моменту приблизно на 50 % і 60 % відповідно в порівнянні з традиційною DTC стратегією. Крім того, запропонований метод керування FP-IPMSM розроблений для забезпечення надійної роботи навіть за зміни параметрів машини.* Бібл. 24, табл. 2, рис. 8.

Ключові слова: **пряме управління крутним моментом, пульсації потоку та крутного моменту, надійність, багатофазний синхронний двигун з внутрішніми постійними магнітами, алгоритм ковзного режиму суперскручування.**

Introduction. Many electrical energy sources are being transformed into mechanical energy through the use of electric motors. The numerous benefits of interior permanent magnet synchronous motors (IPMSM), such as their exceptional efficiency, low operating noise, and high power density, have led to their widespread use in a variety of applications [1–4]. A prolonged flux weakening region is another benefit of IPMSM, along with their strong rotor and reluctance torque, which are essential in high-speed applications [5, 6].

Compared to three-phase systems, multiphase systems offer a number of benefits, such as improved performance, robustness, reduced torque pulsations, high output power rating, and steady speed response [7, 8]. Multiphase machines have attracted interest in a number of application areas where high dependability is required, such as robotics, energy conversion, ship propulsion, pump drives, and multi-machine systems [9, 10].

Several works that make use of the latest technological advancements have addressed the drawbacks of conventional technical approaches. Among them, the following innovative technologies are listed: artificial neural networks (ANNs), adaptive backstepping controller, sliding mode controller (SMC), fuzzy logic, super-twisting sliding mode control (STSMC), high-order sliding mode control, ANFIS algorithm, genetic algorithms and synergetic control.

When compared to the traditional direct torque control (DTC) switching method, the DTC with PI regulator has become more and more popular in polyphase motors due to its higher efficiency.

In the conventional DTC approach uses 2 hysteresis controllers and lookup tables to control rotor flux and torque. Compared to the *V*/*f* technique and field oriented control, DTC features a more robust algorithm and a simpler structure [11]. In [12], the ANN with DTC has been introduced to reduce the torque and flux ripples of the five-phase interior permanent magnet synchronous motor (FP-IPMSM). In [13], the authors designed a master-slave virtual vector duty cycle assignment with an enhanced DTC technique of the dual 3-phase PMSM. It has been experimentally confirmed that the suggested technique improves both dynamic and steady-state performance by reducing the phase current total harmonic distortion (THD), significantly reducing the content of the 5th and 7th current harmonics and effectively suppressing torque and flux ripples. In [14], to choose the optimal voltage vector that may greatly reduce the torque ripple, a unique sequential approach combined with a duty ratio optimization technique. The suggested approach can successfully lower the THD and the ripple in both dynamic and steady-state torque, according to experimental data. Due to the parametric sensitivity that a classical regulator PI has, minimal research has been done to avoid this problem as in papers [15–17].

The **goal** of the paper is to use a modern variable structure control of the DTC scheme based on a super twisting algorithm in order to ensure efficient control of multiphase machine, reduce flux and torque ripples, minimize tracking error, and increase robustness against possible disturbances

DTC principal of FP-IPMSM. Conventional DTC provides motors with a very sensitive and efficient control approach, but it requires accurate switching frequency management and real-time processing, which may make implementation more challenging [14]. Because of the additional phase, using it to an FP-IPMSM offers several advantages, such as improved fault tolerance and reduced torque ripple.

The equation for the stator voltage of a FP-IPMSM in a *d-q*, *x-y* rotating frame [12] is:

$$\begin{cases} v_{ds} = R_s i_{ds} + \dfrac{\mathrm{d}}{\mathrm{d}t}\left(L_d i_{ds} + \phi_f\right) - \omega_r L_q i_{qs}; \\ v_{qs} = R_s i_{qs} + \dfrac{\mathrm{d}}{\mathrm{d}t} L_q i_{qs} + \omega_r \left(L_d i_{ds} + \phi_f\right); \\ v_{xs} = R_s i_{xs} + \dfrac{\mathrm{d}}{\mathrm{d}t} L_{ls} i_{xs}; \\ v_{ys} = R_s i_{ys} + \dfrac{\mathrm{d}}{\mathrm{d}t} L_{ls} i_{ys}, \end{cases} \quad (1)$$

