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# DIRECT TORQUE CONTROL USING SECOND ORDER SLIDING MODE OF A DOUBLE STAR PERMANENT MAGNET SYNCHRONOUS MACHINE

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*This work deals with the performance improvement study of the direct torque control (DTC) of a Double Star Permanent Magnet Synchronous Machine (DSPMSM) based on Second Order Sliding Mode Control (SOSMC), powered by two voltage source inverters. DTC control using conventional PI regulators has certain disadvantages such as significant flux, torque ripples and sensitivity to parametric variations. To overcome these drawbacks, we apply a new type with more robust regulators such as the second order sliding mode control. Simulation results demonstrate the feasibility and validity of the proposed DTC- SOSMC system by effectively accelerating system response, reducing torque and flux ripple and a very satisfactory performance has been achieved.*

**Keywords:** Direct Torque Control (DTC); Double Star Permanent Magnet Synchronous Machine; Second Order Sliding Mode Control

## 1. Introduction

Double star permanent magnet synchronous machine is widely used because of its high-power density, large torque to inertia ratio, high efficiency and exemplary reliability. This machine operates with one or several phases of defective motor. The rotor flux is generated by the permanent magnet. In recent years, variable speed drives consisting of an alternative machine associated with a static converter, have attracted much attention from research groups and industry. They are more and more present in the fields of high-power industrial applications. However, the constraints on the power components limit the switching frequency, and consequently reduce its performances. To enable the use of higher switching frequency components, the power should be divided to realize this, one of the solutions is to use machines with a large number of phases (multi-phase (n > 3) or (multi-star) [1] [2].

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These machines represent for several years a growing interest in the field of electrical machines. They can be used for automotive electric traction systems, marine electric propulsion systems and wind turbines or for high-power industrial electrical applications [3].

One of the most common examples is the double-star synchronous machine (DSSM), which is the most widely used in industry [4] [5]. In the conventional configuration, its stator contains two identical three-phase windings offset by an electric angle of 30 °. The rotor structure remains identical to that of a three-phase conventional synchronous machine. It can be either permanent magnet or coiled type [6] [7]. In recent years, several techniques have been developed to improve the performance of these electrical machines. The Direct Torque Control (DTC) proposed by Depenbrock and Takahashi in the middle of the eighties is a vector control solution [8].

It was introduced especially for three-phase machines and several studies allowed to apply this control technique on multi-phase machines. Like every command, the DTC has advantages and disadvantages, it has to be less dependent on the parameters of the machine (the stator resistance is theoretically the only parameter of the machine, which intervenes in the command) and to provide a faster response of the torque. Despite these advantages, this control scheme also has significant disadvantages, the instability problem such as the lack of control of the switching frequency of the inverter and the use of hysteresis bands generating electromagnetic torque ripples and noise in the machine [1] [9].

Several research works have discussed this subject, initially based on the control principles set out in AL. Takahashi and giving rise to various developments of DTC type strategies. This structure of control is based on PI type controllers, these regulators suffer from sensitivity to variations in the motor parameters. This requires a good identification of the parameters. As a result, the use of robust control regulators to maintain a decoupling and an acceptable performance level is needed [1] [10].

The sliding mode control is a modern control strategy, with higher robustness against load and parameter variations, faster response and higher level of energy efficiency. It relies on fast switching, which made it difficult to implement it that time [1] [10] [11]. The recent revolutions of computers and power semiconductors have made Sliding Mode Control an important research field, which can be developed by a lot of scientists in many countries. Nevertheless, the classic sliding mode of the first order (standard sliding modes) has a significant disadvantage, like the phenomenon of chattering. The main cause of chattering phenomenon has been identified as the presence of unmodelled parasites in the switching device [11]. In order to develop a robust DTC, current researchers have proposed these of a DTC with a speed controller based on the higher order sliding mode control to obtain a more flexible control. This last solution allowed the reduction or even the attenuation of the chattering phenomenon while keeping the properties of robustness [12].

The strategy proposed in this work is the study of the dynamic behavior of double-star permanent magnets synchronous machine controlled by a DTC during a speed adjustment by conventional regulators (PI) and by regulators based on second order sliding mode. Simulation results reveal that the SOSMC-DTC has a very robust behavior against the PI-DTC.

