Sliding Mode Control Based DTC of Sensorless Parallel-Connected Two Five-Phase PMSM Drive System

Tounsi Kamel*, Djahbar Abdelkader*, Barkat Said**, M. Al-Hitmi*** and Atif Iqbal†

Abstract – This paper presents a sensorless direct torque control (DTC) combined with sliding mode approach (SM) and space vector modulation (SVM) to achieve mainly a high performance and reduce torque and flux ripples of a parallel-connected two five-phase permanent magnet synchronous machine (PMSM) drive system. In order to increase the proposed drive robustness and decrease its complexity and cost, the rotor speeds, rotor positions, fluxes as well as torques are estimated by using a sliding mode observer (SMO) scheme. The effectiveness of the proposed sliding mode observer in conjunction with the sliding mode control based DTC is confirmed through the application of different load torques for wide speed range operation. Comparison between sliding mode control and proportional integral (PI) control based DTC of the proposed two-motor drive is provided. The obtained speeds, torques and fluxes responses follow their references; even in low and reverse speed operations, load torques changes, and machines parameters variations. Simulation results confirm also that, the ripples of the torques and fluxes are reduced more than 3.33% and 16.66 %, respectively, and the speed overshots and speed drops are reduced about 99.85% and 92.24%, respectively.

Keywords: Five-phase permanent magnet synchronous machine; Direct torque control; Sliding mode control; Sliding mode observer

1. Introduction

Recently, the use of high power semiconductor devices has opened the door to new scopes in electrical drives. The five-phase PMSM may be one of the newest ideas in this field. This has led to an increasing interest in multiphase (greater than three phases) drives. Here and now, in some industrial applications such as high power ship propulsion, electric aircraft, electric traction, the use of this kind of drives is very suitable due to their tangible benefits over the conventional three-phase drives. Their advantages include reducing the amplitude of torque and current pulsations, increasing the frequency of torque pulsations, reducing the stator current per phase without increasing the stator voltage per phase, lowering the DC link current harmonics, higher reliability, and fault tolerance capability [1-3].

Different control algorithms of the PMSM were proposed in the literature [4-8]. Among all these control methods, the DTC is one of the effective control techniques adopted to control torque and flux linkage. The DTC is considered particularly interesting being less parameters dependency; making the system more robust, fast dynamic response, and a pretty simple control [9]. Furthermore, the DTC avoids the need to the internal current loops, coordinate transformations, and the modulator block; hence the delay caused by current regulator is eliminated. It directly selects voltage vectors according to the error between the reference and the estimated values of the torque and flux [10]. However, the main disadvantages of using hysteresis controllers are: difficulty to control flux and torque at low speed, unfixed switching frequency which changes with rotor speed and load torque [9], a high sampling frequency needed for digital implementation of hysteresis controllers, and high torque ripple responsible for noises and vibrations generation [11]. In order to handle the above-mentioned problems, several researchers have proposed many approaches to overcome the drawbacks of the basic DTC. A space vector modulation was implemented to replace the switching table and provide a constant inverter switching frequency [12-13]. The resulting DTC-SVM approach substitutes the hysteresis controllers by two PI controllers to generate the direct and quadrature voltage components in synchronous frame. This scheme reduces torque and flux ripples as stated in [14-15].

However, some factors such as neglected dynamics, parameter variations, friction forces, and load disturbances are the main disturbances and uncertainties that can affect the effective functioning of the drive system. So, it will be very difficult to limit these disturbances effectively if linear control methods like PI controllers are adopted [11, 16]. To overcome this problems, especially to enhance stability and robustness of the DTC scheme other advanced control; Sliding mode control; Sliding mode observer
methods have been proposed [4, 15, 17-18]. These approaches include among others the sliding mode control. The SMC is a nonlinear control method known to have robust control characteristics under restricted disturbance conditions or when there are limited internal parameter modeling errors as well as when there are some nonlinear behaviors [10, 11, 20-21]. The robustness of the SMC is guaranteed usually by using a switching control law. Unfortunately, this switching strategy often leads to a chattering phenomenon. In order to mitigate the chattering phenomenon, a common method is to use the smooth function instead of the switching function [16, 22-23].

The parallel/series-connected multi-machine systems fed by a single supply become strongly suggested due to the following benefits: low cost drive, compactness, and lightness [24-25]. In the series-connected system, both beginnings and ending of each phase should be brought out to the terminal box of each multiphase machine, these results in system complexity and poor efficiency due to higher losses. As a suitable alternative, the parallel connection of multiphase machines has been suggested in [26]. In multiphase machine there are more than direct and quadrature current components. Actually, to control the torque and flux of any multiphase only direct and quadrature current components are used, the remaining components can be used to control the others machines which are fed by a single multi-leg inverter [27].

It is well established that the PMSM can be efficiently controlled only if the position of the rotor is accurately known. Generally, the rotor position is obtained using some sensors types such as an optical encoder or resolver connected to the rotor shaft [24, 28]. However, the use of these sensors will increase the cost and reduce the reliability of the drive, and may suffer from some restrictions such as temperature, humidity, and vibration. These problems can be solved by using the well-known sensorless control technology. Various methods of sensorless control have been proposed by several researchers [29-31]. These estimation techniques are based mainly on the measurement of the machine currents and voltages. However, few applications deal with sensorless control of multiphase machines such as, model reference system [32], Kalman filtering technique [33] and sliding mode observer of five-phase PMSM [34,35]. Unlike the other approaches, the SMO is more attractive due to its robustness against the system parameters variations, disturbances, and noises [36]. This type of observer is based on the system model and the use of a high frequency switch to force the estimated variables trajectories to remain on the sliding surface. A low pass filter is used to reduce the chattering caused by sign function. However, the adding of this filter generates phase delay. Thus, the resulting SMO cannot improve the control in high performance applications [37]. Indeed, there were several researches that proposed another SMO as alternative to remove low-pass filter and phase delay in [34, 36].

