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High Performance Speed Control of Single-Phase Induction Motors Using Switching Forward and Backward EKF Strategy

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Article Info

ABSTRACT

The aim of this research is to provide a high performance vector control of single-phase Induction Motor (IM) drives. It is shown that in the rotating reference frame, the single-phase IM equations can be separated into forward and backward equations with the balanced structure. Based on this, a method for vector control of the single-phase IM, using two modified Rotor Field-Oriented Control (RFOC) algorithms is presented. In order to accommodate forward and backward rotor fluxes in the presented controller, an Extended Kalman Filter (EKF) with two different forward and backward currents that are switched interchangeably (switching forward and backward EKF), is proposed. Simulation results illustrate the effectiveness of the proposed algorithm.

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1.   INTRODUCTION

Variable Frequency Drives (VFDs) applications are applied in many industries to control a wide range of speed and torque for electrical machines. The aim of using VFDs in these applications can be summarized as follows: energy saving, torques maximization, torque pulsation minimization, power factor improvement, Total Harmonic Distortion (THD) reduction and etc [1].

In particular, the use of VFDs for single-phase Induction Motors (IMs) is recommended in some applications such as blowers, washing machines, mixers, air conditioner, pumps, fans and etc [2]. Besides VFDs for single-phase IMs, drivers control strategies such as scalar-based control and vector-based control have been also proposed to drive the single-phase IMs speed [3]-[21]. Recently, Field-Oriented Control (FOC) of single-phase IMs is extensively adopted to obtain high dynamic performance in drive systems.

Some of the control strategies such as Indirect Rotor Field-Oriented Control (IRFOC) method needs specific knowledge of the rotor flux. A most common technique to obtain the information of rotor flux in IRFOC strategy is using a pure integration. However, using a pure integration to obtain the rotor flux is sensitive to different type of problems such as DC-offset problem. To solve this problem, many efforts based on Artificial Neural Network (ANN), Model Reference Adaptive System (MRAS), Extended Kalman Filter (EKF), Luenberger Observer (LO), Sliding Mode Observer (SMO) and etc are made to improve on the estimation of rotor flux in the IM drives [22]-[33]. Most of these techniques are only applicable to vector controlled 3-phase motor drive systems.

The main focus of the research presented in this paper is to propose a novel method to estimate rotor flux for the case of high performance IRFOC of single-phase IM drives. In order to estimate forward and

backward rotor fluxes in the presented IRFOC strategy, an EKF with two different forward and backward currents that are switched interchangeably (switching forward and backward EKF) is utilized. In spite of computational complexity of the EKF, this method has been recognized as an appropriate method to estimate state variables in vector controlled IM drive systems because of simultaneous identification of parameters and taking system/process and measurement noises. Mathematical analysis and Matlab simulations have been performed to demonstrate the performance of the proposed method.

2.   SINGLE-PHASE IM MODEL

The (d-q) model of a single-phase IM with two different windings can be described by the following equations [7] (in this paper superscript "s" and "e" indicate that the variables are in the stationary and rotating reference frames respectively):

Stator (d-q) voltage equations:

$$\begin{bmatrix} v_{ds}^s \\ v_{qs}^s \end{bmatrix} = \begin{bmatrix} r_{ds}+L_{ds}p & 0 \\ 0 & r_{qs}+L_{qs}p \end{bmatrix}\begin{bmatrix} i_{ds}^s \\ i_{qs}^s \end{bmatrix} + \begin{bmatrix} M_d p & 0 \\ 0 & M_q p \end{bmatrix}\begin{bmatrix} i_{dr}^s \\ i_{qr}^s \end{bmatrix} \tag{1}$$

Rotor (d-q) voltage equations:

$$\begin{bmatrix} v_{dr}^s \\ v_{qr}^s \end{bmatrix} = \begin{bmatrix} M_d p & \omega_r M_q \\ -\omega_r M_d & M_q p \end{bmatrix}\begin{bmatrix} i_{ds}^s \\ i_{qs}^s \end{bmatrix} + \begin{bmatrix} r_r+L_r p & \omega_r L_r \\ -\omega_r L_r & r_r+L_r p \end{bmatrix}\begin{bmatrix} i_{dr}^s \\ i_{qr}^s \end{bmatrix} \tag{2}$$

Stator (d-q) flux equations:

$$\begin{bmatrix} \lambda_{ds}^s \\ \lambda_{qs}^s \end{bmatrix} = \begin{bmatrix} L_{ds} & 0 \\ 0 & L_{qs} \end{bmatrix}\begin{bmatrix} i_{ds}^s \\ i_{qs}^s \end{bmatrix} + \begin{bmatrix} M_d & 0 \\ 0 & M_q \end{bmatrix}\begin{bmatrix} i_{dr}^s \\ i_{qr}^s \end{bmatrix} \tag{3}$$

Rotor (d-q) flux equations:

$$\begin{bmatrix} \lambda_{dr}^s \\ \lambda_{qr}^s \end{bmatrix} = \begin{bmatrix} M_d & 0 \\ 0 & M_q \end{bmatrix}\begin{bmatrix} i_{ds}^s \\ i_{qs}^s \end{bmatrix} + \begin{bmatrix} L_r & 0 \\ 0 & L_r \end{bmatrix}\begin{bmatrix} i_{dr}^s \\ i_{qr}^s \end{bmatrix} \tag{4}$$

Mechanical and torque equations:

$$T_e = \frac{pole}{2}\left(M_q i_{qs}^s i_{dr}^s - M_d i_{ds}^s i_{qr}^s\right)$$

$$T_e - T_l = \frac{2}{pole}\left(Jp\omega_r + B\omega_r\right) \tag{5}$$

In (1)-(5), v_{ds}^s, v_{qs}^s are the stator (d-q) axes voltages, i_{ds}^s, i_{qs}^s denote the stator (d-q) axes currents, i_{dr}^s, i_{qr}^s are the rotor (d-q) axes currents, λ_{ds}^s, λ_{qs}^s are the stator (d-q) axes fluxes and λ_{dr}^s and λ_{qr}^s indicate the rotor (d-q) axes fluxes. r_{ds}, r_{qs} and r_r are the stator and rotor (d-q) axes resistances. L_{ds}, L_{qs}, L_r, M_d and M_q denote the stator and rotor (d-q) axes self and mutual inductances. ω_r is the motor speed. T_e and T_l are electromagnetic torque and load torque. J and B are the moment of inertia and viscous friction coefficient respectively.

