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Speed Sensorless Direct Rotor Field-Oriented Control of Single-Phase Induction Motor Using Extended Kalman Filter

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ABSTRACT

Nowadays, Field-Oriented Control (FOC) strategies broadly used as a vector based controller for Single-Phase Induction Motors (SPIMs). This paper is focused on Direct Rotor FOC (DRFOC) of SPIM. In the proposed technique, transformation matrices are applied in order to control the motor by converting the unbalanced SPIM equations to the balanced equations (in this paper the SPIM with two different stator windings is considered). Besides this control technique, a method for speed estimation of SPIM based on Extended Kalman Filter (EKF) to achieve the higher performance of SPIM drive system is presented. Simulation results are provided to demonstrate the high performance of the presented techniques.

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1. INTRODUCTION

Single-Phase Induction Motors (SPIMs) are used in both domestic and industrial purposes. They can be employed in air conditioners, fans, refrigerators, compressors, dryers, washing machines and other applications. Generally, the stator of SPIMs has two windings which are orthogonal in space. They are different in terms of resistances and impedances. Since the main and auxiliary stator windings are unbalanced, therefore SPIM will be encountered the torque pulsations [1]. Consequently, studying about SPIMs has been increased dramatically. It has been recommended by the researchers, various studies, which focused on improving the performance and efficiency of the SPIMs. These researches, presented design and optimization, study on the power factor, research on improved modeling and analysis, progress on improvement of torque performance and researching on influence of harmonic [2]-[4].Variable Frequency Control (VFC) techniques which are used in the Variable Frequency Drives (VFDs) have advantages in terms of saving of energy and high performance applications of IMs [5]-[7]. VFC methods are categorized into scalar and vector based control. The scalar methods will not be able to fulfill the requirement of dynamic drives and has a slow reaction to transient but, vector control is an excellent control method to handle transient and satisfy the requirement of dynamic drives. Generally vector control is classified into Direct Torque Control (DTC) and Field-Oriented Control (FOC). FOC method is proposed broadly as a vector based controller for IMs and is classified into Stator FOC (SFOC) and Rotor FOC (RFOC). Another classification of this method is also performed based on the calculation of rotor flux position which includes Direct FOC (DFOC) and Indirect FOC (IFOC) [8].

From a review of literature, there are many papers which have been suggested for vector control of SPIMs based on FOC. In 2000, Correa et al. investigated IRFOC technique for SPIM. In the proposed technique, they eliminated the asymmetry terms of the SPIM equations by selecting appropriate transformation for the stator variables [9]. It was suggested in [9], to use hysteresis current controller. In [10], Correa et al. proposed vector control of SPIM based on ISFOC. In the proposed technique, for reduction of electromagnetic torque oscillations in SPIM, they designed a double-sequence current controller to control stator current [10]. In [11], decoupling vector control of SPIM has been proposed by Vaez-Zadeh and Reicy. In the proposed vector control method in paper [12], the maximum potential operation of SPIM is obtained according to maximum torque per ampere. In [13], [14], the authors proposed and implemented ISFOC and IRFOC for SPIM respectively. In fact they used the same variable changing based on [9], to eliminate the asymmetrical terms in SPIM. To have high performance vector control techniques such as [9]-[14], it is necessary to employ feedback speed control. For this purpose, an encoder is normally used to provide this information. Using sensor causes more instrumentation, increasing cost and size, decrease robustness and reliability of the drive system. Therefore, instead of implementation of sensor, it is better to apply speed estimation techniques. Generally, speed estimation is categorized into two main parts, speed estimation based on motor model and speed estimation through signal injection [8]. It is proposed speed estimation methods in IMs by different authors. In [15], a study has been proposed for sensorless IRFOC of SPIM. The applied method for estimation of speed in [15] is based on SPIM model. In paper [16], a method for ISFOC of SPIM with estimation of rotor speed based on the motor currents and reference q-axis current has been proposed. In [17], Model Reference Adaptive System (MRAS) strategy has been used for speed sensorless IRFOC of SPIM. The MRAS speed sensorless vector control of IMs is sensitive to variations of resistance [18]. For this, in [19], MRAS strategy by an online stator resistance estimator and in [20], a Recursive Least Square (RLS) algorithm is employed to calculate the SPIM parameters in sensorless vector control of this motor. Using Extended Kalman Filter (EKF) is another technique to estimate the rotor speed. Since the nonlinearities and uncertainties of IM are well-suited to the EKF, therefore it would be able to estimate the parameters simultaneously at the short interval of time [21], [22]. Moreover, in this method the measurement and system noises which are not normally considered in the previously presented techniques for SPIMs such as [15]-[20] are regarded. In this paper, a novel technique for DRFOC of SPIM (unbalanced two-phase IM) with estimation of mechanical speed using EKF is discussed and verified using MATLAB/SIMULINK. The presented EKF in this paper is the conventional EKF which has been developed of SPIM. Besides the removing of mechanical speed sensor such as tachogenerator and encoder, the proposed DRFOC in this work, eliminates the pure integration which is used in IFOC. Using integration operator in the vector control of IM suffers the well-known difficulties of integration effect especially at the low frequencies [23]. The results of this research show that the proposed speed sensorless control for SPIM has reasonably good torque and speed response dynamics and satisfactory tracking capability.