In conventional sensorless DTC scheme, one possible solution is to combine a current observer and flux estimator [8, 12, 29] to perform the sensorless task, which increases the system complexity and reduce the accuracy of the estimation. To solve this problem, a SMO is proposed in this paper to improve the sensorless control of each five-phase PMSM by using its flux model in the stationary reference frame. Similar to the SMC, in the SMO algorithm the conventional switch function is replaced also by a smooth function to reduce the chattering phenomenon.

Most of the previous works on parallel connected multiphase was done on induction motor drive systems using indirect vector control based on PI controllers to control each motor independently [24, 26]. However, the uncertainties and parameters disturbances can strongly influence the decoupling between the two motor [4]. In addition, all of these research works used sensors to measure the rotors positions, which increase the cost and the complexity of the system.

The purpose of this paper is to study a sensorless DTC sliding mode control scheme (DTC-SMC) equipped with a sliding mode observer for parallel connected two five-phase PMSMs fed by a single five-leg inverter. To obtain the desired characteristics, the SMC is implemented for speeds, fluxes and electromagnetic torques control and the SMO is used for sensorless operation purposes. The developed control scheme combines the features of the robust control and the robust estimation to enhance the performances of the proposed two-machine drive. So, the proposed nonlinear sensorless DTC-SMC based on SMO is attended to minimize the torque and stator flux ripples which are the main disadvantage of the classical DTC.

The performance of the estimation and control scheme is tested with challenging variations of the load torque and speed reference. The obtained results prove that the two machines are totally decoupled under large speeds and loads variations, although they are connected in parallel and supplied by a single inverter. In addition to that, a comparison between SMC, the traditional PI based DTC, and conventional DTC for sensorless operation is also provided.

### 2. Drive System Description and Modeling

The two-machine drive system under consideration is shown in Fig. 1. It consists of a five-leg inverter feeding two five-phase PMSMs. It can be seen from Fig. 1 that the phase transposition rules of parallel-connected two five-phase PMSMs system are as follows: $a_{1}-a_{2}$, $b_{1}-c_{2}$, $c_{3}-e_{5}$, $b_{5}-b_{3}$, $e_{1}-d_{3}$ [24]; where indices 1 and 2 identify the two machines as indicated in Fig. 1. According to this, the relationships between voltages and currents are given as:

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**References:**

[4, 15, 17-18] [10, 11, 20-21] [24-25] [26] [32] [33] [34,35] [36] [29-31] [8, 12, 29] [37]
\[
\begin{align*}
    v_{\text{abdec}} &= \begin{bmatrix} v_{\text{inv}}^a \\ v_{\text{inv}}^b \\ v_{\text{inv}}^c \\ v_{\text{inv}}^d \\ v_{\text{inv}}^e \end{bmatrix} = \begin{bmatrix} v_{\text{ax1}} \\ v_{\text{bx1}} \\ v_{\text{cx1}} \\ v_{\text{dx1}} \\ v_{\text{ex1}} \end{bmatrix} ; \quad i_{\text{abdec}} &= \begin{bmatrix} i_{\text{inv}}^a \\ i_{\text{inv}}^b \\ i_{\text{inv}}^c \\ i_{\text{inv}}^d \\ i_{\text{inv}}^e \end{bmatrix} = \begin{bmatrix} i_{\text{ax1}} + i_{\text{ax2}} \\ i_{\text{bx1}} + i_{\text{bx2}} \\ i_{\text{cx1}} + i_{\text{cx2}} \\ i_{\text{dx1}} + i_{\text{dx2}} \\ i_{\text{ex1}} + i_{\text{ex2}} \end{bmatrix}
\end{align*}
\]

(1)

where \( v_{\text{inv}}^a, v_{\text{inv}}^b, v_{\text{inv}}^c, v_{\text{inv}}^d, v_{\text{inv}}^e \) and \( i_{\text{inv}}^a, i_{\text{inv}}^b, i_{\text{inv}}^c, i_{\text{inv}}^d, i_{\text{inv}}^e \) are the inverter voltages and currents, \( v_{\text{ax1},2,3}, v_{\text{bx1,2,3}}, v_{\text{cx1,2,3}}, v_{\text{dx1,2,3}}, v_{\text{ex1,2,3}} \) and \( i_{\text{ax1,2,3}}, i_{\text{bx1,2,3}}, i_{\text{cx1,2,3}}, i_{\text{dx1,2,3}}, i_{\text{ex1,2,3}} \) are the voltages and currents of the two machines.

The main five dimensional systems can be decomposed into five dimensional uncoupled subsystems (\( \alpha, \beta, x, y, \theta \)). The correlation between the original phase variables and the new (\( \alpha, \beta, x, y, \theta \)) variables is given by 

\[
    f_{\alpha,\beta,\gamma,\delta,\epsilon} = f_{\alpha,\beta,\gamma,\delta,\epsilon}
\]

where \( f_{\alpha,\beta,\gamma,\delta,\epsilon} \) is the following transformation matrix [24]:

\[
    [C] = \frac{2}{5} \begin{bmatrix} 1 & \cos(2\pi/5) & \cos(4\pi/5) & \cos(6\pi/5) & \cos(8\pi/5) \\ 0 & \sin(2\pi/5) & \sin(4\pi/5) & \sin(6\pi/5) & \sin(8\pi/5) \\ 1 & \cos(2\pi/5) & \cos(4\pi/5) & \cos(6\pi/5) & \cos(8\pi/5) \\ 0 & \sin(2\pi/5) & \sin(4\pi/5) & \sin(6\pi/5) & \sin(8\pi/5) \\ 1/2 & 1/2 & 1/2 & 1/2 & 1/2 \end{bmatrix}
\]

