Sliding Mode Sensorless Control Of Symmetrical Six-Phase Induction Machines

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Abstract

This paper proposes a new scheme for mechanical sensorless control of symmetrical six phase induction motor. The motor has two sets of three-phase windings, spatially phase shifted by 60 electrical degrees. This sliding mode observer used, is composed of three other observers: current, flux, and speed observers. The estimated currents in the current observer are used in the flux estimation block, and the rotor speed is estimated using estimated currents and flux. It will be shown by the simulation results that the method estimates speed accurately.

1. Introduction

In multi-phase drive systems, the electric machine has more than three phases in the stator and the same numbers of inverter legs are in the inverter side. So the current per phase in the machine and inverter is reduced. The most common multi-phase machine-drive structure is the symmetrical six-phase induction machine (SPIM), which has two sets of three-phase windings, spatially phase shifted by 60 electrical degrees. Fig. 1 shows the structure of a SPIM which is studied in this paper.

In electric machines control, the motor speed (or position) feedback is required for torque control. This presents a problem in low performance systems where the motor mechanical sensors are not available. This has led to sensorless control of ac machines that has been a field of research since late 80's[1-8]. This paper studies the sensorless speed control of SPIM.

In this paper, we propose a sliding mode observer for speed estimation of symmetrical six-phase induction machines. Effectiveness of this method is verified by simulations.

The paper is organized in six sections. The next section presents the model of SPIM. The third section describes the proposed sliding mode observer for mechanical sensorless control algorithm. Then, in section four the simulation results are given. Finally, some conclusions and perspectives will be discussed in section five.

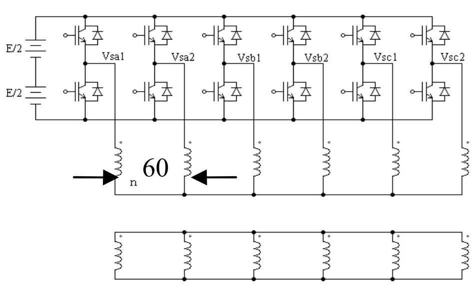

Fig. 1. SPIM with one common neutral

2. Model of six-phase induction machine

The model of SPIM under normal conditions has been given in [1]. The SPIM in the normal mode is a double-six-dimensional system (six stator and six rotor variables). It is shown in [1] that the SPIM model can be decomposed into three double-two-dimensional orthogonal subspaces, (α, β), (z1, z2), (z3, z4), by the following transformation:

$$[T6]=\frac{1}{\sqrt{3}}\begin{bmatrix} 1 & \cos(\gamma) & -\frac{1}{2} & \cos(2\pi/3+\gamma) & -\frac{1}{2} & \cos(4\pi/3+\gamma) \\ 0 & \sin(\gamma) & \frac{\sqrt{3}}{2} & \sin(2\pi/3+\gamma) & -\frac{\sqrt{3}}{2} & \sin(4\pi/3+\gamma) \\ 1 & \cos(\pi-\gamma) & -\frac{1}{2} & \cos(\pi/3-\gamma) & -\frac{1}{2} & \cos(5\pi/3-\gamma) \\ 0 & \sin(\pi-\gamma) & -\frac{\sqrt{3}}{2} & \sin(\pi/3-\gamma) & \frac{\sqrt{3}}{2} & \sin(5\pi/3-\gamma) \\ 1 & 0 & 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 & 0 & 1 \end{bmatrix} \quad (1)$$

In this matrix, γ is the electrical angle between the two three phase stator windings that is 60 electrical degrees. The decoupled model is as follows:

2.1. Machine model in α–β subspace

The stator and rotor voltage equations are:

$$\begin{bmatrix} v_{s\alpha} \\ v_{s\beta} \\ 0 \\ 0 \end{bmatrix}=\begin{bmatrix} r_s+L_s p & 0 & Mp & 0 \\ 0 & r_s+L_s p & 0 & Mp \\ Mp & \omega_r M & r_r+L_r p & \omega_r L_r \\ -\omega_r M & Mp & -\omega_r L_r & r_r+L_r p \end{bmatrix}\cdot\begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \\ i_{r\alpha} \\ i_{r\beta} \end{bmatrix} \quad (2)$$

with: $L_s = L_{ls} + M$, $L_r = L_{lr} + M$, $M = 3L_{ms}$

This model is similar to the three phase machine model in the stationary reference frame.