3.   ROTOR FIELD-ORIENTED CONTROL STRATEGY OF A SINGLE-PHASE IM

It can be shown that using conventional (balanced) transformation matrix, the single-phase IM (unbalanced 2-phase IM) equations in the rotating reference frame can be obtained as following equations [34]:

$$
\begin{bmatrix} v_{ds}^{e} \\ v_{qs}^{e} \\ 0 \\ 0 \end{bmatrix} =
\begin{bmatrix}
\frac{(r_{ds}+r_{qs})}{2}+\frac{(L_{ds}+L_{qs})}{2}\frac{d}{dt} & -\omega_e\frac{(L_{ds}+L_{qs})}{2} & \frac{(M_d+M_q)}{2}\frac{d}{dt} & -\omega_e\frac{(M_d+M_q)}{2} \\
\omega_e\frac{(L_{ds}+L_{qs})}{2} & \frac{(r_{ds}+r_{qs})}{2}+\frac{(L_{ds}+L_{qs})}{2}\frac{d}{dt} & \omega_e\frac{(M_d+M_q)}{2} & \frac{(M_d+M_q)}{2}\frac{d}{dt} \\
\frac{(M_d+M_q)}{2}\frac{d}{dt} & -(\omega_e-\omega_r)\frac{(M_d+M_q)}{2} & r_r+L_r\frac{d}{dt} & -(\omega_e-\omega_r)L_r \\
(\omega_e-\omega_r)\frac{(M_d+M_q)}{2} & \frac{(M_d+M_q)}{2}\frac{d}{dt} & (\omega_e-\omega_r)L_r & r_r+L_r\frac{d}{dt}
\end{bmatrix}
\underbrace{\begin{bmatrix} i_{ds}^{+e} \\ i_{qs}^{+e} \\ i_{dr}^{+e} \\ i_{qr}^{+e} \end{bmatrix}}_{\begin{bmatrix} v_{ds}^{+e} \\ v_{qs}^{+e} \\ v_{dr}^{+e} \\ v_{qr}^{+e} \end{bmatrix}}
$$

$$
+
\begin{bmatrix}
\frac{(r_{ds}-r_{qs})}{2}+\frac{(L_{ds}-L_{qs})}{2}\frac{d}{dt} & \omega_e\frac{(L_{ds}-L_{qs})}{2} & \frac{(M_d-M_q)}{2}\frac{d}{dt} & \omega_e\frac{(M_d-M_q)}{2} \\
\omega_e\frac{(L_{ds}-L_{qs})}{2} & -\frac{(r_{ds}-r_{qs})}{2}-\frac{(L_{ds}-L_{qs})}{2}\frac{d}{dt} & \omega_e\frac{(M_d-M_q)}{2} & -\frac{(M_d-M_q)}{2}\frac{d}{dt} \\
\frac{(M_d-M_q)}{2}\frac{d}{dt} & (\omega_e-\omega_r)\frac{(M_d-M_q)}{2} & 0 & 0 \\
(\omega_e-\omega_r)\frac{(M_d-M_q)}{2} & -\frac{(M_d-M_q)}{2}\frac{d}{dt} & 0 & 0
\end{bmatrix}
\underbrace{\begin{bmatrix} i_{ds}^{-e} \\ i_{qs}^{-e} \\ i_{dr}^{-e} \\ i_{qr}^{-e} \end{bmatrix}}_{\begin{bmatrix} v_{ds}^{-e} \\ v_{qs}^{-e} \\ v_{dr}^{-e} \\ v_{qr}^{-e} \end{bmatrix}}
\tag{6}
$$

where,

$$
\begin{bmatrix} i_{ds}^{+e} \\ i_{qs}^{+e} \\ i_{ds}^{-e} \\ i_{qs}^{-e} \end{bmatrix} =
\begin{bmatrix}
\cos\theta_e & \sin\theta_e & 0 & 0 \\
-\sin\theta_e & \cos\theta_e & 0 & 0 \\
\cos\theta_e & -\sin\theta_e & 0 & 0 \\
\sin\theta_e & \cos\theta_e & 0 & 0
\end{bmatrix}
\begin{bmatrix} i_{ds}^{s} \\ i_{qs}^{s} \\ i_{dr}^{s} \\ i_{qr}^{s} \end{bmatrix}
$$

$$
\begin{bmatrix} i_{dr}^{+e} \\ i_{qr}^{+e} \\ i_{dr}^{-e} \\ i_{qr}^{-e} \end{bmatrix} =
\begin{bmatrix}
0 & 0 & \cos\theta_e & \sin\theta_e \\
0 & 0 & -\sin\theta_e & \cos\theta_e \\
0 & 0 & \cos\theta_e & -\sin\theta_e \\
0 & 0 & \sin\theta_e & \cos\theta_e
\end{bmatrix}
\begin{bmatrix} i_{ds}^{s} \\ i_{qs}^{s} \\ i_{dr}^{s} \\ i_{qr}^{s} \end{bmatrix}
\tag{7}
$$