where v_{ds}, v_{qs}, v_{xs}, v_{ys} are the stator voltages in the *d-q*, *x-y* axis; i_{ds}, i_{qs}, i_{xs}, i_{ys} are the stator currents in *d-q*, *x-y* axis; R_s is the stator resistance; L_d, L_q are the stator inductances in the *d-q* axis; ϕ_f is magnetic flux; ω_r is the rotation speed; L_{ls} is the leakage inductances.

The electromagnetic torque T_{em} of the FP-IPMSM is:

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

The equation for dynamics ω_r is:

$$J_m \frac{\mathrm{d}\omega_r}{\mathrm{d}t} = pT_{em} - pT_r - f_m \omega_r , \quad (3)$$

where J_m is the moment of inertia; T_r is the load torque; f_m is the viscous damping; p is number of pairs poles.

DTC controls the opening and closing of the voltage source inverter switches by directly determining the control sequence that is applied to these switches [12].

In terms of flux stator Φ and current i, the electromagnetic torque of the FP-IPMSM is expressed as:

$$T_{em} = \frac{5}{2} p(\Phi_\alpha i_\beta - \Phi_\beta i_\alpha) . \quad (4)$$

The torque and flux errors determine the inverter's switching states:

$$\begin{cases} \Delta\Phi_s = \Phi_s^* - \Phi_s; \\ \Delta T_{em} = T_{em}^* - T_{em}, \end{cases} \quad (5)$$

where Φ_s^* is the reference flux; T_{em}^* is the reference torque.

The amplitude of the stator flux is expressed as follows using the Concordia quantities:

$$\Phi_s = \sqrt{\Phi_\alpha^2 + \Phi_\beta^2} . \quad (6)$$

The position (angle) of the stator flux θ_s is:

$$\theta_s = \tan^{-1}\left(\Phi_\beta / \Phi_\alpha\right). \quad (7)$$

The authors [18] provided a switching table for conventional DTC of FP-IPMSM (Table 1).

Table 1

Switch table for conventional DTC

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

The block diagram of conventional DTC technique for the FP-IPMSM is shown in Fig. 1.

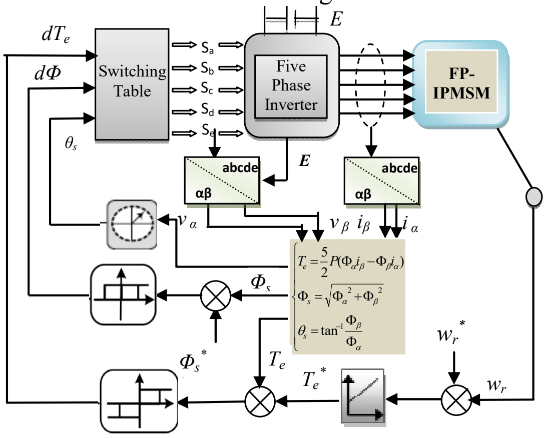

Fig. 1. The block diagram of conventional DTC technique for the FP-IPMSM

DTC-SVM technique. Conventional DTC provides motors with a very sensitive and efficient control approach, but it requires accurate switching frequency management and real-time processing, which may make implementation more challenging [12, 17]. Applying it to a FP-IPMSM provides a number of benefits because of the additional phase, including decreased torque ripple and enhanced fault tolerance.