## 2. Modeling of The Double Star Permanent Magnet Synchronous Machine

By applying the Park transformation to the model of the DSPMSM, the equations are expressed in a reference frame linked to the rotating field as follows [13] [14]:

$$\begin{aligned} V_{ds1} &= R_{s1} i_{ds1} + \frac{d}{dt}\psi_{ds1} - \omega\psi_{qs1} \\ V_{qs1} &= R_{s1} i_{qs1} + \frac{d}{dt}\psi_{qs1} + \omega\psi_{ds1} \end{aligned} \qquad (1)$$

$$\begin{aligned} V_{ds2} &= R_{s2} i_{ds2} + \frac{d\,\psi_{ds2}}{d\,t} - \omega\psi_{qs2} \\ V_{qs2} &= R_{s2} i_{qs2} + \frac{d\,\psi_{qs2}}{d\,t} + \omega\psi_{ds2} \end{aligned} \qquad (2)$$

The symbols used in the above equations have the following meanings: subscript *s*, indicate the variable and parameter of stator, subscripts *1*, *2* denote variables and parameters of stator *1* and *2* respectively $V_{ds1}$, $V_{qs1}$, $V_{ds2}$,$V_{qs2}$ are respectively stator voltages in the *d-q* axis , $I_{ds1}$, $I_{qs1}$, $I_{ds2}$,$I_{qs2}$are components of the stator currents in the *d-q* axis, $\psi_{ds1}$, $\psi_{qs1}$, $\psi_{ds2}$,$\psi_{qs2}$are components of the stator flux linkage vectors in *d-q*.

Where the expressions for stator flux are:

$$\begin{aligned} \psi_{ds1} &= L_{ds1} i_{ds1} + M_{ds2} i_{ds2} + \psi_{PM} \\ \psi_{qs1} &= L_{qs1} i_{qs1} + M_{qs2} i_{qs2} \\ \psi_{ds2} &= L_{ds2} i_{ds2} + M_{ds1} i_{ds1} + \psi_{PM} \\ \psi_{qs1} &= L_{qs2} i_{qs2} + M_{qs1} i_{qs1} \end{aligned} \qquad (3)$$

For studying the dynamic behavior, the following equation of motion was added:

$$J\frac{d\Omega}{dt}=T_e-T_r-f_r\,\Omega \quad (4)$$

Where: $J$ is the moment of inertia, $f_r$ is the friction coefficient, $T_e$ is the electromagnetic torque, $T_r$ is the load torque and $\Omega$ is the mechanical rotation speed of the rotor [15].

The model of the DSPMSM has been completed by the expression of the electromagnetic torque $T_e$ given below [3]:

$$\begin{aligned}
&T_e = p(\psi_{ds1}\, i_{qs1} - \psi_{qs1}\, i_{ds1} + \psi_{ds2}\, i_{qs2} - \psi_{qs2}\, i_{ds2})\\
&T_e = p(\psi_{PM}(i_{qs1} + i_{qs2}) + (L_d - L_q)(i_{d1}i_{q1} + i_{d2}i_{q2}) \quad (5)\\
&+(M_d - M_q)(i_{d1}i_{q2} + i_{d2}i_{q1}))
\end{aligned}$$

Where: $p$ is the number of pole pairs, $\psi_{PM}$ permanent magnet.

The structure of the DSPMSM is represented in the electrical space by Fig. 1.

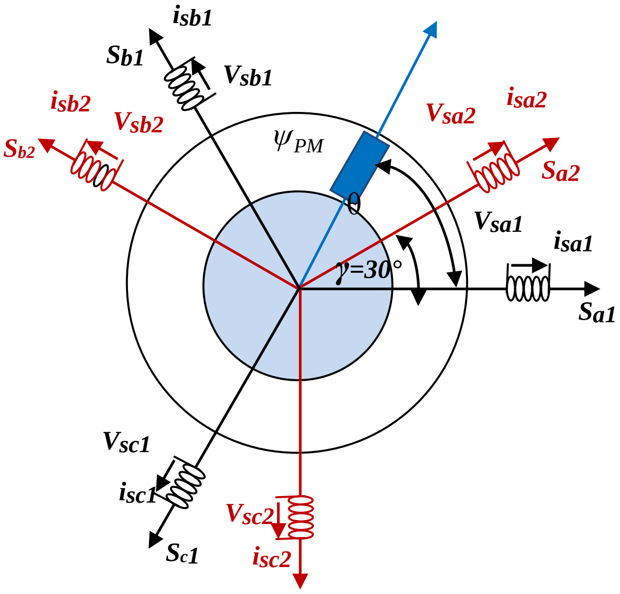


Fig. 1. Schematic representation of DSPMSM windings

## 3. Direct Torque Control (DTC) of the DSPMSM

The principle of the DTC control is based on the direct determination of the command sequences applied to the switches of a voltage inverter to deliver the stator voltage vectors. These vectors are chosen from a selection table as a function of the flow and torque errors as well as the position of the stator flow vector.