By applying the transformation matrix (2) on equation (1), the voltage and current components of the five-phase inverter become:

\[
    \begin{align*}
    v_{\text{ax1}} &= v_{\text{sv1}} \\
    v_{\text{bx1}} &= v_{\text{sv2}} \\
    v_{\text{cx1}} &= v_{\text{sv3}} \\
    v_{\text{dx1}} &= v_{\text{sv4}} \\
    v_{\text{ex1}} &= v_{\text{sv5}} \\
    i_{\text{ax1}} + i_{\text{ax2}} &= i_{\text{sx1}} + i_{\text{sx2}} \\
    i_{\text{bx1}} + i_{\text{bx2}} &= i_{\text{sx1}} + i_{\text{sx2}} \\
    i_{\text{cx1}} + i_{\text{cx2}} &= i_{\text{sx1}} + i_{\text{sx2}} \\
    i_{\text{dx1}} + i_{\text{dx2}} &= i_{\text{sx1}} + i_{\text{sx2}} \\
    i_{\text{ex1}} + i_{\text{ex2}} &= i_{\text{sx1}} + i_{\text{sx2}} \\
    0 &= 0
    \end{align*}
\]

(3)

where \( L_x, L_y \) are the inductances in the rotating frame and \( r_1, r_2 \) is the stator resistance; \( \Phi_\beta \) is the magnetic flux; \( \omega_1, \omega_2 \) and \( \theta \) are electrical speed and rotor position, respectively.

Where \( v_{\text{inv}}^a, v_{\text{inv}}^b, v_{\text{inv}}^c, v_{\text{inv}}^d, v_{\text{inv}}^e \) and \( i_{\text{inv}}^a, i_{\text{inv}}^b, i_{\text{inv}}^c, i_{\text{inv}}^d, i_{\text{inv}}^e \) are the inverter voltages and currents in the \( \alpha, \beta, x, y, \theta \) axes, respectively. \( v_{\text{ax1},2,3}, v_{\text{bx1,2,3}}, v_{\text{cx1,2,3}}, v_{\text{dx1,2,3}}, v_{\text{ex1,2,3}} \) and \( i_{\text{ax1,2,3}}, i_{\text{bx1,2,3}}, i_{\text{cx1,2,3}}, i_{\text{dx1,2,3}}, i_{\text{ex1,2,3}} \) are the stator voltages and currents in the \( \alpha, \beta, x, y, \theta \) axes, respectively.

The model of each five-phase PMSM (\( j=1,2 \)) is presented in a rotating \( \alpha, \beta -x, y \) frame, and is given as:

\[
\begin{align*}
    \frac{dl_{\text{axj}}}{dt} &= (-r_1 i_{\text{axj}} + \omega_1 \Phi_{\text{axj}} \sin(\theta) + v_{\text{axj}}) / L_{\text{axj}} \\
    \frac{dl_{\text{bxj}}}{dt} &= (-r_1 i_{\text{bxj}} - \omega_1 \Phi_{\text{bxj}} \cos(\theta) + v_{\text{bxj}}) / L_{\text{bxj}} \\
    \frac{dl_{\text{sxj}}}{dt} &= (-s_1 i_{\text{sxj}} + v_{\text{sxj}}) / L_{\text{sxj}} \\
    \frac{dl_{\text{syj}}}{dt} &= (-s_1 i_{\text{syj}} + v_{\text{syj}}) / L_{\text{syj}} \\
    \frac{dl_{\text{syj}}}{dt} &= (-s_1 i_{\text{syj}} + v_{\text{syj}}) / L_{\text{syj}}
\end{align*}
\]

(4)

The stator flux linkage components of each machine are given by:

\[
\begin{align*}
    \frac{d\Phi_{\text{axj}}}{dt} &= -r_1 i_{\text{axj}} + v_{\text{axj}} \\
    \frac{d\Phi_{\text{bxj}}}{dt} &= -r_1 i_{\text{bxj}} + v_{\text{bxj}} \\
    \frac{d\Phi_{\text{sxj}}}{dt} &= -s_1 i_{\text{sxj}} + v_{\text{sxj}} \\
    \frac{d\Phi_{\text{syj}}}{dt} &= -s_1 i_{\text{syj}} + v_{\text{syj}}
\end{align*}
\]

(5)

where \( \Phi_{\text{axj}}, \Phi_{\text{bxj}}, \Phi_{\text{sxj}}, \Phi_{\text{syj}} \) are the flux linkage in the \( \alpha, \beta, x, y \) frame.

The torques equations for the first and the second machines are given by:

\[
\begin{align*}
    T_{\text{em1}} &= \frac{5}{2} \left( \Phi_{\text{ax1}} i_{\text{ax1}} - \Phi_{\text{bx1}} i_{\text{bx1}} \right) \\
    T_{\text{em2}} &= \frac{5}{2} \left( \Phi_{\text{sx1}} i_{\text{sx1}} - \Phi_{\text{sy1}} i_{\text{sy1}} \right)
\end{align*}
\]

(6)

where \( p_1, p_2 \) are the pole pairs.

The proposed sensorless DTC-SMC of the parallel-connected two five-phase permanent magnet synchronous machines is presented in Fig. 2, where the two main parts SMC and SMO are considered. The SMO has been proved being strong robust and accurate with a fast convergence and having a good estimation performance over full speed range [34, 37]. The SMO is designed to estimate the rotor position, speed, torque and flux of each machine by using voltages and currents measurements. The actual speed, estimated speed and load torques are the inputs of the
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3. Sliding Mode Control

The design of a sliding mode controller requires mainly two stages. The first stage is choosing an appropriate sliding surface. The second stage is designing a control law, which will drive the state variables to the sliding surface and will keep them there.