2.2. Machine model in z1-z2 subspace

$$\begin{bmatrix} v_{sz1} \\ v_{sz2} \end{bmatrix}=\begin{bmatrix} r_s+L_{ls} p & 0 \\ 0 & r_s+L_{ls} p \end{bmatrix}\cdot\begin{bmatrix} i_{sz1} \\ i_{sz2} \end{bmatrix} \quad (3a)$$

$$\begin{bmatrix} 0 \\ 0 \end{bmatrix}=\begin{bmatrix} r_r+L_{lr} p & 0 \\ 0 & r_r+L_{lr} p \end{bmatrix}\cdot\begin{bmatrix} i_{rz1} \\ i_{rz2} \end{bmatrix} \quad (3b)$$

2.3. Machine model in z3-z4 subspace

$$\begin{bmatrix} v_{sz3} \\ v_{sz4} \end{bmatrix} = \begin{bmatrix} r_s + L_{ls}p & 0 \\ 0 & r_s + L_{ls}p \end{bmatrix} . \begin{bmatrix} i_{sz3} \\ i_{sz4} \end{bmatrix} \tag{4a}$$

$$\begin{bmatrix} 0 \\ 0 \end{bmatrix} = \begin{bmatrix} r_r + L_{lr}p & 0 \\ 0 & r_r + L_{lr}p \end{bmatrix} . \begin{bmatrix} i_{rz3} \\ i_{rz4} \end{bmatrix} \tag{4b}$$

As it can be seen from these three subsystems, the electromechanical energy conversion takes place only in $\alpha-\beta$ subsystem, and the other subsystems have not any contribution in the energy conversion. The z1-z2 and z3-z4 subsystems produce only losses, so they should be controlled to be as small as possible. It can be concluded that the torque and speed controller synthesis and analysis for six-phase induction machines is almost the same as for three-phase induction machines: it is done with the equivalent model in $\alpha-\beta$ subspace.

3. Sliding Mode Observer

In this section, the sliding mode algorithm that used for speed estimation will be discussed. This observer is composed of three other observers: current, flux, and speed observers. The estimated currents in the current observer are used in the flux estimation block. Finally, the rotor speed is estimated using estimated currents and flux.

3.1. Current Observer

For clearness, the state space model of the machine can be written as [2]:

$$\begin{aligned} \dot{I} &= \beta A\phi - k_1 I + k_2 V \\ \dot{\Lambda} &= -A\phi + \frac{L_m}{T_r} I \end{aligned} \tag{5}$$

Where:

$$\dot{I} = \left[\frac{\partial i_{sd}}{\partial t}, \frac{\partial i_{sq}}{\partial t}\right]^T \quad , \quad \dot{\phi} = \left[\frac{\partial \lambda_{rd}}{\partial t}, \frac{\partial \lambda_{rq}}{\partial t}\right]^T$$

$$I = [i_{sd}, i_{sq}]^T \quad , \quad \phi = [\lambda_{rd}, \lambda_{rq}]^T$$

$$A = \begin{bmatrix} \frac{1}{T_r} & p\Omega \\ -p\Omega & \frac{1}{T_r} \end{bmatrix}^T \quad , \quad V = [V_{sd}, V_{sq}]^T$$

And:

$$k_2 = \frac{1}{\sigma L_s} \qquad \beta = \frac{k_2 L_m}{L_r} \qquad k_1 = k_2 (R_s + \frac{L_m^2}{L_r T_r})$$