2. SPIM MODEL

The mathematical model of squirrel cage SPIM can be shown in a stationary reference frame as follows [9]:

$$\begin{bmatrix} v_{ds}^s \\ v_{qs}^s \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R_{ds} + L_{ds}\frac{d}{dt} & 0 & M_{ds}\frac{d}{dt} & 0 \\ 0 & R_{qs} + L_{qs}\frac{d}{dt} & 0 & M_{qs}\frac{d}{dt} \\ M_{ds}\frac{d}{dt} & \omega_r M_{qs} & R_r + L_r\frac{d}{dt} & \omega_r L_r \\ -\omega_r M_{ds} & M_{qs}\frac{d}{dt} & -\omega_r L_r & R_r + L_r\frac{d}{dt} \end{bmatrix} \begin{bmatrix} i_{ds}^s \\ i_{qs}^s \\ i_{dr}^s \\ i_{qr}^s \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} \lambda_{ds}^s \\ \lambda_{qs}^s \\ \lambda_{dr}^s \\ \lambda_{qr}^s \end{bmatrix} = \begin{bmatrix} L_{ds} & 0 & M_{ds} & 0 \\ 0 & L_{qs} & 0 & M_{qs} \\ M_{ds} & 0 & L_r & 0 \\ 0 & M_{qs} & 0 & L_r \end{bmatrix} \begin{bmatrix} i_{ds}^s \\ i_{qs}^s \\ i_{dr}^s \\ i_{qr}^s \end{bmatrix} \tag{2}$$

$$\tau_e = \frac{Pole}{2}(M_{qs} i_{qs}^s i_{dr}^s - M_{ds} i_{ds}^s i_{qr}^s) \tag{3}$$

$$\frac{Pole}{2}(\tau_e - \tau_l) = J\frac{d\omega_r}{dt} + F\omega_r \tag{4}$$

Where, v^s_{ds}, v^s_{qs}, i^s_{ds}, i^s_{qs}, i^s_{dr}, i^s_{qr}, λ^s_{ds}, λ^s_{qs}, λ^s_{dr} and λ^s_{qr} are the d and q axes voltages, currents and fluxes of the stator and rotor, R_{ds}, R_{qs}, R_r, L_{ds}, L_{qs}, L_r, M_{ds} and M_{qs} denote the d and q axes resistances, self and mutual inductances of the stator and rotor. Moreover, ω_r, τ_e, τ_l, J and F are the motor speed, electromagnetic torque, load torque, inertia and viscous friction coefficient, respectively. Based on Equation (1)-(4) it is assumed that the main and auxiliary stator windings have different values ($R_{ds}\neq R_{qs}$, $L_{ds}\neq L_{qs}$ and $M_{ds}\neq M_{qs}$). To compensate the asymmetry in unbalanced IMs in [24]-[29], Jannati et al. proposed the use of unbalanced transformation matrices for stator voltage and current variables. In this work, similar to [25]-[29], these transformation matrices are employed to compensate the asymmetry between the main and auxiliary stator windings in SPIM (in [27]-[29], the transformation matrices have been used for IRFOC of three-phase IM under open-phase fault). These matrices are as follows:

Transformation matrix for stator voltage variables:

$$\begin{bmatrix} v^e_{ds} \\ v^e_{qs} \end{bmatrix} = \left[T^e_{vs}\right]\begin{bmatrix} v^s_{ds} \\ v^s_{qs} \end{bmatrix} = \begin{bmatrix} \dfrac{M_{qs}}{M_{ds}}\cos\theta_e & \sin\theta_e \\ -\dfrac{M_{qs}}{M_{ds}}\sin\theta_e & \cos\theta_e \end{bmatrix}\begin{bmatrix} v^s_{ds} \\ v^s_{qs} \end{bmatrix} \tag{5}$$

Transformation matrix for stator current variables:

$$\begin{bmatrix} i^e_{ds} \\ i^e_{qs} \end{bmatrix} = \left[T^e_{is}\right]\begin{bmatrix} i^s_{ds} \\ i^s_{qs} \end{bmatrix} = \begin{bmatrix} \dfrac{M_{ds}}{M_{qs}}\cos\theta_e & \sin\theta_e \\ -\dfrac{M_{ds}}{M_{qs}}\sin\theta_e & \cos\theta_e \end{bmatrix}\begin{bmatrix} i^s_{ds} \\ i^s_{qs} \end{bmatrix} \tag{6}$$

Where, θe is the angle between the stationary reference frame and the rotor flux-oriented reference frame (in this paper superscript "*e*" indicates that the variables are in the rotating reference frame and superscript "*s*" indicates that the variables are in the stationary reference frame. Ii is shown by using these transformation matrices, the stator and rotor variables of the main and auxiliary windings are transformed into equations that have similar structure to balanced IM equations. The stator and rotor voltage equations, rotor flux equations and electromagnetic torque equation after applying Equation (5) and Equation (6) are given by (7)-(11).

Stator voltage equations:

$$\begin{aligned}\begin{bmatrix} v^e_{ds} \\ v^e_{qs} \end{bmatrix} &= \begin{bmatrix} R_{ds} + L_{qs}\dfrac{d}{dt} & -\omega_e L_{qs} \\ \omega_e L_{qs} & R_{qs} + L_{qs}\dfrac{d}{dt} \end{bmatrix}\begin{bmatrix} i^e_{ds} \\ i^e_{qs} \end{bmatrix} + \begin{bmatrix} M_{qs}\dfrac{d}{dt} & -\omega_e M_{qs} \\ \omega_e M_{qs} & M_{qs}\dfrac{d}{dt} \end{bmatrix}\begin{bmatrix} i^e_{dr} \\ i^e_{qr} \end{bmatrix} \\ &+ \begin{bmatrix} \left(\begin{array}{l} (\dfrac{M^2_{qs}}{M^2_{ds}}R_{ds} - R_{qs}) + \\ (\dfrac{M^2_{qs}}{M^2_{ds}}L_{ds} - L_{qs})\dfrac{d}{dt} \end{array} \right) & -\omega_e(\dfrac{M^2_{qs}}{M^2_{ds}}L_{ds} - L_{qs}) \\ \omega_e(\dfrac{M^2_{qs}}{M^2_{ds}}L_{ds} - L_{qs}) & \left(\begin{array}{l} (\dfrac{M^2_{qs}}{M^2_{ds}}R_{ds} - R_{qs}) + \\ (\dfrac{M^2_{qs}}{M^2_{ds}}L_{ds} - L_{qs})\dfrac{d}{dt} \end{array} \right) \end{bmatrix}\begin{bmatrix} i^{-e}_{ds} \\ i^{-e}_{qs} \end{bmatrix}\end{aligned} \tag{7}$$