Two comparators control the status of system control variables, stator flux and electromagnetic torque. The hysteresis corrector is the simplest and best suited to DTC. Its role is to maintain the error between the value to be set and its reference in a hysteresis band. For a two-state controller, the choice of the voltage vector depends only on the sign of the error and does not depend on its amplitude.

However, a hysteresis band is added around zero to avoid unnecessary switching when the flow error is very small [8].

A two-level voltage inverter allows to have 7 distinct positions in the phase plane, corresponding to the 8 voltage vectors of the inverter. These positions are illustrated in Fig. 2.

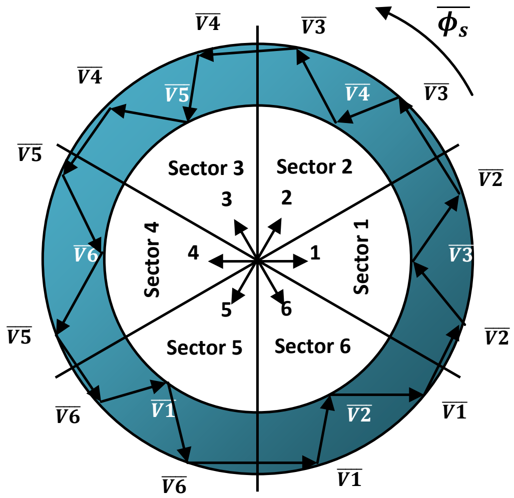


Fig. 2. Voltage vector

Moreover, Table 1 presents the sequences corresponding to the position of the stator flux vector to the different sectors (see Fig. 2). The flux and the torque are controlled by two hysteresis comparators at 2 and 3 levels, respectively, in the case of a two-level voltage inverter.

*Table 1*

**Vectors voltage localization**

| **Cflx** | **CTe** | **1** | **2** | **3** | **4** | **5** | **6** | **Comparator** | |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | $V_2$ | $V_3$ | $V_4$ | $V_5$ | $V_6$ | $V_1$ | Two levels | Threelevels |
| 1 | 0 | $V_7$ | $V_0$ | $V_7$ | $V_0$ | $V_7$ | $V_0$ | | |
| 1 | -1 | $V_6$ | $V_1$ | $V_2$ | $V_3$ | $V_4$ | $V_5$ | | |
| 0 | 1 | $V_3$ | $V_4$ | $V_5$ | $V_6$ | $V_1$ | $V_2$ | Two levels | Three levels |
| 0 | 0 | $V_0$ | $V_7$ | $V_0$ | $V_7$ | $V_0$ | $V_7$ | | |
| 0 | -1 | $V_5$ | $V_6$ | $V_1$ | $V_2$ | $V_3$ | $V_4$ | | |

Direct torque control is based on the orientation of the stator flux. The expression of the stator flux in the park frame of reference is described by [2] [16]:

$$\begin{aligned} \psi_{ds1.2} &= \int_0^t (V_{ds1,2} - R_s i_{ds1,2}) dt \\ \psi_{qs1.2} &= \int_0^t (V_{qs1,2} - R_s i_{qs1,2}) dt \end{aligned} \qquad (6)$$

Where $V_{sd1.2}$ and $V_{sq1.2}$ are the estimated components of the vector voltage. They are expressed from the model of the inverter.

Thus, the stator flux module becomes:

$$\begin{aligned} \psi_{s1} &= \sqrt{\psi_{ds1}^2 + \psi_{qs1}^2} \\ \psi_{s2} &= \sqrt{\psi_{ds2}^2 + \psi_{qs2}^2} \end{aligned} \qquad (7)$$

The electromagnetic torque can be estimated from the estimated magnitudes of the flux, and the measured magnitudes of the line currents, by the equation below:

$$\hat{T}_e = p(\psi_{ds1} i_{qs1} - \psi_{qs1} i_{ds1} + \psi_{ds2} i_{qs2} - \psi_{qs2} i_{ds2}) \quad (8)$$

The block scheme of the investigated DTC for a voltage source inverter fed DSPMSM is presented on Fig. 3.