Based on the model given in (5), the current observer structure is the following:

$$\dot{\hat{I}} = \beta\psi - k_1 \hat{I} + k_2 V \tag{6}$$

Where:

$$\psi = [\psi_d, \psi_q]^T \quad , \quad \hat{I} = [\hat{i}_{sd}, \hat{i}_{sq}]^T$$

$\hat{i}_{sq}$ and $\hat{i}_{sd}$ are the observed stator current components in the stationary reference frame. The sliding functions ψ_q and ψ_d are defined as:

$$\begin{aligned} \psi_d &= -U_0 \, sign(S_d) \quad , \quad S_d = \hat{i}_{sd} - i_{sd} \\ \psi_q &= -U_0 \, sign(S_q) \quad , \quad S_q = \hat{i}_{sq} - i_{sq} \end{aligned} \tag{7}$$

Where:

$$sign(S_{dq}) = \begin{cases} 1 & , \quad if \quad S_{dq} > 0 \\ -1 & , \quad if \quad S_{dq} > 0 \end{cases} \tag{8}$$

and the sliding mode surface is defined as:

$$S_n = \lfloor S_{sd}, S_{sq} \rfloor \tag{9}$$

When the estimation error trajectories reach the sliding surface, i.e., $s_n = 0$, observed current will converge to the actual values, i.e., $\hat{i}_{sd} = i_{sd}$ and $\hat{i}_{sq} = i_{sq}$.

3.2. Flux and Speed Estimation

When the trajectories of the system reach the sliding surface $s_n = 0$, the observed currents $\hat{i}_{sq}$ and $\hat{i}_{sd}$ match the actual currents i_{sq} and i_{sd}, i.e,

$$\psi = A\,\phi \tag{10}$$

When this is substituted in (5) , then:

$$\begin{bmatrix} \frac{\partial \lambda_{rd}}{\partial t} \\ \frac{\partial \lambda_{rq}}{\partial t} \end{bmatrix} = -\begin{bmatrix} \psi_d^{eq} \\ \psi_q^{eq} \end{bmatrix} + \frac{1}{T_r} L_m \begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} \tag{11}$$

from which the rotor flux λ_{rq} and λ_{rd} can be found. Now, using the flux values and (10), speed and rotor time constant can be found. Let (10) be written as:

$$\begin{bmatrix} \psi_d^{eq} \\ \psi_q^{eq} \end{bmatrix} = \begin{bmatrix} \frac{1}{T_r} & p\Omega \\ -p\Omega & \frac{1}{T_r} \end{bmatrix} \begin{bmatrix} \lambda_{rd} \\ \lambda_{rq} \end{bmatrix} \tag{12}$$

which can be reorganized as:

$$\begin{bmatrix} \frac{1}{T_r} \\ p\Omega \end{bmatrix} = \frac{1}{|\lambda_r|} \begin{bmatrix} -\lambda_{rd} & -\lambda_{rq} \\ -\lambda_{rq} & \lambda_{rd} \end{bmatrix} \begin{bmatrix} \psi_d^{eq} \\ \psi_q^{eq} \end{bmatrix} \tag{13}$$

Where:

$$|\lambda_r| = -(\lambda_{rd})^2 - (\lambda_{rq})^2 \tag{14}$$

Finally, from (14), ω_r are found as:

$$\hat{\Omega} = \frac{1}{p|\lambda_r|} \left(\lambda_{rd}\,\psi_q^{eq} - \lambda_{rq}\,\psi_d^{eq}\right) \tag{15}$$

4. Simulation results

In order to verify the efficiency of the proposed method, we have developed a program based on the proposed algorithm. The parameters of the machine are given in table 1. Figs. 2 shows the simulation results of the method for a startup and speed inversion test. As can be seen, the estimated speed follows the real speed very well. The real and estimated currents are not distinguishable. Figs. 3 shows the simulation results of the method for load torque rejection test.