3.1 Sliding surfaces choice

In order to prescribe the desired dynamic characteristics of the controlled system, the following general form of sliding surface can be adopted [38].

\[ S(x) = \left( \frac{d}{dt} + \lambda \right)^{-1} e(x) \]  

with \( e(x) = x_{ref} - x \), \( \lambda \) is a positive coefficient, and \( r \) is the relative degree, which is the number of times required to differentiate the surface before the input appears explicitly.

3.2 Controller design

In order to drive the state variables to the sliding surface, the following control law is adopted:

\[ u = u_{equiv} + u_{dic} \]  

The equivalent control \( u_{equiv} \) is capable to keep the state variables on the switching surface, once they reach it, and to achieve the desired performance under nominal model. It is derived as the solution of the following equation:

\[ S(x) = \dot{S}(x) = 0 \]
The discontinuous control $u_{dic}$ is needed to assure the convergence of the system states to sliding surfaces in finite time, and it should be designed to eliminate the effect of any unpredictable perturbation. The discontinuous control input can be determined with the help of the following Lyapunov function candidate:

$$V = \frac{1}{2} S(x)^2 \quad (10)$$

The control stability is ensured under the following two conditions:
- The Lyapunov function $V$ is positive definite.
- The derivative of the Lyapunov function should be negative $\dot{V} = S^T \dot{S}(x) < 0 \quad (\forall S)$. The so-called reaching stability condition $V = S \dot{S} < 0$ is fulfilled using the following discontinuous control:

$$u_{dic} = k \text{sign}(S(x)) \quad (11)$$

where $k$ is a control gain.

In order to reduce the chattering phenomenon, a saturation function instead of the switching one can be used. The saturation function is expressed as follows:

$$sat(S(x)) = \begin{cases} 
\text{sgn}(S(x)) & \text{if } |S(x)| > \delta \\
\frac{S(x)}{\delta} & \text{if } |S(x)| < \delta 
\end{cases} \quad (12)$$

with $\delta$ is the boundary layer width.

4. Sliding Mode Control of the Five-Phase Two-Machine Drive

4.1 Speed SMC design

The sliding mode speed controller for each five-phase PMSM is designed by selecting the suitable sliding surfaces $S(\Omega_j)$, Since the relative degree is one, the following sliding surfaces are adopted:

$$S(\Omega_j) = \Omega_{refj} - \Omega_j, \quad j = 1, 2 \quad (13)$$

By taking the derivative of the sliding surfaces given by (13) with respect to time and using the machines motion equations, it yields:

$$\dot{S}(\Omega_1) = \Omega_{ref1} - \Omega_1 = \frac{5p_1\Phi_{f1}^2 i_{q1}}{2J_1} + \frac{T_{l1}}{J_1} + \frac{f_1\Omega_1}{J_1} \quad (14)$$

$$\dot{S}(\Omega_2) = \Omega_{ref2} - \Omega_2 = \frac{5p_2\Phi_{f2}^2 i_{q2}}{2J_2} + \frac{T_{l2}}{J_2} + \frac{f_2\Omega_2}{J_2}$$

where $J_j$, $f_j$ and $T_j$ are the moment of inertia, damping coefficient, and load torque of each machine, respectively. The currents controls $i_{q1}$ and $i_{y2}$ are defined by:

$$i_{q1} = i_{qseqc1} + i_{ydic1} \quad (15)$$

$$i_{y2} = i_{yseqc2} + i_{ydic2}$$

where:

$$i_{qseqc1} = -\frac{J_1\Omega_{ref1} + T_{l1} + f_1\Omega_1}{5p_1\Phi_{f1}}, \quad \text{and} \quad i_{ydic1} = k_{\Omega_1} sat(S(\Omega_1))$$

$$i_{yseqc2} = -\frac{J_2\Omega_{ref2} + T_{l2} + f_2\Omega_2}{5p_2\Phi_{f2}}, \quad \text{and} \quad i_{ydic2} = k_{\Omega_2} sat(S(\Omega_2))$$

$k_{\Omega_1}$ and $k_{\Omega_2}$ are positive constants.

The reference torques are computed as:

$$T_{emref1} = \frac{5p_1}{2} \Phi_{f1} i_{q1} \quad (16)$$

$$T_{emref2} = \frac{5p_2}{2} \Phi_{f2} i_{y2}$$

4.2 Stability analysis

During the convergence mode, the condition $\dot{V}(x) = S^T \dot{S}(x) < 0 \quad (\forall S(x))$ must be verified. Indeed, by replacing (15) into (14), one gets:

$$\dot{V}(\Omega_1) = -S^T \frac{5p_1\Phi_{f1}}{2J_1} k_{\Omega_1} sat(\Omega_1) < 0 \quad (17)$$

$$\dot{V}(\Omega_2) = -S^T \frac{5p_2\Phi_{f2}}{2J_2} k_{\Omega_2} sat(\Omega_2) < 0$$

From (17) the derivatives are negative, which means that the stability condition is ensured.

4.3 Torques and fluxes SMCs design

The DTC-SMC is designed to generate the stator voltage command from the torque and flux errors to track the electromagnetic torque and flux by controlling the input voltage of the motor.