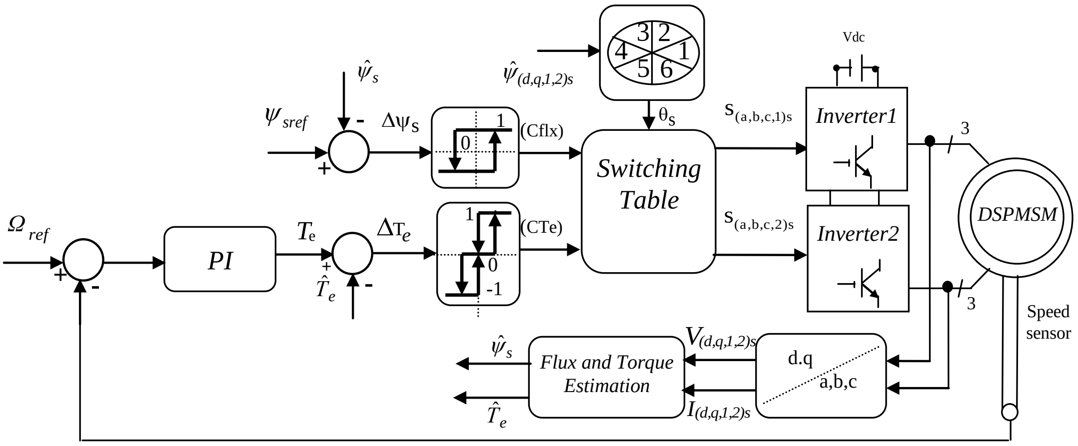


Fig. 3. Block diagram of the proposed PI-DTC of DS-PMSM

## 4. Second Order Sliding Mode Control of (DSPMSM)

The proposed control strategy is based on the Super Twisting Algorithm. This algorithm is an exception that only requires information about the sliding surface [18] [19]. The application of this control strategy begins with the determination of the relative degree of the variable to be regulated. This variable is the speed, so we choose a surface that is sufficient to make the command appear.

We define the following sliding surface [20] [21]:

$$S_\Omega = \Omega_{ref} - \Omega \qquad (9)$$

$$\frac{d\Omega}{dt} = \frac{T_e - T_r - f_r\,\Omega}{J} \qquad (10)$$

$$S_\Omega^* = \Omega_{ref}^* - \Omega^* = \Omega_{ref}^* - \frac{1}{J}(T_e - f_r\Omega_t - T_r) \qquad (11)$$

If we define the functions $A_\Omega$ as follows:

$$A_\Omega = \Omega_{ref}^* - \frac{1}{J}(f_r\,\Omega - T_r) \qquad (12)$$

Thus: $S_{\Omega t}^{**} = A_\Omega^* - \frac{1}{J}T_e^*$

The second-order sliding mode controllers contain two parts:

$$I_{ref} = I_{eq} + I_N \tag{13}$$

Where: $I_N = I_1 + I_2$

$$\begin{aligned} I_1^* &= -\alpha_1 sign(s_\Omega) \\ I_2^* &= -\beta_1 \left|s_\Omega\right|^{\rho} sign(s_\Omega) \end{aligned} \tag{14}$$

To ensure convergence to zero in finite time, the gains can be chosen as follows:

$$\begin{cases} \alpha_1 > \dfrac{\phi}{\Gamma_{mi}} \\ \beta_1^2 \geq \dfrac{4\phi\left(\alpha_1 + \phi\right)}{T_e^2\left(\alpha_1 - \phi\right)} \\ 0 < \rho \leq 0.5 \end{cases} \tag{15}$$