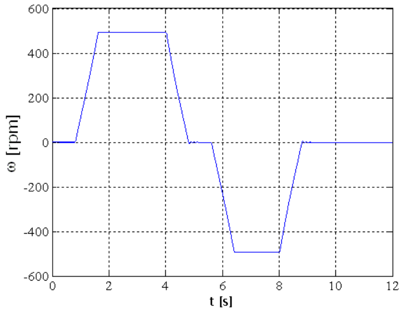

Fig. 2.-a: real speed.

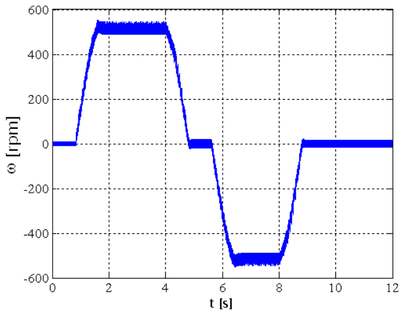

Fig. 2.-b: estimated speed.

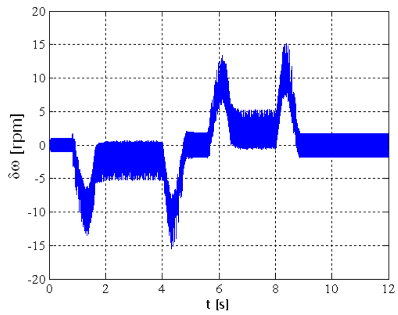

Fig. 2.-c: error between real and estimated speed.

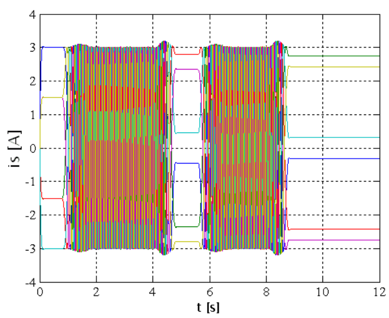

Fig. 2.-d: six phase current of stator

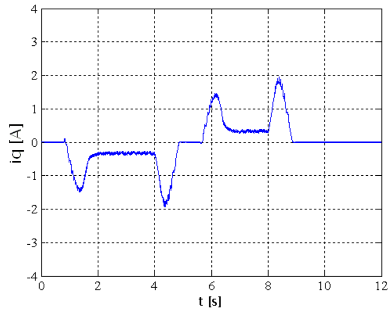

Fig. 2.-e: quadratic component of stator current

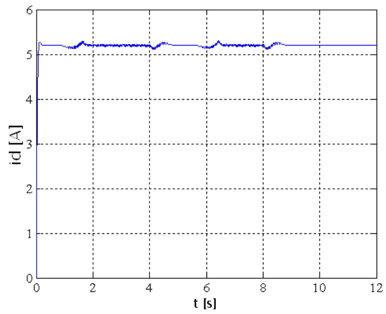

Fig. 2.-f: direct component of stator current

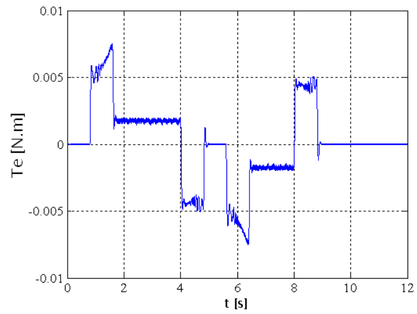

Fig. 2.-g: electromagnetic torque

Fig. 2.-startup and speed inversion test

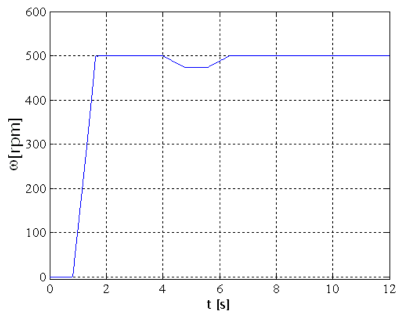

Fig. 3.-a: real speed.