The electromagnetic torque and stator flux linkage squared are given by:

$$T_{em} = \frac{5p}{2}(\Phi_{asj} i_{yj} - \Phi_{ysj} i_{qsj}) \quad (18)$$

$$\Phi_{ysj}^2 = \Phi_{asj}^2 + \Phi_{ysj}^2$$

The control objectives are to track the desired torques and fluxes trajectories. So, the sliding surfaces can be
calculated as follows:

\[
S = \begin{bmatrix} T_{emj}^* - T_{emj} \\ \Phi_{sj}^* + \Phi_{sj}^2 \end{bmatrix} = \begin{bmatrix} S(T_{emj}) \\ S(\Phi_{sj}) \end{bmatrix}
\]  

(19)

Using (4) and (5), the time derivative of (19) can be rewritten as:

\[
\begin{bmatrix} \dot{S}(T_{emj}) \\ \dot{S}(\Phi_{sj}) \end{bmatrix} = \begin{bmatrix} -5p_j (r_j'_{hss} - \sigma_j \Phi_{yj} \sin(\theta_j))\Phi_{hls} -5p_j (r_j'_{hss} + \sigma_j \Phi_{yj} \cos(\theta_j))\Phi_{hls} \\ -2r_j'_{hss}\Phi_{hls} -2r_j'_{hss}\Phi_{hls} -5p_j (r_j'_{hss} - \sigma_j \Phi_{yj} \sin(\theta_j))\Phi_{hls} -5p_j (r_j'_{hss} + \sigma_j \Phi_{yj} \cos(\theta_j))\Phi_{hls} \\ -2\Phi_{hls} -2\Phi_{hls} \end{bmatrix}
\]

(20)

with \(h_1=\alpha, x \) and \(h_2=\beta, y\).

So, the equation (20) can be expressed in the following matrix form:

\[
\dot{S} = F + DU
\]

(21)

with:

\[
\begin{aligned}
\dot{S} &= \begin{bmatrix} \dot{S}(T_{emj}) \\ \dot{S}(\Phi_{sj}) \end{bmatrix} \\
F &= \begin{bmatrix} -5p_j (r_j'_{hss} - \sigma_j \Phi_{yj} \sin(\theta_j))\Phi_{hls} -5p_j (r_j'_{hss} + \sigma_j \Phi_{yj} \cos(\theta_j))\Phi_{hls} \\ -2r_j'_{hss}\Phi_{hls} -2r_j'_{hss}\Phi_{hls} -5p_j (r_j'_{hss} - \sigma_j \Phi_{yj} \sin(\theta_j))\Phi_{hls} -5p_j (r_j'_{hss} + \sigma_j \Phi_{yj} \cos(\theta_j))\Phi_{hls} \\ -2\Phi_{hls} -2\Phi_{hls} \end{bmatrix} \\
D &= \begin{bmatrix} v_{hls} \\ v_{hls} \end{bmatrix} \\
U &= \begin{bmatrix} v_{hls} \\ v_{hls} \end{bmatrix}
\end{aligned}
\]

So, it is possible to choose the control laws for stator voltages as follows:

\[
v_{hls} = v_{hls}\text{seqc} + v_{hls}\text{adic} \\
v_{hls} = v_{hls}\text{seqc} + v_{hls}\text{adic}
\]

(22)

where

\[
\begin{bmatrix} v_{hls}\text{seqc} \\ v_{hls}\text{adic} \end{bmatrix} = -D^{-1} \begin{bmatrix} F_1 \\ F_2 \end{bmatrix}
\]

\[
\begin{bmatrix} v_{hls}\text{adic} \\ v_{hls}\text{adic} \end{bmatrix} = -D^{-1} \begin{bmatrix} k_{T_{emj}} \text{sat}(T_{emj}) \\ k_{\Phi_{sj}} \text{sat}(\Phi_{sj}) \end{bmatrix}
\]

with \(k_{T_{emj}}, k_{\Phi_{sj}}\) are positive gains.

### 4.4 Stability analysis

During the convergence mode, the condition \(\dot{V}(x) = S^T(x)\dot{S}(x) < 0 \ (\forall S(x))\) must be verified. Indeed, by replacing (22) into (21), one gets:

\[
\dot{V}(S) = -S^T \begin{bmatrix} k_{T_{emj}} \text{sat}(T_{emj}) \\ k_{\Phi_{sj}} \text{sat}(\Phi_{sj}) \end{bmatrix} < 0
\]

(23)

From (23) it is obvious that the system is globally stable, \(S\) and \(\dot{S}\) will be forced to zero in a definite period, which also means that the torque and flux of the five-phase PMSM will follow their reference values.

### 5. SVM Technique Based DTC-SMC

Hysteresis controllers used in the conventional DTC generate a variable switching frequency, causing electromagnetic torque ripples [2, 15]. In order to overcome this problem, the adopted solution consists in replacing the hysteresis controllers and the switching table by two SMC controllers and a space vector modulator.

The five-phase inverter has totally thirty-two space voltage vectors, thirty non-zero voltage vectors and two zero voltage vectors. Each voltage vector can be mapped by (24) onto the \(\alpha-\beta\) subspace and \(x-y\) subspace as shown in Fig. 3.
Fig. 3 [27]:

\[
\begin{align*}
\dot{v}_{x_{sj}}^{inv} &= \frac{2}{5} (v_{a_{sj}}^{inv} + v_{b_{sj}}^{inv} e^{j\alpha} + v_{c_{sj}}^{inv} e^{j2\alpha} + v_{d_{sj}}^{inv} e^{j3\alpha} + v_{e_{sj}}^{inv} e^{j4\alpha}), \\
\dot{v}_{y_{sj}}^{inv} &= \frac{2}{5} (v_{a_{sj}}^{inv} + v_{b_{sj}}^{inv} e^{j2\alpha} + v_{c_{sj}}^{inv} e^{j4\alpha} + v_{d_{sj}}^{inv} e^{j6\alpha} + v_{e_{sj}}^{inv} e^{j8\alpha})
\end{align*}
\]  

(24)

where \( \alpha = 2\pi/5 \).

From Fig. 3 the space vectors are divided into three groups in accordance with their magnitudes: small, medium and large space vector groups. The magnitudes are identified with indices s, m, and l, and are given as: \( |V_s| = 4/5 \cos(2\pi/5) v_{dc} \), \( |V_m| = 2/5 v_{dc} \), and \( |V_l| = 4/5 \cos(\pi/5) v_{dc} \), respectively [27, 39]. It can be observed from Fig. 3 that medium length space vectors of the \( \alpha-\beta \) plane are mapped into medium length vectors in the \( x-y \) plane, and large vectors of the \( \alpha-\beta \) plane are mapped into small vectors in the \( x-y \) plane, and vice-versa.