In (7), "θ_e" is the angle between the stationary reference frame and rotating reference frame. As can be seen from (6), using conventional (balanced) transformation matrix, the single-phase IM equations can be divided into two forward (superscript "$+e$") and backward (superscript "$-e$") equations. It can be also seen that, the structure of the forward and backward equations is similar to the RFOC equations of a 3-phase IM. As a result, vector control of the single-phase IM using two independent RFOC algorithms (one of them to compensate forward equations and one of them to compensate backward equations) is possible. The block diagram of the proposed RFOC method for a single-phase IM is shown in Figure 1. In this paper, as shown in Figure 1, the single-phase IM is fed from a Sine Pulse Width Modulation (SPWM) two-leg voltage source inverter. In Figure 1, the conventional (balanced) transformation matrix ($[T_s^{e}]$) is as follows:

$$
\begin{bmatrix} i_{ds}^{e} \\ i_{qs}^{e} \end{bmatrix} = [T_s^{e}]\begin{bmatrix} i_{ds}^{s} \\ i_{qs}^{s} \end{bmatrix} =
\begin{bmatrix}
\cos\theta_e & \sin\theta_e \\
-\sin\theta_e & \cos\theta_e
\end{bmatrix}
\begin{bmatrix} i_{ds}^{s} \\ i_{qs}^{s} \end{bmatrix}
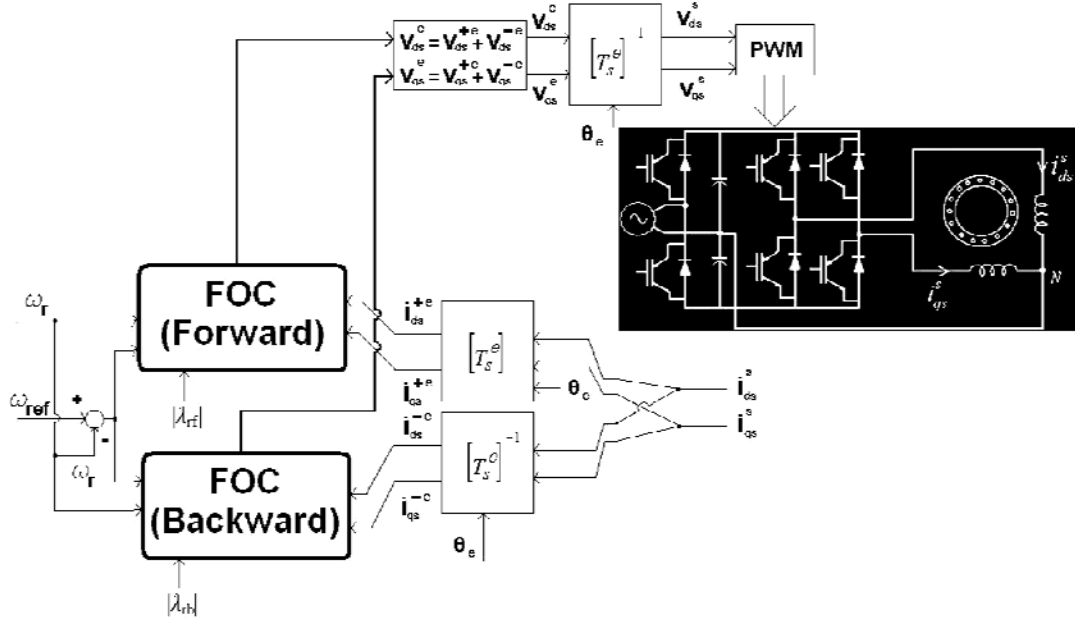\tag{8}
$$

Figure 1. Block diagram of RFOC method for a single-phase IM

4.   SWITCHING FORWARD AND BACKWARD EKF STRATEGY OF A SINGLE-PHASE IM

As mentioned before, some of the control techniques such as RFOC strategy require particular knowledge of the rotor flux. The most popular method to obtain the rotor flux information in indirect RFOC method is using integration. However, using an integration to obtain the rotor flux is sensitive to the different type of problems such as DC-offset problem.

As shown in Figure 1, to control a single-phase IM, two modified RFOC algorithms (forward and backward FOCs) need to be used. In order to accommodate forward and backward rotor fluxes ($|\lambda_{rf}|$ and $|\lambda_{rb}|$) in Figure 1, in this paper an EKF with two different forward and backward currents that are switched interchangeably (switching forward and backward EKF), is proposed. To estimate the forward and backward rotor fluxes, the stator currents and rotor fluxes of the single-phase IM are chosen as the state variables. The state space model of a single-phase IM can be shown as equations (9) and (10):

$$\dot{x} = Ax + Bu \tag{9}$$

$$y = Cx \tag{10}$$

where,

$$x = \begin{bmatrix} i_{ds} & i_{qs} & \lambda_{dr} & \lambda_{qr} \end{bmatrix}^T \tag{11}$$

$$y = \begin{bmatrix} i_{ds} & i_{qs} \end{bmatrix}^T \tag{12}$$

$$u = \begin{bmatrix} v_{ds} & v_{qs} \end{bmatrix}^T \tag{13}$$

In (9) and (10), A, B and C are the system matrix, input matrix and output matrix. Moreover, x, u and y are the system state matrix, system input matrix and system output matrix. Based on equations of the single-phase IM in the rotating reference frame (equation (6)), the matrices of A_f, B_f, C_f, A_b, B_b and C_b in equations (9) and (10) are obtained as follows:

$$
A_f = \begin{bmatrix} a_{11f} & a_{12f} & a_{13f} & a_{14f} \\ a_{21f} & a_{22f} & a_{23f} & a_{24f} \\ a_{31f} & a_{32f} & a_{33f} & a_{34f} \\ a_{41f} & a_{42f} & a_{43f} & a_{44f} \end{bmatrix}
\tag{14}
$$

$$
B_f = \begin{bmatrix} b_{11f} & b_{12f} & b_{13f} & b_{14f} \\ b_{21f} & b_{22f} & b_{23f} & b_{24f} \end{bmatrix}^T
\tag{15}
$$