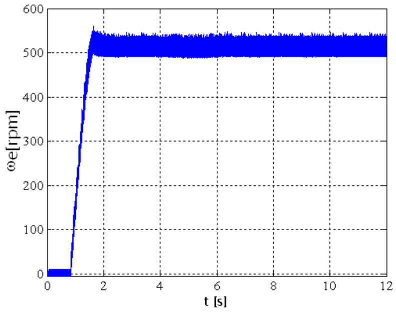

Fig. 3.-b: estimated speed.

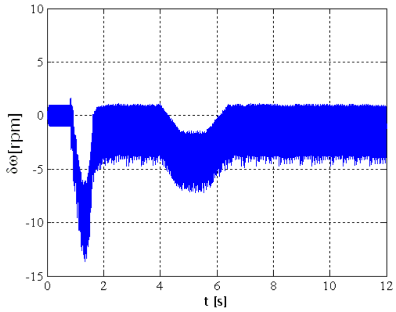

Fig. 3.-c: error between real and estimated speed.

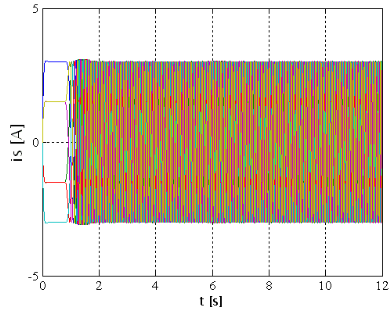

Fig. 3.-d: six phase current of stator

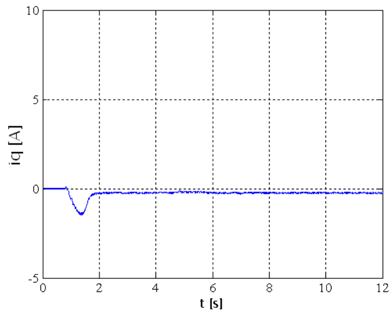

Fig. 3.-e: quadratic component of stator current

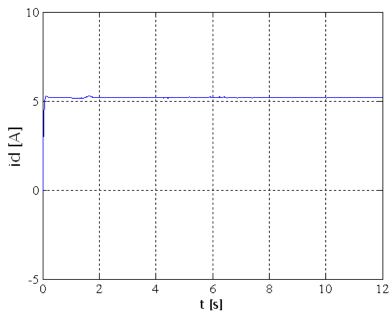

Fig. 3.-f: direct component of stator current

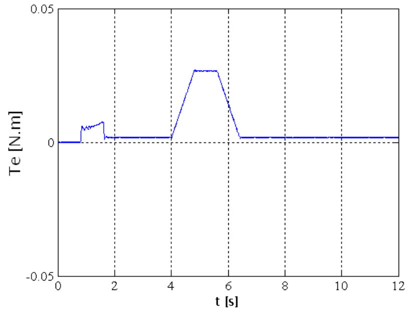

Fig. 3.-g: electromagnetic torque

Fig. 3. load rejection test

5. Conclusion

In this paper sliding mode observer for sensorless control of six phase induction machine is proposed. Validity of this method is tested by two standard tests: start up and speed inversion test and load torque rejection test. In start up and speed inversion test estimated speed can follow reference speed very well and error between real and estimated speed is negligible. In load torque rejection test when load torque is applied, motor speed is decreased. Comparing previous works like reduced order linear observers [3], this method is more complicated and consumes more time for executing the program.

6. References

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Table 1. Parameters of the simulated motor.

No. of poles	*2*
Rated output	90 W
Rated voltage	42 V
Rated current	2.6 A
Rated speed	2800 rpm
Rated torque	0.3 Nm
Stator resistance (R_s)	1.04 Ω
Stator inductance (L_s)	0.0127 mH
Rotor resistance (R_r)	*0.4107 Ω*
Rotor inductance (L_r)	*0.0127 mH*
Mutual inductance (M)	*0.0115 mH*

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