Where,

$$\begin{bmatrix} i^{-e}_{ds} \\ i^{-e}_{qs} \end{bmatrix} = \begin{bmatrix} \cos^2\theta_e & -\sin\theta_e\cos\theta_e \\ -\sin\theta_e\cos\theta_e & \sin^2\theta_e \end{bmatrix}\begin{bmatrix} i^e_{ds} \\ i^e_{qs} \end{bmatrix} \tag{8}$$

Rotor voltage equations:

$$\begin{bmatrix} 0 \\ 0 \end{bmatrix} = \begin{bmatrix} M_{qs}\frac{d}{dt} & -(\omega_e-\omega_r)M_{qs} \\ (\omega_e-\omega_r)M_{qs} & M_{qs}\frac{d}{dt} \end{bmatrix} \begin{bmatrix} i_{ds}^e \\ i_{qs}^e \end{bmatrix} + \begin{bmatrix} R_r + L_r\frac{d}{dt} & -(\omega_e-\omega_r)L_r \\ (\omega_e-\omega_r)L_r & R_r + L_r\frac{d}{dt} \end{bmatrix} \begin{bmatrix} i_{dr}^e \\ i_{qr}^e \end{bmatrix} \tag{9}$$

Rotor flux equations:

$$\begin{bmatrix} \lambda_{dr}^e \\ \lambda_{qr}^e \end{bmatrix} = \begin{bmatrix} M_{qs} & 0 \\ 0 & M_{qs} \end{bmatrix} \begin{bmatrix} i_{ds}^e \\ i_{qs}^e \end{bmatrix} + \begin{bmatrix} L_r & 0 \\ 0 & L_r \end{bmatrix} \begin{bmatrix} i_{dr}^e \\ i_{qr}^e \end{bmatrix} \tag{10}$$

Electromagnetic torque equation:

$$\tau_e = \frac{Pole}{2} M_{qs} (i_{qs}^e i_{dr}^e - i_{ds}^e i_{qr}^e) \tag{11}$$

In (7), ω_e is the angle between the stationary reference frame and the rotor flux reference frame. As can be seen from Equation (7)-(11), using Equation (5) and Equation (6), the asymmetrical equations of SPIM changed into symmetrical equations. Thus, the FOC principles can be applied.

3. DRFOC OF SPIM

In this study, the DRFOC technique for vector control of SPIM was used. Based on (7)-(11) and after simplifying of equations, the equations of the RFOC technique for a SPIM are obtained as following equations (in this method the rotor flux vector is aligned with d-axis):

$$\omega_e = \omega_r + \frac{M_{qs} i_{qs}^e}{T_r |\lambda_r|} \tag{12}$$

$$\tau_e = \frac{Pole}{2} \frac{M_{qs}}{L_r} |\lambda_r| i_{qs}^e \tag{13}$$

$$|\lambda_r| = \frac{M_{qs} i_{ds}^e}{1 + T_r \frac{d}{dt}} \tag{14}$$

$$v_{ds}^e = v_{ds}^d + v_{ds}^{ref} + v_{ds}^{-e} \quad , \quad v_{qs}^e = v_{qs}^d + v_{qs}^{ref} + v_{qs}^{-e} \tag{15}$$

Where,

$$v_{ds}^d = -\omega_e i_{qs}^e (L_{qs} - \frac{M_{qs}^2}{L_r}) + \frac{M_{qs}}{L_r} (\frac{M_{qs} i_{ds}^e - |\lambda_r|}{T_r}) \tag{16}$$

$$v_{qs}^d = \omega_e i_{qs}^e (L_{qs} - \frac{M_{qs}^2}{L_r}) + \omega_e M_{qs} \frac{|\lambda_r|}{L_r} \tag{17}$$

$$v_{ds}^{ref} = (\frac{R_{ds} M_{qs}^2 + R_{qs} M_{ds}^2}{2 M_{ds}^2}) i_{ds}^e + (L_{qs} - \frac{M_{qs}^2}{L_r}) \frac{d i_{ds}^e}{dt} \tag{18}$$