$$
C_f = \begin{bmatrix} c_{11f} & c_{12f} & c_{13f} & c_{14f} \\ c_{21f} & c_{22f} & c_{23f} & c_{24f} \end{bmatrix}
\tag{16}
$$

$$
A_b = \begin{bmatrix} a_{11b} & a_{12b} & a_{13b} & a_{14b} \\ a_{21b} & a_{22b} & a_{23b} & a_{24b} \\ a_{31b} & a_{32b} & a_{33b} & a_{34b} \\ a_{41b} & a_{42b} & a_{43b} & a_{44b} \end{bmatrix}
\tag{17}
$$

$$
B_b = \begin{bmatrix} b_{11b} & b_{12b} & b_{13b} & b_{14b} \\ b_{21b} & b_{22b} & b_{23b} & b_{24b} \end{bmatrix}^T
\tag{18}
$$

$$
C_b = \begin{bmatrix} c_{11b} & c_{12b} & c_{13b} & c_{14b} \\ c_{21b} & c_{22b} & c_{23b} & c_{24b} \end{bmatrix}
\tag{19}
$$

$$
a_{11f} = 1 - \frac{1}{k_s}\left(\frac{r_{ds}+r_{qs}}{2} + \frac{r_r\left(\frac{M_d+M_q}{2}\right)^2}{L_r^2} \right)dt \quad , \quad a_{12f} = 0 \quad , \quad a_{13f} = \frac{r_r\left(\frac{M_d+M_q}{2}\right)}{k_s L_r^2}dt
$$

$$
a_{14f} = \frac{r_r\left(\frac{M_d+M_q}{2}\right)}{k_s L_r}dt \quad , \quad a_{21f} = 0 \quad , \quad a_{22f} = 1 - \frac{1}{k_s}\left(\frac{r_{ds}+r_{qs}}{2} + \frac{r_r\left(\frac{M_d+M_q}{2}\right)^2}{L_r^2} \right)dt
$$

$$
a_{23f} = -\frac{r_r\left(\frac{M_d+M_q}{2}\right)}{k_s L_r}dt \quad , \quad a_{24f} = \frac{r_r\left(\frac{M_d+M_q}{2}\right)}{k_s L_r^2}dt \quad , \quad a_{31f} = \frac{r_r\left(\frac{M_d+M_q}{2}\right)}{L_r}dt
\tag{20a}
$$

$$
a_{32f} = 0 \quad , \quad a_{33f} = 1 - \frac{r_r}{L_r}dt \quad , \quad a_{34f} = -r_r dt \quad , \quad a_{41f} = 0
$$

$$
a_{42f} = \frac{r_r\left(\frac{M_d+M_q}{2}\right)}{L_r}dt \quad , \quad a_{43f} = r_r dt \quad , \quad a_{44f} = 1 - \frac{r_r}{L_r}dt
$$

$$b_{11f} = \frac{1}{k_s} dt \quad , \quad b_{12f} = 0 \quad , \quad b_{13f} = 0 \quad , \quad b_{14f} = 0$$

$$b_{21f} = 0 \quad , \quad b_{22f} = \frac{1}{k_s} dt \quad , \quad b_{23f} = 0 \quad , \quad b_{24f} = 0 \tag{20b}$$

$$c_{11f} = 1 \quad , \quad c_{12f} = 0 \quad , \quad c_{13f} = 0 \quad , \quad c_{14f} = 0$$

$$c_{21f} = 0 \quad , \quad c_{22f} = 1 \quad , \quad c_{23f} = 0 \quad , \quad c_{24f} = 0 \tag{20c}$$

where,

$$k_s = \left(\frac{L_{ds} + L_{qs}}{2} \right) - \frac{\left(\dfrac{M_d + M_q}{2} \right)^2}{L_r} \tag{20d}$$

moreover,

$$a_{11b} = 1 \quad , \quad a_{12b} = -\omega_r dt \quad , \quad a_{13b} = 0 \quad , \quad a_{14b} = 0$$

$$a_{21b} = \omega_r dt \quad , \quad a_{22b} = 1 \quad , \quad a_{23b} = 0 \quad , \quad a_{24b} = 0$$

$$a_{31b} = 0 \quad , \quad a_{32b} = -\omega_r \left(\frac{M_d - M_q}{2} \right) dt \quad , \quad a_{33b} = 1 \quad , \quad a_{34b} = 0 \tag{21a}$$

$$a_{41b} = \frac{r_r \left(\dfrac{M_d + M_q}{2} \right)}{L_r} dt \quad , \quad a_{42b} = 0 \quad , \quad a_{43b} = 0 \quad , \quad a_{44b} = 1$$

$$b_{11b} = 0 \quad , \quad b_{12b} = 0 \quad , \quad b_{13b} = 0 \quad , \quad b_{14b} = 0$$

$$b_{21b} = 0 \quad , \quad b_{22b} = 0 \quad , \quad b_{23b} = 0 \quad , \quad b_{24b} = 0 \tag{21b}$$

$$c_{11b} = 1 \quad , \quad c_{12b} = 0 \quad , \quad c_{13b} = 0 \quad , \quad c_{14b} = 0$$

$$c_{21b} = 0 \quad , \quad c_{22b} = 1 \quad , \quad c_{23b} = 0 \quad , \quad c_{24b} = 0 \tag{21c}$$

Based on (14)-(21c), two EKF algorithms with the forward and backward currents can be used to estimate forward and backward rotor fluxes in the FOC (Forward) and FOC (Backward) of Figure 1. As an alternative method, to simplify the proposed scheme, single EKF algorithm with only changes in the motor parameters can be used for estimation of rotor fluxes. In this method, the forward and backward currents to obtain the rotor fluxes are switched interchangeably for every sampling time.