The 5-phase SVM can be applied via 2 or 4 vector approaches. There are 3 groups that comprise the active switching vectors; medium (V_m), large (V_l), and small (V_s) switching vectors. The formula for switching time while applying the 4-vector approach is:

$$V_s^* T_s = V_{al} T_{al} + V_{bl} T_{bl} + V_{am} T_{am} + V_{bm} T_{bm} ; \quad (8)$$

$$\begin{cases} \left|V_{al}\right| = \left|V_{bl}\right| = \left|V_l\right| = \dfrac{2}{5} V_{dc} 2\cos\left(\dfrac{\pi}{5}\right); \\ \left|V_{am}\right| = \left|V_{bm}\right| = \left|V_m\right| = \dfrac{2}{5} V_{dc}; \end{cases} \quad (9)$$

$$T_{al} / T_{am} = T_{bl} / T_{bm} = \left|V_l\right| / \left|V_m\right| = \tau = 1.618 . \quad (10)$$

Equations (8–10) when be solved, yield the equation for the switching time:

$$\begin{cases} T_{am} = \dfrac{\left|0.2764 V_{ref}\right| \sin\left(k\pi/5 - \theta\right)}{\left|V_m\right| \sin\left(\pi/5\right)} T_s; \\ T_{al} = \dfrac{\left|0.7236 V_{ref}\right| \sin\left(k\pi/5 - \theta\right)}{\left|V_l\right| \sin\left(\pi/5\right)} T_s; \\ T_{bm} = \dfrac{\left|0.2764 V_{ref}\right| \sin\left(\theta - (k-1)\pi/5\right)}{\left|V_m\right| \sin\left(\pi/5\right)} T_s; \\ T_{bl} = \dfrac{\left|0.2764 V_{ref}\right| \sin\left(\theta - (k-1)\pi/5\right)}{\left|V_l\right| \sin\left(\pi/5\right)} T_s; \\ T_0 = T_s - \left(T_{am} + T_{al} + T_{bm} + T_{bl}\right), \end{cases} \quad (11)$$

where V_{ref} is the reference voltage vector; T_s is the switching period; T_{am}, T_{bm}, T_{al}, T_{bl} are the switching times of medium and large voltage vectors; k is the number of sector; T_0 the switching time of zero voltage vectors; θ the angle of position for the reference voltage vector.

STSMC-DTC strategy of FP-IPMSM. The conventional method of controlling multi-phase PMSM is to use PI controllers. This method reduces the robustness of the system by increasing torque ripples [19, 20]. There are several different types of SMC procedures in the literature and all these proposed methods aim to reduce chattering phenomena [21–23].

In order to provide robust control, a unique method for FP-PMSM is proposed in this section. The developed method, known as super-twisting sliding mode control (STSMC), effectively addresses the primary shortcomings of the standard SMC technique as documented in the literature for uncertain systems. The following is the selection of the sliding surfaces based on (1) and (4):

$$\begin{cases} S(\Phi_s) = \Phi_s^{\ *} - \Phi_s; \\ S(T_{em}) = T_{em}^{\ *} - T_{em}; \\ S(w_r) = \omega_r^{\ *} - \omega_r. \end{cases} \quad (12)$$

The suggested second-order SMC is composed of 2 parts and is predicated on the super twisting technique that Levant originally introduced in [15]:

$$v_{ds} = v_1 + v_2 \quad (13)$$

with

$$\begin{cases} \dot{v}_1 = -K_1 \mathrm{sign}(S(\Phi_s)); \\ v_2 = -l_1 \left| S(\Phi_s) \right|^{\gamma} \mathrm{sign}(S(\Phi_s)); \end{cases} \quad (14)$$

$$v_{qs} = w_1 + w_2 \quad (15)$$

with

$$\begin{cases} \dot{w}_1 = -K_2 \mathrm{sign}(S(T_{em})); \\ w_2 = -l_2 \left| S(T_{em}) \right|^{\gamma} \mathrm{sign}(S(T_{em})); \end{cases} \quad (16)$$

$$i_{qs} = z_1 + z_2 \quad (17)$$

with

$$\begin{cases} \dot{z}_1 = -K_3 \mathrm{sign}(S(\omega_r)); \\ z_2 = -l_3 \left| S(\omega_r) \right|^{\gamma} \mathrm{sign}(S(\omega_r)). \end{cases} \quad (18)$$

The gains can be selected as follows to guarantee that the sliding manifolds will converge to zero within a finite time [15]:

$$\begin{cases} k_j > \dfrac{\lambda_j}{k_{mj}}, \quad l_j^{\ 2} \geq \dfrac{4\lambda_j}{K^2_{mj}} \dfrac{K_{Mj}(k_j + \lambda_j)}{K_{mj}(k_j - \lambda_j)}; \\ 0 < \gamma \leq 0.5; \quad j = 1, 2, 3. \end{cases} \quad (19)$$

Figure 2 provides the block diagram for the STSMC-DTC of the FP-IPMSM.