$$v_{qs}^{ref} = (\frac{R_{ds} M_{qs}^2 + R_{qs} M_{ds}^2}{2 M_{ds}^2}) i_{qs}^e + (L_{qs} - \frac{M_{qs}^2}{L_r}) \frac{d i_{qs}^e}{dt} \tag{19}$$

$$\begin{bmatrix} v_{ds}^{-e} \\ v_{qs}^{-e} \end{bmatrix} = \left(\frac{R_{ds} M_{qs}^2 - R_{qs} M_{ds}^2}{2 M_{ds}^2} \right) \begin{bmatrix} \cos 2\theta_e & -\sin 2\theta_e \\ -\sin 2\theta_e & -\cos 2\theta_e \end{bmatrix} \begin{bmatrix} i_{ds}^e \\ i_{qs}^e \end{bmatrix} \tag{20}$$

Where, $T_r=L_r/R_r$ is the rotor time constant. In (14) and (15), $v_{ds}{}^d$ and $v_{qs}{}^d$ are generated using Decoupling Circuit and $v_{ds}{}^{ref}$ and $v_{qs}{}^{ref}$ are generated using current PI controllers in the RFOC block diagram of the SPIM (see Figure 2). Moreover, the values of ω_r, λ_r and θ_e in (12)-(20) are calculated using estimated values of rotor d and q axis fluxes as follows (in this paper, the motor speed and rotor d and q axis fluxes are estimated using EKF):

$$\hat{\lambda}_r = \sqrt{\hat{\lambda}_{dr}^2 + \hat{\lambda}_{qr}^2} \tag{21}$$

$$\hat{\theta}_r = \tan^{-1}\left(\frac{\hat{\lambda}_{dr}}{\hat{\lambda}_{qr}}\right) \tag{22}$$

4. EKF FOR ROTOR SPEED ESTIMATION IN SPIM

In this paper, an Extended Kalman Filter is used to estimate the mechanical speed and rotor fluxes. The state space model of SPIM is shown by Equation (23):

$$\dot{x} = Ax + Bu + w(t) \quad , \quad y = Cx + v(t) \tag{23}$$

Where, A_n, B_n and C_n are the input and output matrixes of system and x, y and u are the system state matrix, system output matrix and system input matrix respectively. The covariance matrices of $w(t)$ and $v(t)$ are defined as follows ($w(t)$: system noise; $v(t)$: measurement noise):

$$Q = \text{cov}\,(w) = E\{ww^t\} \quad , \quad R = \text{cov}\,(v) = E\{vv^t\} \tag{24}$$

In this filter, the state matrix (x_n) is the stator d and q axis currents, rotor d and q axis fluxes and rotor speed, the input matrix (u_n) is stator d and q axis voltages and the output matrix (y_n) is stator d and q axis currents.

$$x_n = \begin{bmatrix} i_{ds}^{(n)} & i_{qs}^{(n)} & \lambda_{ds}^{(n)} & \lambda_{qs}^{(n)} & \omega_r^{(n)} & \tau_l^{(n)} \end{bmatrix}^T \tag{25}$$

$$u_n = \begin{bmatrix} v_{ds}^{(n)} & v_{qs}^{(n)} \end{bmatrix}^T \tag{26}$$

$$y_n = \begin{bmatrix} i_{ds}^{(n)} & i_{qs}^{(n)} \end{bmatrix}^T \tag{27}$$

Based on d-q model of SPIM (Equation (1)-(4)) and Equation (25)-(27), the matrixes A_n, B_n and C_n are obtained as Equation (28).

$$A_n = \begin{bmatrix} 1-\frac{1}{k_1}\left(R_{ds}+\frac{M_{ds}^2 R_r}{L_r^2}\right)dt & 0 & \frac{M_{ds}R_r}{k_1 L_r^2}dt & \frac{M_{ds}R_r}{k_1 L_r}dt & 0 & 0 \\ 0 & 1-\frac{1}{k_2}\left(R_{qs}+\frac{M_{qs}^2 R_r}{L_r^2}\right)dt & \frac{-M_{qs}R_r}{k_2 L_r}dt & \frac{M_{qs}R_r}{k_2 L_r^2}dt & 0 & 0 \\ \frac{M_{ds}R_r}{L_r}dt & 0 & 1-\frac{R_r}{L_r}dt & -R_r dt & 0 & 0 \\ 0 & \frac{M_{qs}R_r}{L_r}dt & R_r dt & 1-\frac{R_r}{L_r}dt & 0 & 0 \\ -\frac{1.5(Pole)^2 M_{ds}\lambda_{qr}^s}{2JL_r}dt & \frac{1.5(Pole)^2 M_{qs}\lambda_{dr}^s}{2JL_r}dt & 0 & 0 & 1 & -\frac{1}{J} \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