It can be mentioned that the structure of proposed scheme during forward and backward conditions is the same as a conventional EKF algorithm (the conventional EKF algorithm is given as (22a)-(22c)). The only difference between proposed estimator during forward and backward conditions with the conventional EKF algorithm is in the motor parameters.

As can be seen from equation (6), the single-phase IM voltage equations have extra terms due to the backward components (superscript "-e"). Since the backward terms are proportional to the difference of the resistances, mutual and self inductances, it is possible to neglect them (In this paper it is assumed that there is not the backward terms).

This EKF algorithm is computed into three main steps as follows [22]:
1. Prediction:

$$x_k^P = A\hat{x}_{k-1} + Bu_{k-1}$$
$$P_k^P = AP_{k-1}A^T + Q \tag{22a}$$

2. Computation of Kalman Filter Gain:

$$K_k = P_k^P C^T \left(CP_k^P C^T + R\right)^{-1} \tag{22b}$$

3. Update:

$$\hat{x}_k = x_k^P + K_k\left(y_k - Cx_k^P\right)$$
$$\hat{P} = \left(1 - K_k C\right)P_k^P \tag{22c}$$

where, R and Q are the covariance matrices of the noises.
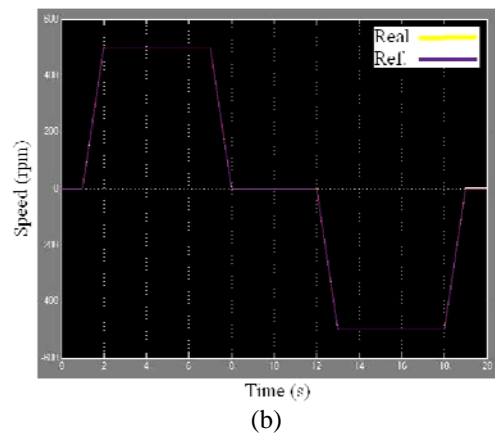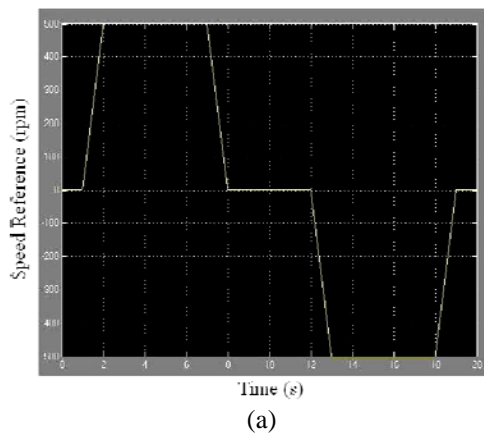
5.   SIMULATION RESULTS

To verify the performance of the proposed drive system, different cases using Matlab/Simulink software for a single-phase IM with two different windings based on Figure 1 are simulated:

(1) Figure 2: vector control of a single-phase IM using proposed controller under load
(2) Figure 3: vector control of a single-phase IM using proposed controller at different speed

In the simulations as shown in this Figure 1 the single-phase IM is fed from a 2-leg voltage source inverter. An EKF with the forward and backward currents is also used to estimate forward and backward rotor fluxes in the FOC (Forward) and FOC (Backward) of Figure 1. The Ratings and parameters of the simulated single-phase IM are as follows:

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_q=0.1772H, J=0.0146kg.m^2

Figure 2 shows the simulation results of the proposed method for vector control of a single-phase IM under load. Figure 2 (a) shows the reference speed, Figure 2 (b) shows the motor speed, Figure 2 (c) shows the speed error, Figure 2 (d) shows the estimated rotor flux (forward flux) and Figure 2 (e) shows the motor torque. In Figure 2, the reference rotor flux is set to 1.1wb. Moreover, in this figure, the value of load is changed from zero to -0.4 at t=15s and removed at t=17s. It can be seen that the proposed controller can maintain the good performance during zero reference speed, ramp reference speed and load condition. It can be seen that the motor speed closely follows the reference speed before and after the load disturbance. In this test the maximum error between reference and real motor speed is about 1.5rpm (see Figure 2 (c)). It is evident from Figure 2 (d) that the estimated rotor flux can follow the reference rotor flux during different conditions. As can be seen from Figure 2 (e), the torque of single-phase IM changes accordingly to applied load disturbance.