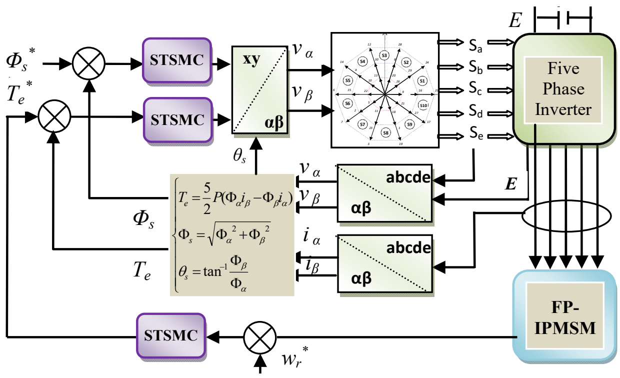

Fig. 2. The block diagram for the STSMC-DTC of the FP-IPMSM

Results and discussion. In MATLAB/Simulink numerical simulations have been carried out to validate strategies created for a DTC scheme employing the STSMC-based SVM algorithm of the FP-IPMSM. The machine's parameters are as follows: f = 50 Hz, p = 2, J_m = 0.004 kg/m^2, φ_f = 0.2 Wb, L_d = 8.5 mH, L_q = 8.5 mH, R_s = 0.67 Ω [24]. The conventional DTC and STSMC-DTC with SVM approaches will be examined and contrasted in 2 different tests – tracking performance and robustness.

Test 1. The reference tracking test is the initial test. The objective is to determine which approach yields superior reference tracking outcomes under the influence of load torque T_r variation. Additionally, in terms of torque ripple value and flux. At initialization, the FP-IPMSM's reference speed is set to 125 rad/s. The rotor speed rises to 50 rad/s at t = 0.2 s. A nominal T_r = 10 N·m was applied at t = [0.4, 0.6] s, and at t = 0.8 s, a consign inversion –50 rad/s was performed.

The results of the rotation speed simulation are shown in Fig. 3. In contrast to the second-order SMC-DTC strategy, which maintains its reference speed within an excellent range, the conventional DTC showed a speed decline from 50 rad/s to 36 rad/s at the instant t = 0.4 s while applying T_r. Figure 4 displays the torque T_{em} simulation results. The second-order SMC-DTC strategy minimizes torque oscillations in comparison to the conventional DTC method, where the T_{em} ripple values reached 3 N·m using the proposed technique and 7.5 N·m using the conventional technique (Table 2).

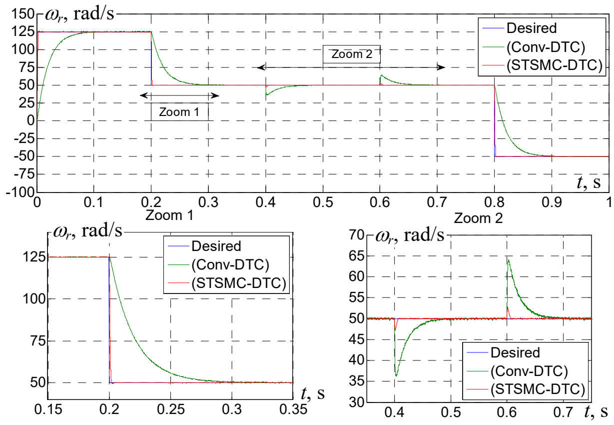

Fig. 3. Rotation speed (Test 1)