$$B_n = \begin{bmatrix} \frac{1}{k_1}dt & 0 \\ 0 & \frac{1}{k_2}dt \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \tag{28}$$

$$C_n = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Where:

$$k_1 = L_{ds} - \frac{M_{ds}^2}{L_r} \quad , \quad k_2 = L_{qs} - \frac{M_{qs}^2}{L_r} \tag{29}$$

Using (28), (29) and EKF algorithm (Equations (30)-(36)), the rotor speed and rotor fluxes can be estimated (in (30)-(36), H is the matrix of output prediction, P_n is error covariance matrix and Φ is the matrix of state prediction).

EKF Algorithm:

Prediction of State:

$$x_{n+1\ n} = \Phi\left(n+1, n, x_{n\ n-1}, u_n\right) \tag{30}$$

Where,

$$\Phi\left(n+1, n, x_{n\ n-1}, u_n\right) = A_n\left(x_{n\ n}\right)x_{n\ n} + B_n\left(x_{n\ n}\right)u_n \tag{31}$$

Estimation of Error Covariance Matrix:

$$P_{n+1\ n} = \frac{d\Phi}{dx}\Big|_{x=x_{n\ n}} P_{n\ n} \frac{d\Phi^T}{dx}\Big|_{x=x_{n\ n}} + Q \tag{32}$$

Computation of Kalman Filter Gain:

$$K_n = P_{n\ n-1} \frac{\partial H^T}{\partial x}\Big|_{x=x_{n\ n-1}} \left(\frac{\partial H}{\partial x}\Big|_{x=x_{n\ n-1}} P_{n\ n-1} \frac{\partial H^T}{\partial x}\Big|_{x=x_{n\ n-1}} + R \right)^{-1} \tag{33}$$

Where,

$$H\left(x_{n\ n-1}, n\right) = C_n\left(x_{n\ n-1}\right)x_{n\ n-1} \tag{34}$$

State Estimation:

$$x_{n\ n} = x_{n\ n-1} + K_n\left(y_n - H\left(x_{n\ n-1}, n\right)\right) \tag{35}$$

Update of the Error Covariance Matrix:

$$P_{n\ n} = P_{n\ n-1} - K_n \frac{\partial H}{\partial x}\Big|_{x=x_{n\ n-1}} P_{n\ n-1} \tag{36}$$

Based on Equation (30)-(36), the block diagram of EKF can be shown as Figure 1.

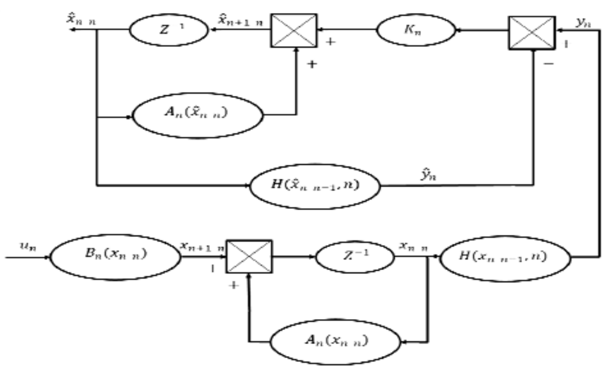


Figure 1. Block diagram of EKF

5. SIMULATIONS AND RESULTS

In this section, MATLAB simulation results were obtained for a SPIM. The simulated SPIM parameters are:

Voltage:110V, f=60Hz, No. of poles=4, R_{ds}=7.14Ω, R_{qs}=2.02Ω, R_r=4.12Ω, L_{ds}=0.1885H, L_{qs}=0.1844H, L_r=0.1826H, M_{qs}=0.1772H, J=0.0146kg.m^2

The simulated drive system is presented in Figure 2. As shown in this figure, the SPIM was fed by two-leg Voltage Source Inverter (VSI). In the simulation test, the motor speed varied from zero to ±400rpm (a trapezoidal reference speed) as shown in Figure 3(a), and the control drive system was feedback with the EKF.