The reference voltage can be obtained by averaging a certain number of active space vectors for adequate time intervals, without saturating the VSI. Four active space vectors are required to reconstruct the reference voltage vector [27, 40].

6. Sliding Mode Observer Based Speed Estimator for Parallel-Connected Two-Motor Drive

Normally, speed observers used for three-phase machines can be easily extended to multi-phase multi-machine drives. For each machine the speed estimator requires only stator voltages and currents components. In the five-phase PMSM control case, \( x, y \) currents and voltages are measured.

In this section, a sliding mode observer based on flux model is presented to estimate directly the flux and speed as well as the electromagnetic torque by using stator voltages and currents as inputs. Using the flux model of the five-phase PMSM and based on the sliding-mode variable structure theory, the proposed sliding mode observer for each five-phase PMSM is designed as:

\[
\begin{align*}
\frac{d\Phi_{x_{sj}}}{dt} &= v_{x_{sj}} - (r_{y_{sj}} / L_{y_{sj}}) \Phi_{x_{sj}} + r_{y_{sj}} \Phi_{y_{sj}} \cos(\hat{\theta}_{y_{sj}}) + k_{sat}(\Phi_{y_{sj}}) \\
\frac{d\Phi_{y_{sj}}}{dt} &= v_{y_{sj}} - (r_{y_{sj}} / L_{y_{sj}}) \Phi_{y_{sj}} - r_{y_{sj}} \Phi_{x_{sj}} \sin(\hat{\theta}_{x_{sj}}) + k_{sat}(\Phi_{x_{sj}}) \\
\frac{d\Phi_{x_{sj}}}{dt} &= v_{x_{sj}} - (r_{y_{sj}} / L_{y_{sj}}) \Phi_{x_{sj}} + k_{sat}(\Phi_{x_{sj}}) \\
\frac{d\Phi_{y_{sj}}}{dt} &= v_{y_{sj}} - (r_{y_{sj}} / L_{y_{sj}}) \Phi_{y_{sj}} + k_{sat}(\Phi_{y_{sj}}) \\
\frac{d\hat{\theta}_{j}}{dt} &= \frac{5}{2} p_{j} (\Phi_{y_{sj}}) \Phi_{x_{sj}} \cos(\hat{\theta}_{y_{sj}}) - \Phi_{x_{sj}} \sin(\hat{\theta}_{y_{sj}})
\end{align*}
\]

(27)

with \( \hat{\Omega}_j = \Omega_j - \hat{\Omega}_j \) and \( \hat{\theta}_{j} = \theta_{j} - \hat{\theta}_{j} \).

In order to demonstrate the stability of the proposed sliding mode observer, the following Lyapunov function candidate is adopted:

\[
V = \frac{1}{2} (\Phi_{x_{sj}}^2 + \Phi_{y_{sj}}^2 + \Phi_{x_{sj}}^2 + \Phi_{y_{sj}}^2 + \Phi_{x_{sj}}^2 + \Phi_{y_{sj}}^2)
\]

(28)

Its time derivative is:
The load starting up, load torque application, speed direction reversing, low-speed operation and robustness test. In every test, speeds, estimation errors, torques, stator fluxes and their circular trajectories will be presented.

Case 1: Two motors operating in the same direction

Fig. 4 shows the operation of the two-machine drive system for many different speeds references with no load at starting up phase. At steady state condition, the two machines are loaded simultaneously or not by their nominal loads. At the beginning, the first machine is running at 60 rad/s; at t=0.25 s, it is accelerated to 100 rad/s, after that, its direction of rotation is reversed to -80 rad/s at t=0.5 s and then to -40 at t=0.75 s. For the second machine the speed reference is set at 40 rad/s, 80 rad/s, -100 rad/s, and -60 rad/s at t=0 s, 0.25 s, 0.5 s, 0.75 s, respectively. From Figs. 4(a), it can be seen that using DTC-SMC approach the two machines reach their speed references rapidly at starting phase without overshoots compared to the DTC-PI and conventional DTC approach. The load variations have not any tangible effects on the speeds responses, contrary to DTC-PI and conventional DTC where drops and rises are observed during the same variations instants. Furthermore, faster dynamic and better reference tracking during the speed reversing operation are observed when the proposed DTC-SMC is used.

The estimations errors are illustrated in Figs. 4(b). From these figures, the speed estimation errors converge toward zero in steady state, which means that the SMO shows good speed estimation, and the load does not have a significant effect on the tracking performance. Indeed, the maximum speeds estimation errors in DTC-SMC scheme are less than 0.08% (Fig. 4(b) (DTC-SMC)), but for the DTC-PI and conventional DTC schemes, they are less than 0.11%, Fig. 4(b) (DTC-PI) with noticeable ripples in case of conventional DTC.

The electromagnetic torques, generated by the two machines during the simulated speed step response, are shown in Figs. 4(c). Compared to DTC-PI and conventional DTC controllers, the proposed DTC-SMC controller shows a significant improvement in torque response time as well as in the overshoots and undershoots magnitudes. It can also be seen that DTC-SMC has a better dynamic and faster torque response during the startup and direction reversing states. In addition, it can be seen that the torque ripple in conventional DTC is greater than DTC-PI and DTC-CMC.

Figs. 4(d) show the stator flux magnitudes using the proposed DTC-SMC, DTC-PI, and conventional DTC approach. In case of DTC-SMC controller, it can be observed that the stator flux ripples in steady state are less than those obtained by DTC-PI and conventional DTC.

Figs. 4(e) describe the stator flux trajectories in $ab$ and $xy$ plane. The $ab$ trajectories are almost circular but the $xy$ trajectories are closed to zero. In these figures, it can be
seen again that DTC-SMC controller offers the better and fast response without overshoot and less ripple compared to the DTC-PI and conventional DTC.