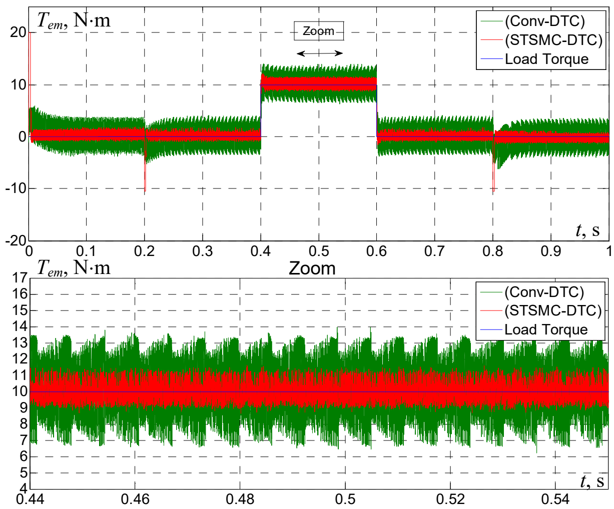

Fig. 4. Electromagnetic torque (Test 1)

The stator flux was improved using the proposed technique (Fig. 5) with very low ripple (7 mWb) when compared with the conventional DTC method (14 mWb).

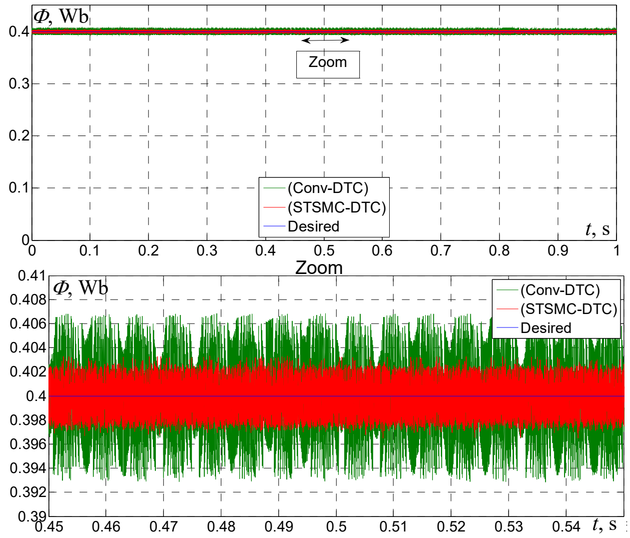

Fig. 5. Stator flux (Test 1)

Table 2

The comparative analysis of the various techniques

Parameter	Conventional DTC	STSMC-DTC
ω_r response time	0.1 s	0.02 s
Torque ripple	6.3–13.8 (7.5 N·m)	8.6–11.6 (3 N·m)
ω_r dropping due to T_r application	36 rad/s	43 rad/s
Flux ripple	0.393–0.407 Wb (0.014 Wb)	0.3965–0.4035 Wb (0.007 Wb)

As can be observed, the second-order SMC-DTC strategy has a better dynamic response for speed, torque and flux when compared to the conventional DTC technique, suggesting that the second-order SMC controller was less sensitive to load disturbance.

Test 2. The robustness test is the second test. The stator resistance R_s and machine's moment of inertia J_m values from the 1st test are multiplied by 2 in this test. The values for the L_q and L_d are reduced by 20 %. Simulation results are presented in Fig. 6–8.

Figure 6 indicates that the conventional DTC speed responses are more impacted by changes in machine's parameters than the STSMC-DTC for the FP-IPMSM. It is also observed that the speed is overshoot at the start as well as when the speed is reduced to 50 rad/s (t = 0.2 s), unlike the STSMC-DTC strategy for the FP-IPMSM results where the speed continues to follow the reference without overshot.

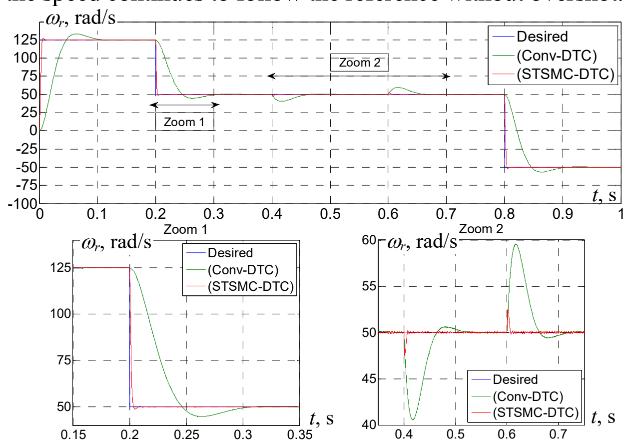

Fig. 6. Rotation speed (Test 2)

The torque T_{em} and stator flux utilizing the conventional DTC, where the torque ripple values reached 11.4 N·m, are clearly impacted by these changes in machine parameters (Fig. 7). Figure 8 shows that the flux ripple values reached 22 mWb for conventional DTC.