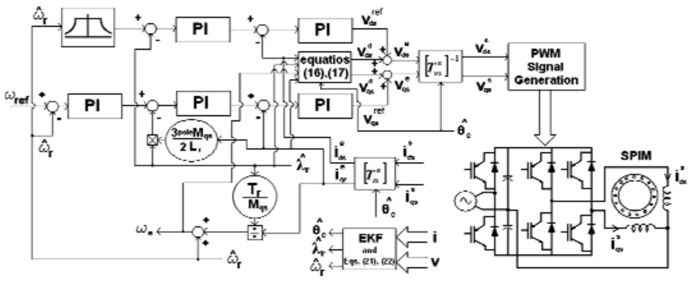
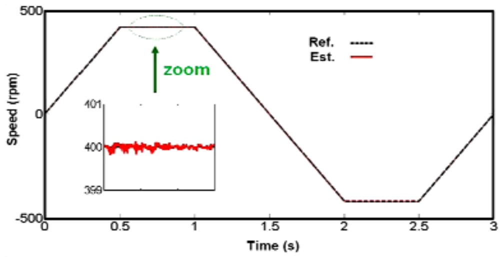
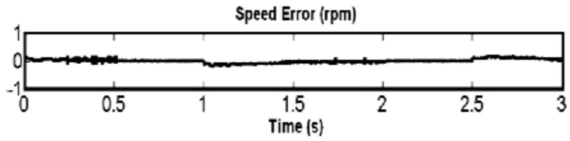


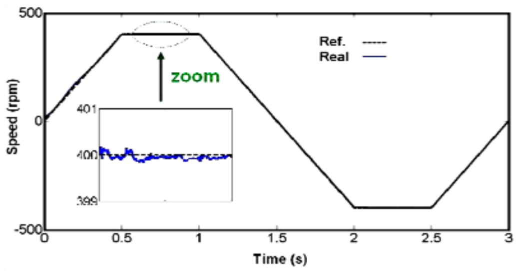
Figure 2. Block diagram of the proposed speed sensorless DRFOC for SPIM



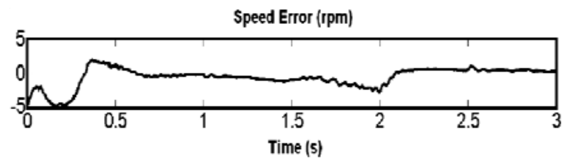
(a)



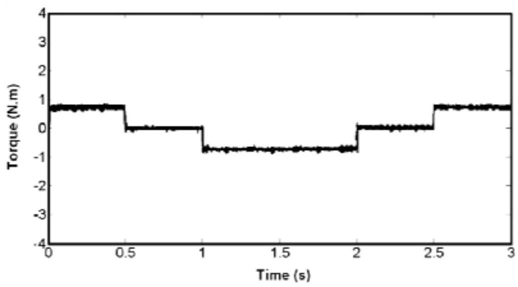
(b)



(c)



(d)