(a)   (b)
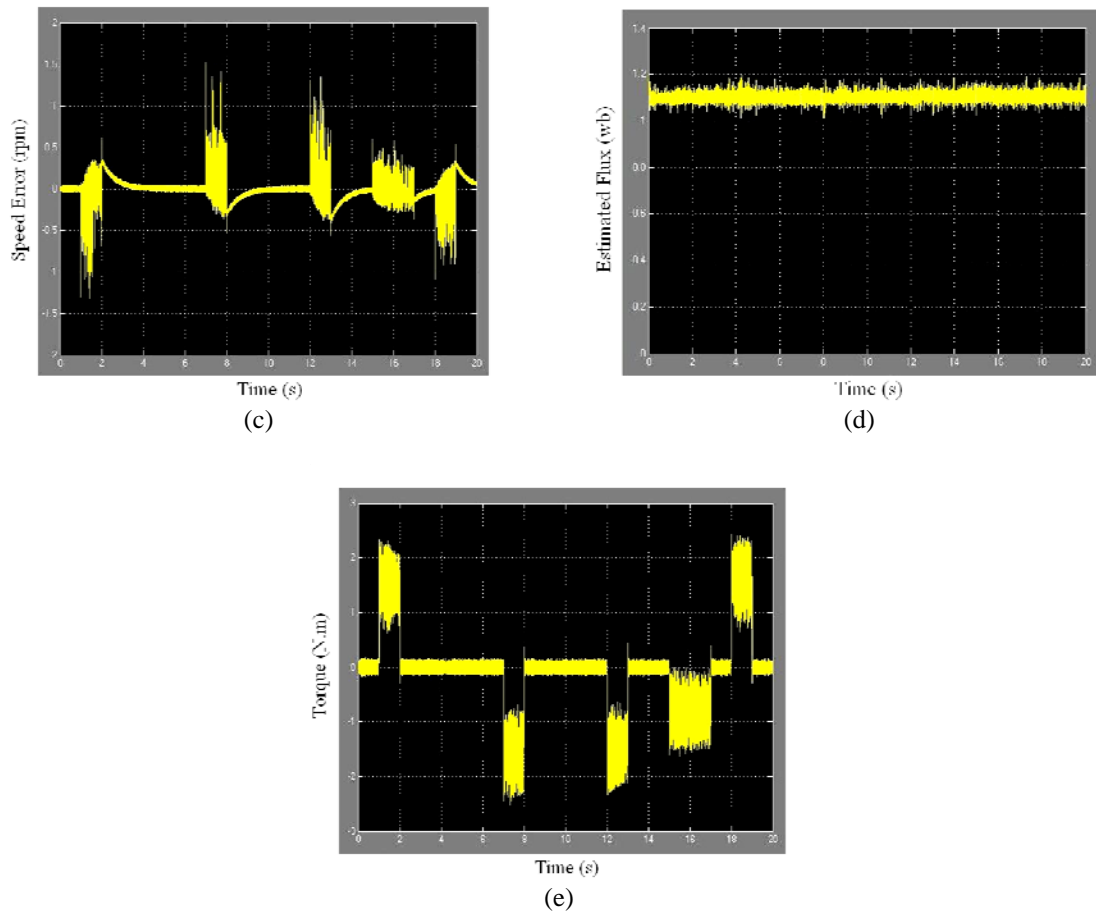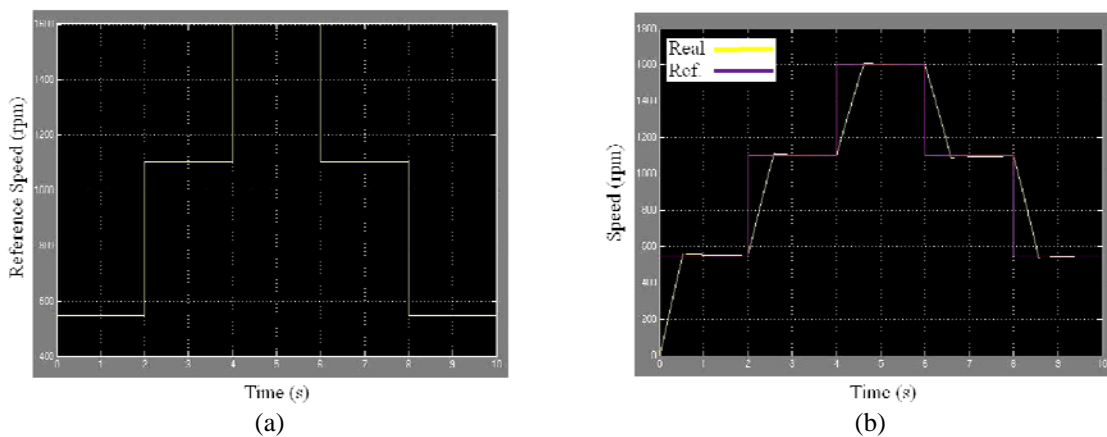
(c)

(d)

(e)

Figure 2. Simulation results of the RFOC of a single-phase IM under load; (a) reference speed, (b) motor speed, (c) speed error, (d) estimated flux and (e) torque

Figure 3 shows simulation results of the proposed method for vector control of a single-phase IM at the different values of reference speed. It is evident from Figure 3 that using proposed technique the single-phase IM can follow the reference speed without any overshoot and steady-state error (see Figure 3 (c)). Figure 3 (d) illustrates the sinusudal form of the currents of main and auxiliary windings during different values of reference speed. As shown from Figure 3 (e), the single-phase IM torque has a quick response with no pulsations. It can be seen from the presented simulation results (Figures 2 and 3) that the performance of the presented control technique and proposed estimator for the single-phase IM drive is acceptable.
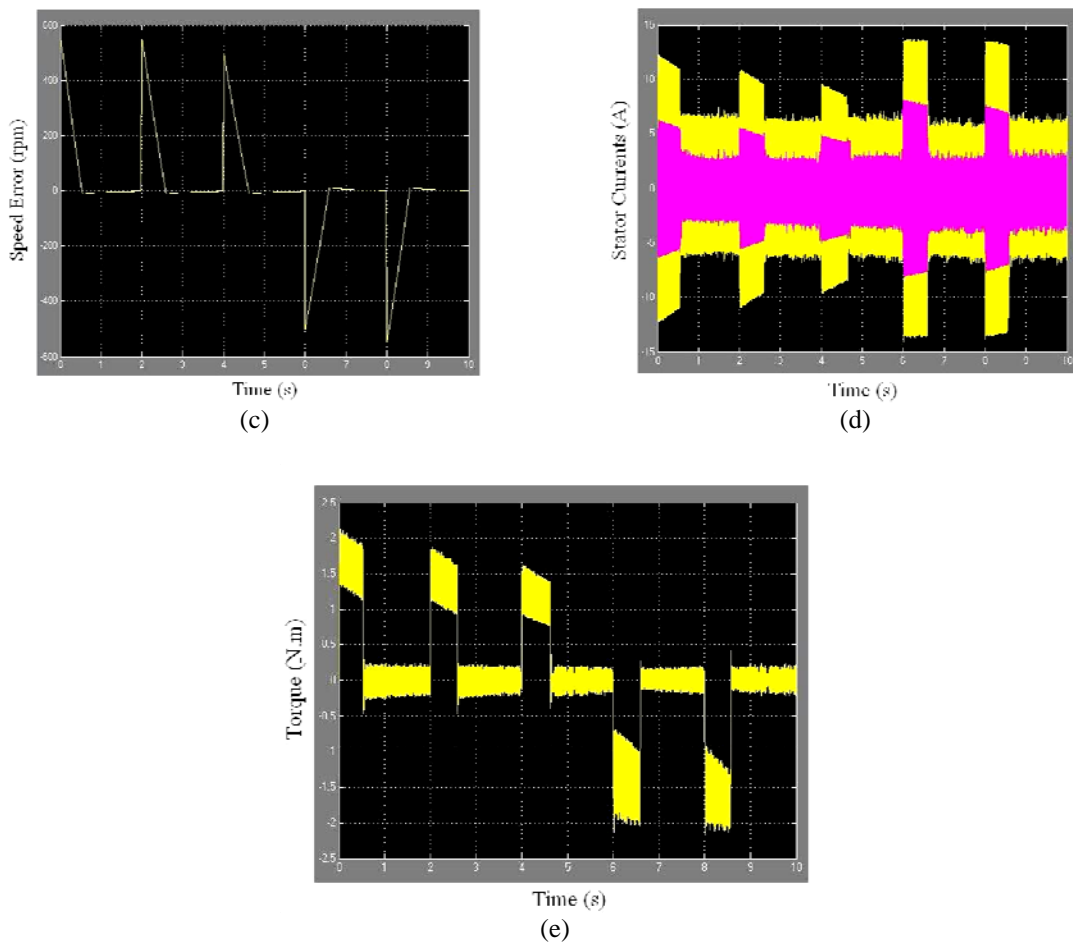