Fig. 4. illustrates the general structure of the SOSMC-DTC of DSPMSM

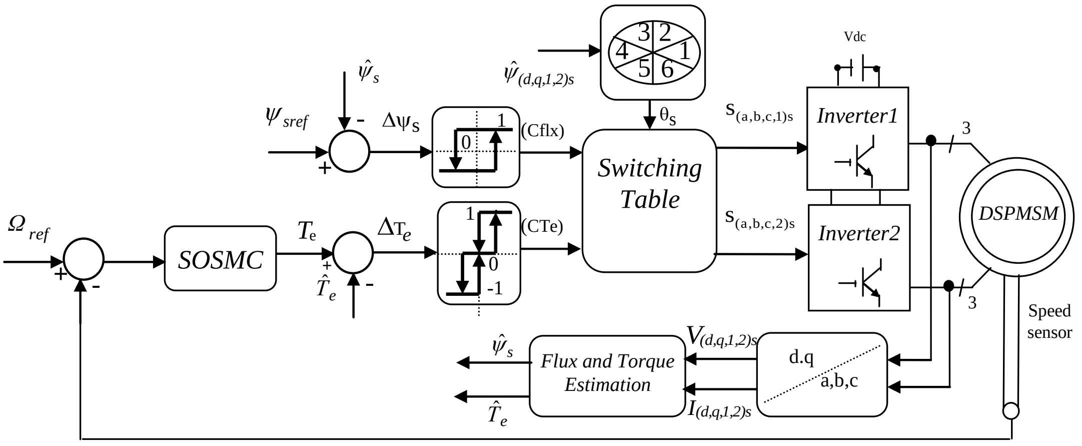


Fig. 4. Block diagram of the proposed SOSMC-DTC of DSPMSM.

### 5. Simulation Results and Discussion

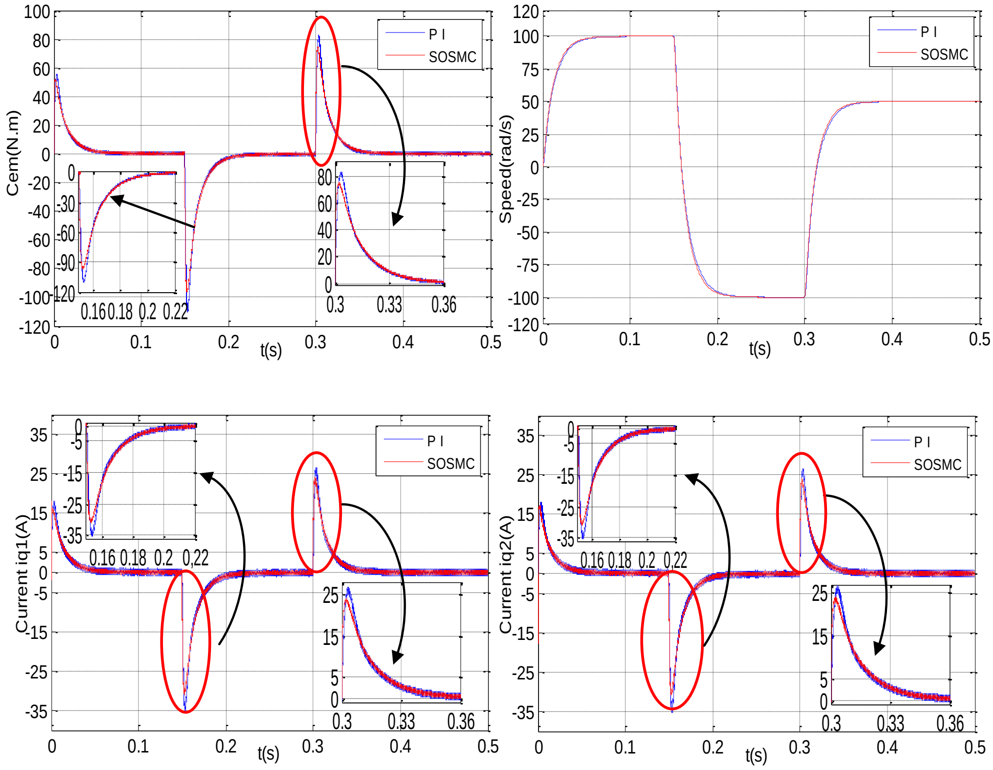
In order to have a better appreciation of the results obtained through the direct torque control DTC based on the two types of speed regulators PI and SOSMC applied to the DSPMSM, it is necessary to compare the static and dynamic characteristics of the two speed controllers under the same operating conditions (reference, disturbance loads) and in the same simulation configuration.

A series of numerical simulations under the Matlab/Simulink environment have been undertaken for the following two modes of operation:

- Operation with speed reversal;
- Operation with variation of the load torque.