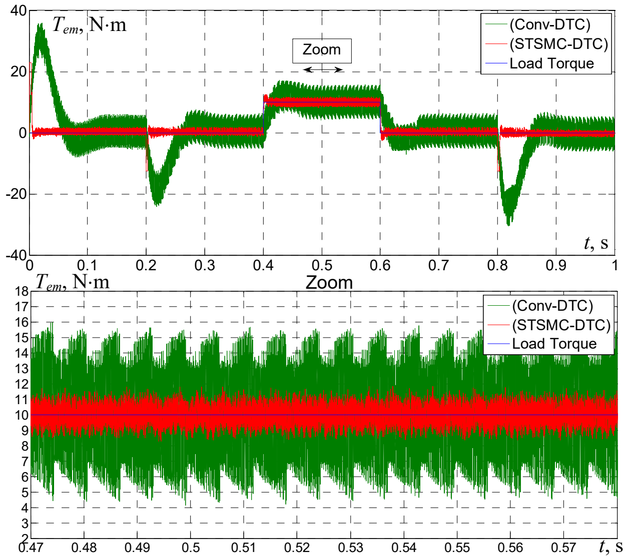

Fig. 7. Electromagnetic torque (Test 2)

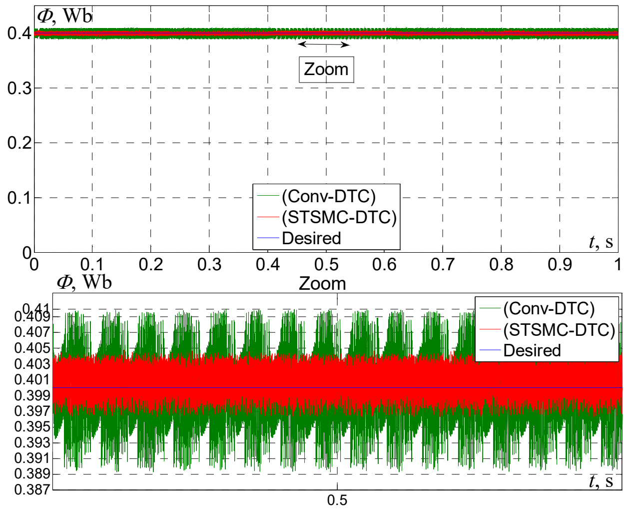

Fig. 8. Stator flux (Test 2)

Conclusions. In this research we proposed a novel method for the DTC scheme applied to the FP-IPMSM drive. We improved the control and the behavior of the FP-IPMSM by controlling the speed, torque, and stator flux using the STSMC technique with SVM approach. A comparison between the conventional DTC and the suggested STSMC-DTC based on SVM is presented where the modification goal was reduce some of the drawbacks of conventional DTC such as flux and torque ripples overshoot, rise time, and decrease in both robustness against changes in machine parameters, stability, and dynamic response.

The following are the main findings:

- A new STSMC-DTC based on SVM technique of the FP-IPMSM was proposed and designed.
- The proposed STSMC-DTC technique is much more robust compared to the conventional DTC technique.
- Minimization of ripples for flux and torque has been shown in two different tests – tracking performance and robustness. The proposed STSMC-DTC-SVM method

lowers torque ripple ≈60 % and flux ripple ≈50 % when compared to the conventional DTC method.

The STSMC-DTC-SVM technique will be experimentally implemented and validated in the future work.

Conflict of interest. The authors declare that they have no conflicts of interest.

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