Case 2: Two motors operating in the opposite directions

The effect of the speed rotation reversion of one machine on the other machine performance is investigated in Fig. 5. In the stating phase, the first machine is rotating at +100 rad/s; the other is running at the opposite speed. After that

Ω₁ is kept at standstill, while Ω₂ is reversed from -100 to +100 rad/s at t=0.4 s, and it is returned to zero at t=0.6 s. At the subsequent test, the speed Ω₂ is held at zero, while Ω₁ is set at -100 rad/s at 0.7s.

Compared with DTC-PI and conventional DTC, the DTC-SMC shows again no overshoots and no significant influence of the load application. Furthermore the results

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illustrated in Fig. 5 show once more that the control of the two machines is completely decoupled. Indeed, the speed of one machine and its electromagnetic torque remain completely undisturbed during the reversion of the other machine, indicating a complete decoupling of the control. So, there is hardly any evidence of torque disturbance of one machine during the reversal of the other one. As shown from Figs. 5(a), the starting and reversing transients of one machine do not have any tangible consequence on the operation of the second machine. The decoupled control is
preserved and the characteristics of both machines are unaffected.

**Case 3: Operation at different loading conditions**

Fig. 6 shows the performance of the two-machine drive controlled by DTC-SMC, DTC-PI, and conventional DTC controllers under load torques variations condition. The reference of the first speed is set at 100 rad/s, while the speed reference of the second machine is set at 50 rad/s. A set of load torques from 5 Nm to 2.5 Nm are applied on the two machines shafts in different times. It is clear from Fig. 6 that when one machine is either loaded or unloaded, the
second machine performance is unaffected; which proves once again that both motors connected in parallel are totally decoupled. In case of sliding mode control, no variation whatsoever can be observed in the speeds responses of the both machines during these transients. It is worth noticing that there is no impact on the speed and electromagnetic torque of one machine when the speed or the load of the other machine in parallel-connected system changes. Thus, through proper phase transformation rules, the decoupled control of two five-phase PMSMs connected
in parallel can be achieved with a single supply from a five-phase voltage source inverter. Furthermore, measured and estimated speeds are in excellent agreement in both steady state and transient operations.

Case 4: Low speed operation

Fig. 7 shows the performance of the sensorless feedback control under low speed condition. The speed reference of the first machine is set to 7 rad/s, -3 rad/s, 4

![Graphs showing speed, speeds error, electromagnetic torques, stator fluxes magnitudes, and stator fluxes trajectories for different control methods: DTC-SMC, DTC-PI, and conventional DTC-switching up-table.](http://www.jeet.or.kr)
Table 3. Comparison between SMC and PI based DTC

<table>
<thead>
<tr>
<th>Controlled variable</th>
<th>Comparison criterion</th>
<th>DTC-SMC</th>
<th>DTC-PI</th>
<th>Conventional DTC</th>
<th>Reduction rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor speed</td>
<td>Settling time (s)</td>
<td>0.01</td>
<td>0.09</td>
<td>0.09</td>
<td>88.88</td>
</tr>
<tr>
<td></td>
<td>Overshoot (rad/s)</td>
<td>0.02</td>
<td>13.63</td>
<td>13.63</td>
<td>99.85</td>
</tr>
<tr>
<td></td>
<td>Speeds drops (%)</td>
<td>0.9</td>
<td>11.6</td>
<td>11.6</td>
<td>92.24</td>
</tr>
<tr>
<td></td>
<td>Recovery time (at abrupt load) (s)</td>
<td>0.01</td>
<td>0.08</td>
<td>0.08</td>
<td>87.5</td>
</tr>
<tr>
<td></td>
<td>Overshoot in reversal mode (%)</td>
<td>0</td>
<td>48</td>
<td>61</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>The maximum speed estimation error (%)</td>
<td>0.04</td>
<td>0.1</td>
<td>0.09</td>
<td>60</td>
</tr>
<tr>
<td>Electromagnetic torque</td>
<td>Settling time (s)</td>
<td>0.009</td>
<td>0.07</td>
<td>0.07</td>
<td>87.71</td>
</tr>
<tr>
<td></td>
<td>Overshoot (rad/s)</td>
<td>2.5</td>
<td>1.6</td>
<td>10.9</td>
<td>36 (increase)</td>
</tr>
<tr>
<td></td>
<td>Ripple (N.m)</td>
<td>1.16</td>
<td>1.2</td>
<td>3.5</td>
<td>3.33</td>
</tr>
<tr>
<td>Stator flux</td>
<td>Settling time (s)</td>
<td>0.002</td>
<td>0.0046</td>
<td>0.004</td>
<td>56.32</td>
</tr>
<tr>
<td></td>
<td>Overshoot (rad/s)</td>
<td>0</td>
<td>0.034</td>
<td>0</td>
<td>100</td>
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<tr>
<td></td>
<td>Overshoot in reversal mode (%)</td>
<td>0</td>
<td>0.016</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>Ripple (N.m)</td>
<td>0.007</td>
<td>0.0084</td>
<td>0.28</td>
<td>16.66</td>
</tr>
</tbody>
</table>

rad/s and -5 rad/s at t=0 s, 0.3 s, 0.55 s, 0.8 s, respectively. For the second machine, the speed reference is set to 5 rad/s, -4 rad/s, 5 rad/s, and -7 rad/s at the same times as previous one. A torque of 5 Nm was applied on the shafts of the first and second machines at the instants t = 0.1 s and 0.2 s, respectively. In case of the DTC-PI and conventional DTC controls, the application of the load torque causes a noticeable speed drop up to -5 rad/s. The speed controller compensates this drop after a necessary recovery time, and it is clear that the conventional DTC suffers during low speed operation. However, with the DTC-SMC control, this influence is reduced and better reference tracking during the speed reversing are observed. Furthermore, it can be seen that in case of DTC-SMC control the estimation using the SMO is more robust during low speed operations.