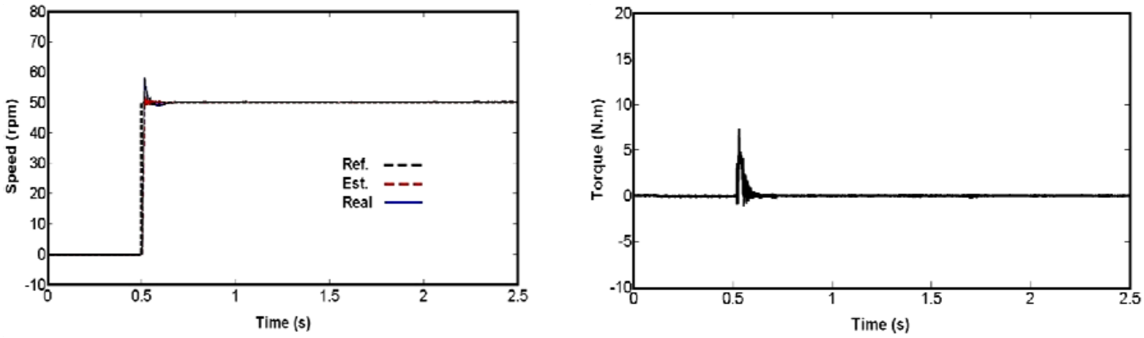
(e)

Figure 3. Simulation results of the speed sensorless DRFOC for a trapezoidal reference speed

Figure 3(a) presents the reference speed and estimated speed, while Figure 3(b) shows the error between reference speed and estimated speed. Figures 3(c) and 3(d) show the reference speed and motor speed and the error between reference speed and actual speed respectively. Figure 3(e) shows the simulated electromagnetic torque of SPIM. The simulation results have been shown the good speed and torque identification performance of the proposed drive system (e.g., the oscillations of electromagnetic torque is about 0.2N.m).

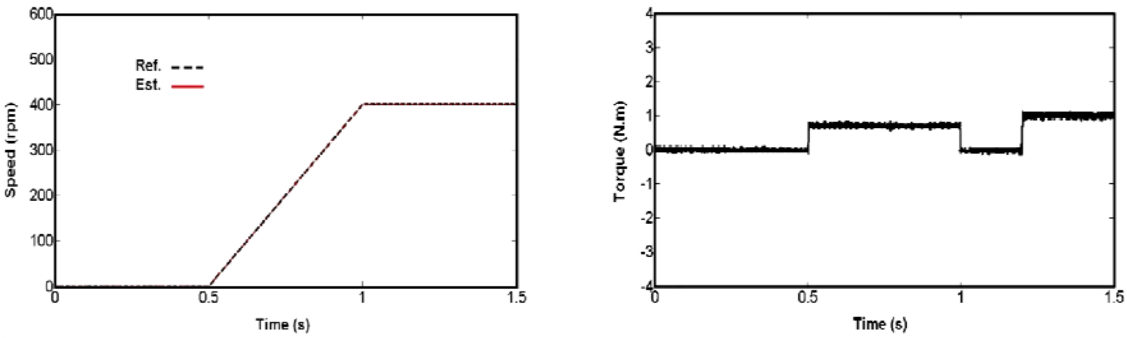
Figure 4 shows the good performance of the proposed drive system for speed sensorless DRFOC of SPIM at zero and low speed operation (ω_{ref}=0 and ω_{ref}=50rpm). It can be seen from Figure 4 that the dynamic performance of the proposed drive system for speed sensorless of SPIM at zero and low speed is extremely acceptable.

Figure 5 shows the simulation results of the proposed controller under load (step load). From t=0s to t=1.2s, the value of the load is 0N.m and from t=1.2s to t=1.5s, the value of the load is 1N.m. Results show that the proposed controller for vector control of SPIM is also robust to the load torque variations and produced good results (in this case, as can be seen in Figure 5(b), by using proposed controller, the torque oscillation after applying load torque and phase cut-off and at steady state is ~ 0.1N.m at load torque of 1N.m).



(a) (b)

Figure 4. Simulation results of the speed sensorless DRFOC at zero and low speed; (a) Speed, (b) Torque



(a) (b)

Figure 5. Simulation results of the speed sensorless DRFOC under load; (a) Speed, (b) Torque

6. CONCLUSION

This paper made a contribution to the speed sensorless DRFOC of SPIM. First, by applying transformation matrices to the SPIM equations, a novel DRFOC for SPIM is presented. Secondly, in order to get higher performance of SPIM drive, a speed estimation method based on EKF is proposed. The simulation results in this paper demonstrate the good performance of the suggested methods, in both controlling and speed estimation strategies.

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