### 5.1 Robustness test for speed reversal

The purpose of this test is to validate the robustness of the controllers PI-DTC and SOSMC-DTC for speed reversal. Fig. 5 depicts the waveforms of the improved performances of speed control in the case of a no-load:



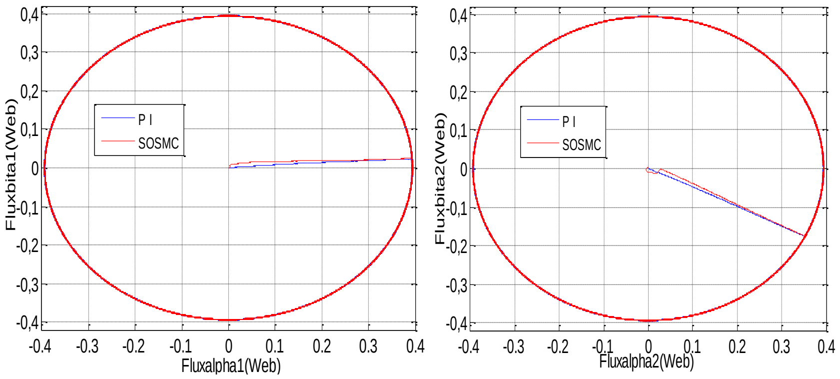


Fig. 5. Comparison of the speed regulation of the PI- DTC and SOSMC-DTC.

It can be noticed that the use of the SOSMC controller allows the speed to judiciously follow its reference value of +100rad/s to -100rad/s at time t=0.15s and at 50rad/s at t=0.3s. In fact, this behavior represents a clear improvement in dynamic response with a SOSMC-DTC, contrary to a drive with a standard PI-DTC.

Performance with each controller is also analyzed through these of Integral Squared Error (ISE), Integral Absolute Error (IAE) and Integral Time Squared Error (ITSE), and the results described in Appendix Table 3 confirm the improved performance with the SOSMC-DTC, algorithm.

### 5.2 Robustness Test for a Variation of the Load Torque

Fig. 6. shows the simulation result (speed, the torque and the currents ....) during a load torque setpoint variation of 10 N.m at time t = 0.15s with 20 Nm and at time t = 0.25 then 10 N.m at time t = 0.35s. In this case of simulation, we realize that the torque is perfectly following the setpoint value, the speed reaches its reference after a small deformation for the case of PI-DTC and with a negligible influence which is recovered quickly with its reference for the SOSMC-DTC which presents a high dynamic performance. Moreover, the tracking performances are improved by the use of the SOSMC-DTC control, in comparison with those of the PI–DTC controller.

The electromagnetic torque produced by the DSIM controlled by PI-DTC, SOSMC- DTC is presented in Fig. 6, it can be noticed that the ripple is not the same for the two techniques. A zoom of the electromagnetic torque for the two strategies is shown. It’s clear that the classical PI-DTC suffer from two problems: steady state error and high torque ripple.Howere, the SOSMC corrects the steady state error and reduces the torque ripple. The locus of the stator flux vector for the two controllers are depicted in Fig. 6. The two locuses present coincident responses, the locus of SOSMC-DTChave less ripple.