(a)

(b)

(c)

(d)

(e)

Figure 3. Simulation results of the RFOC of a single-phase IM at different speed; (a) reference speed, (b) motor speed, (c) speed error, (d) motor currents and (e) torque

6. CONCLUSION

This paper showed that the equations of a single-phase IM with two different windings in the rotating reference frame can be separated into two set of equations with the balanced structure. Based on this, a vector control method using two developed RFOC algorithms was proposed. In order to accommodate forward and backward rotor fluxes in the presented RFO controller, an Extended Kalman Filter (EKF) with two different forward and backward currents that are switched interchangeably was proposed. Simulation results showed that the proposed scheme for vector control of single-phase IMs works well over most speed ranges.

REFERENCES

[1]   C. Mademlis, I. Kioskeridis, and T. Theodoulidis, "Optimization of single-phase induction Motors-part I: maximum energy efficiency control", *IEEE Transactions on Energy Conversion* , vol. 20, no. 1, pp. 187–195, 2005.

[2]   H.W. Beaty and J.L. Kirtley, "Electric Motor Handbook", McGraw-Hill, 1998.

[3]   N.M. Abdel-Rahim and A.A. Shaltout, "Slip-frequency control of single-phase induction motor operated as two-phase motor", *In 30th Annual Conference of Industrial Electronics Society (IECON 2004)*, 2004, pp. 1417–1422.

[4]   R. de F Campos, J. De Oliveira, L.C. Marques, A. Nied, and S.I. Seleme Jr, " SVPWM-DTC strategy for single-phase induction motor control", *In Electric Machines & Drives Conference (IEMDC'07)*, 2007, pp. 1220–1225.

[5]   N. Abdel-Rahim and A. Shaltout, "An unsymmetrical two-phase induction motor drive with slip-frequency control", *IEEE Transactions on Energy Conversion*, vol. 24, no. 3, pp. 608–616, 2009.

[6]   M. Jemli, H. Ben Azza, M. Boussak, and M. Gossa, "Sensorless indirect stator field orientation speed control for single-phase induction motor drive", *IEEE Transactions on Power Electronics*, vol. 24, no. 6, pp. 1618–1627, 2009.

[7]   M.B. de Rossiter Corrêa, C. B. Jacobina, A.M.N. Lima, and E.R.C. da Silva, "Rotor-flux-oriented control of a single-phase induction motor drive", *IEEE Transactions on Industrial Electronics*, vol. 47, no. 4, pp. 832–841, 2000.

[8]   M. Jannati, N.R.N. Idris, M.J.A. Aziz, A. Monadi, and A.A.M. Faudzi, "A Novel Scheme for Reduction of Torque and Speed Ripple in Rotor Field Oriented Control of Single Phase Induction Motor Based on Rotational Transformations", *Research Journal of Applied Sciences, Engineering and Technology*, vol. 7, no. 16, pp. 3405–3409, 2014.

[9]   M. Jannati, A. Monadi, N.R.N. Idris, and A.A.M. Faudzi, "Analytical calculation of the RFOC method in single-phase induction motor", *International Journal of Electronics*, pp. 1–19, 2015.

[10]   M.B. de Rossiter Corrêa, C.B. Jacobina, E.R.C. Da Silva, and A.M.N. Lima, "Vector control strategies for single-phase induction motor drive systems," *IEEE Transactions on Industrial Electronics*, vol. 51, no. 5, pp. 1073–1080, 2004.

[11]   S. Reicy and S. Vaez-Zadeh, "Vector Control of Single-Phase Induction Machine with Maximum Torque Operation", *Proceedings of the IEEE International Symposium on Industrial Electronics*, 2005, pp. 923–928.

[12]   M. Jemli, H.B. Azza, and M. Gossa, "Real-time implementation of IRFOC for Single-Phase Induction Motor drive using dSpace DS 1104 control board", *Simulation Modelling Practice and Theory*, vol. 17, no. 6, pp. 1071–1080, 2009.

[13]   H. Ben Azza, N. Zaidi, M. Jemli, and M. Boussak, "Development and experimental evaluation of a sensorless speed control of SPIM using adaptive sliding mode-MRAS strategy", *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 2, no. 2, pp. 319–328, 2014.