Case 5: Parameters variations

In this test, the influence of the variation of the stator resistance on the decoupling between the flux and the torque and the speed regulation performance is studied. For that end, the resistance of the first machine is increased by +100% at t=0.2 s, whereas the resistance of the second machine is increased by the same rate at 0.3 s.

Fig. 8 shows the responses of the five-phase machines under a sudden change in load torque from 0 Nm to 5 Nm at t = 0.2 s and 0.3 s, respectively. In this test, the reference speed is step changed from 100 rad/s to -90 rad/s at t=0.5 s for the first machine and from 70 rad/s to -100 rad/s at t=0.6 s for the second one. From this figure, this parameter variation has no influence on the decoupling between the flux and the torque, but its influence on the decoupling between the two machines and the estimation errors is not so considerable and has been recovered quickly thanks to the robustness of the SMO.

A general comparison between DTC-SMC, DTC-PI and conventional DTC is given in Table 3. Compared to the DTC-PI and conventional DTC controllers, the DTC-SMC shows superiority in terms of settling time and overshoot magnitude.

8. Conclusion

In this paper, a sliding mode control and sliding mode observer are combined to enhance the direct torque control of a parallel-connected two five-phase PMSMs drive system fed by a single five-leg inverter. The resulting control system has been developed using Lyapunov theory in order to guarantee the system stability. The SMC is adopted to control torques, fluxes and speeds, due its inherent advantages such as, robustness, high precision, stability and simplicity. The same quantities are estimated by using a sliding mode observer based on a flux model of the five-phase PMSM. The effectiveness of the proposed control approach has been verified through extensive computer simulations and compared with PI controller and conventional DTC as well.

Simulation results have demonstrated not only truly decoupled operation between the two machines but also many improvements on the dynamic response as well as the steady state performance, in terms of speed response, accuracy, and ripple reduction. The main improvements brought by the proposed DTC-SMC compared to the DTC-PI and conventional DTC have been summarized in Table 3, and they are listed below:

- Faster rise time.
- Good speed tracking without overshoots or drops.
- Reduction in the torque and flux ripples.

The added value of the SMO based sensorless control is the amelioration in the system dynamics through the accuracy in speeds, fluxes, and torques estimation. Indeed, the obtained simulation results show better speed tracking performance at both dynamic and steady state, acceptable estimations errors, robustness in different tests including speed variation, load application, low speed operation, and stator resistance variation. So, these results affirm the ability of the proposed observer to guarantee good estimations in steady state and transients as well.

However, the lack of load torque estimator and more developed technique dealing with chattering phenomenon is the main drawback of the proposed control approach.
References


Proofreading

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Tounsi Kamel was born in Bousaada, Algeria in 1990. He received the Licence degree in Electrical Engineering from M’sila University, Algeria in 2012, his Master degree from M’sila University in 2014. He is currently working towards his PhD degree in Electrical Engineering from Chief University, Algeria. His areas of interest are multi machine and Process Control, wind energy conversion.

Abdelkader Djahbar was born in Chlef, Algeria, in February 1970. He received the Eng. And M.Sc. degrees in electrical engineering from the National Polytechnic school of Algiers, Algeria, in 1995 and 1998, respectively, and the Ph.D. degree in electrical engineering from the Mohamed Boudiaf University of Science and Technology of Oran (USTO), Algeria, in 2008 and the Habilitation to lead


Researches in 2012 at the USTO University, Algeria. In December 2002, he joined the electrical engineering department of Hassiba Ben Bouali University of Chlef, Algeria. Since August 2012, he is Associate Professor in the same department. He is associate researcher in the LMOPS laboratory of the Université de Lorraine and Centrale Supélec since April 2014 and researcher at the GEER laboratory of UHBC since 2013. His scientific work is related to electrical machines and drives and Power Electronics. His present research interests include multi machine drives, matrix converter and power quality.

Said Barkat received the Engineer, Magister, and Ph.D. degrees, all in electrical engineering, from the National Polytechnic School of Algiers, Algeria, in 1994, 1997, and 2008, respectively. In 2000, he joined the Department of Electrical Engineering, Faculty of Technology at University of M'sila, Algeria. His research interests include renewable energy conversion, power electronics, and advanced control theory and applications.

Atif Iqbal Senior Member IEEE, PhD (UK), Fellow IE (India)- Associate Editor IEEE Tran. On Industry Application, Associate Professor at Electrical Engineering, Qatar University and Former Full Professor at Electrical Engineering, Aligarh Muslim University (AMU), Aligarh, India. Recipient of Outstanding Faculty Merit Award AY 2014-2015 and Research excellence award at Qatar University, Doha, Qatar. He received his B.Sc. (Gold Medal) and M.Sc. Engineering (Power System & Drives) degrees in 1991 and 1996, respectively, from the Aligarh Muslim University (AMU), Aligarh, India and PhD in 2006 from Liverpool John Moores University, Liverpool, UK. He has been employed as a Lecturer in the Department of Electrical Engineering, AMU, Aligarh since 1991 where he served as Full Professor until Aug. 2016. He is recipient of Maulana Tufail Ahmad Gold Medal for standing first at B.Sc. Engg. Exams in 1991 from AMU. He has received best research papers awards at IEEE ICIT-2013 and IET-SESICON-2013. He has published widely in International Journals and Conferences his research findings related to Power Electronics and Renewable Energy Sources. Dr. Iqbal has authored/coauthored more than 280 research papers and one book and two chapters in two other books. He has supervised several large R&D projects. His principal area of research interest is modeling and simulation of power electronic converters, control of multi-phase motor drives and renewable energy sources.