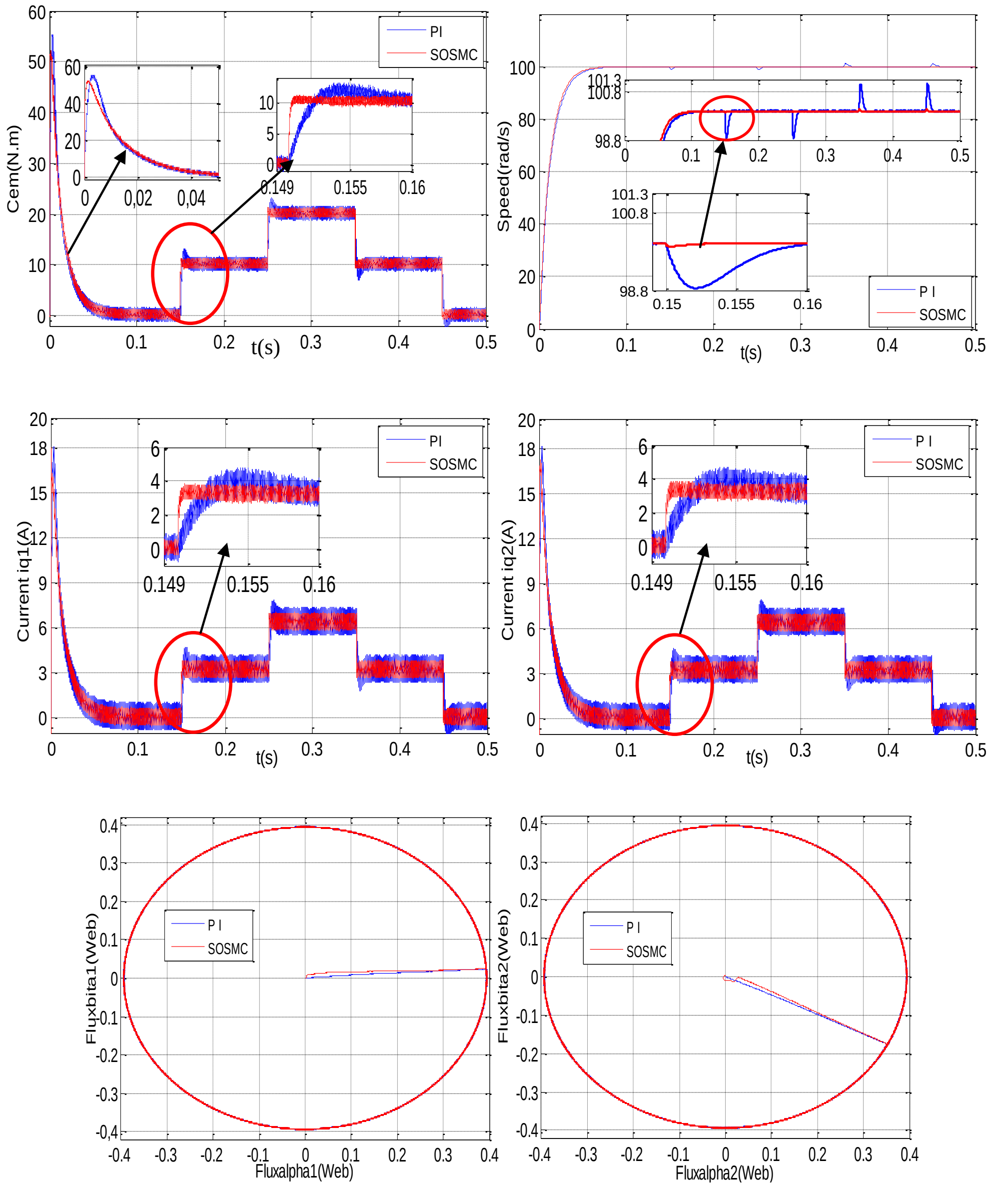


Fig. 6. Comparison of thespeed regulation in presence of load torque, PI- DTC and SOSMC-DTC.

## 6. Conclusion

In this paper, a comparative study between the conventional PI-DTC, SOSMC-DTC has been carried out for speed controller of DSPMSM. Simulation results reveal an improvement in the control performance of the torque including ripple, steady state error reduction and a satisfactory performance with the use of the SOSMC-DTC controller. Furthermore, the effectiveness of the proposed algorithms is evaluated and justified from performance indices IAE, ISE and ITSE. So this algorithm is suitable for applications requiring a high tracking accuracy when external disturbances occur.

## 7. Appendix

*Table 2*

**DSPMSM parameters**

| | |
|---|---|
| Nominal voltage | 220 V |
| Stator resistance $R_{s1}= R_{s2}$ | 0.12 Ω |
| Stator inductance $L_s$ | 0.8 mH |
| Mutual inductance $L_m$ | 0.3 mH |
| Flux linkage $\psi_{PM}$ | 0.394 Wb |
| Pole pairs P | 4 |
| Machine inertia J | $5\ 10^{-5}$[kg.m2] |
| Viscous friction coefficient $f_r$ | 0 $N.m.s^2$ / rad |

*Table 3*

**Comparison of performance index**

| Controllers | IAE | ISE | ITSE |
|---|---|---|---|
| PI-DTC | 0.056 | 0.1331 | $3.3310^{-3}$ |
| SOSMC-DTC | 0.0093 | 0.0125 | $5.37510^{-5}$ |

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