[14]   B. Zahedi and S. Vaez-Zadeh, "Efficiency optimization control of single-phase induction motor drives", *IEEE Transactions on Power Electronics*, vol. 24, no. 4, pp. 1062–1070, 2009.

[15]   F.A. Neves, J.M.S. Cruz, R.P. Landim, Z.D. Lins, and A.G.H. Accioly, "Single-phase induction motor drives with direct torque control", *In 28th Annual Conference of the Industrial Electronics Society (IECON 02)*, 2002, pp. 241–246.

[16]   R. de F Campos, L.F.R. Pinto, J. De Oliveira, A. Nied, L.C. de Marques, and A.H. De Souza, "Single-Phase Induction Motor Control Based on DTC Strategies", *In International Symposium on Industrial Electronics (ISIE 2007)*, 2007, pp. 1068–1073.

[17]   R.P. Vieira and H. Grundling, "Sensorless speed control with a MRAS speed estimator for single-phase induction motors drives", *In 13th European Conference on Power Electronics and Applications (EPE'09)*, 2009, pp. 1–10.

[18]   M. Jannati, T. Sutikno, N.R.N. Idris, and M.J.A. Aziz, "A Novel Technique for Fault-Tolerant Control of Single-Phase Induction Motor", *TELKOMNIKA (Telecommunication Computing Electronics and Control)*, vol. 13, no. 3, pp. 783–793, 2015.

[19]   M. Jannati, T. Sutikno, N.R.N. Idris, and M.J.A. Aziz, "A Novel Method for Rotor Field-Oriented Control of Single-Phase Induction Motor", *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 5, vol. 2, pp. 205–212, 2015.

[20]   M. Jannati, N.R.N. Idris, M.J.A. Aziz, S.H. Asgari, A. Monadi, and A.A.M. Faudzi, "A new method for RFOC of single-phase induction motor based on rotational transformations", *In 2013 IEEE Student Conference on Research and Development (SCOReD)*, 2013, pp. 215–220.

[21]   S. Kascak, M. Prazenica, and B. Dobrucky, "Position control of Two-Phase Induction motor using dSpace environment", *In 38th Annual Conference on IEEE Industrial Electronics Society (IECON 2012)*, 2012, pp. 1958–1963.

[22]   M. Barut, R. Demir, E. Zerdali, and R. Inan, "Real-time implementation of bi input-extended Kalman filter-based estimator for speed-sensorless control of induction motors", *IEEE Transactions on Industrial Electronics*, vol. 59, no. 11, pp. 4197–4206, 2012.

[23]   M. Tursini, R. Petrella, and F. Parasiliti, "Adaptive sliding-mode observer for speed-sensorless control of induction motors", *IEEE Transactions on Industry Applications*, vol. 36, no. 5, pp. 1380–1387, 2000.

[24]   B. Karanayil, M.F. Rahman, and C. Grantham, "Online stator and rotor resistance estimation scheme using artificial neural networks for vector controlled speed sensorless induction motor drive", *IEEE Transactions on Industrial Electronics*, vol. 54, no. 1, pp. 167–176, 2007.

[25]   S. Bogosyan, M. Barut, and M. Gokasan, "Braided extended Kalman filters for sensorless estimation in induction motors at high-low/zero speed", *IET Control Theory Appl.*, vol. 1, no. 4, pp. 987–998, 2007.

[26]   E.S. De Santana, E. Bim, and W.C.D. Amaral, "A predictive algorithm for controlling speed and rotor flux of induction motor", *IEEE Transactions on Industrial Electronics*, vol. 55, no. 12, pp. 4398–4407, 2008.

[27]   M. Hajian, J. Soltani, G.A. Markadeh, and S. Hosseinnia, "Adaptive nonlinear direct torque control of sensorless IM drives with efficiency optimization", *IEEE Transactions on Industrial Electronics*, vol. 57, no. 3, pp. 975–985, 2010.

[28]   F.R. Salmasi and T.A. Najafabadi, "An adaptive observer with online rotor and stator resistance estimation for induction motors with one phase current sensor", *IEEE Transactions on Energy Conversion*, vol. 26, no. 3, pp. 959–966, 2011.

[29]   T. Orlowska-Kowalska and M. Dybkowski, "Stator-current-based MRAS estimator for a wide range speed-sensorless induction-motor drive", *IEEE Transactions on Industrial Electronics*, vol. 57, no. 4, pp. 1296–1308, 2010.

[30] K. Kouzi, L. Mokrani, and M.S. Nait, "High performances of fuzzy self-tuning scaling factor of PI fuzzy logic controller based on direct vector control for induction motor drive without flux measurements", *In 2004 IEEE International Conference on Industrial Technology (IEEE ICIT'04)*, 2004, pp. 1106–1111.

[31] B. Purwahyudi, "RNN Based Rotor Flux and Speed Estimation of Induction Motor", *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 1, no. 1, pp. 58–64, 2011.

[32] A. Savoia, M. Mengoni, L. Zarri, and D. Casadei, "A nonlinear luenberger observer for sensorless vector control of induction motors", *In 2011 International Aegean Conference on Electrical Machines and Power Electronics and 2011 Electromotion Joint Conference (ACEMP)*, 2011, pp. 544–549.

[33] X. Zhang, "Sensorless Induction Motor Drive Using Indirect Vector Controller and Sliding-Mode Observer for Electric Vehicles", *IEEE Transactions on Vehicular Technology*, vol. 62, no. 7, pp. 3010–3018, 2013.

[34] M. Jannati, N.R.N. Idris, and M.J.A. Aziz, "A new method for RFOC of Induction Motor under open-phase fault", *In 39th Annual Conference of the Industrial Electronics Society (IECON 2013)*, 2013, pp. 2530–2535.