The Sensorless Speed Controller of Induction Motor in DFOC Model Based on the Voltage and Current

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Abstract. *This paper presents the Sensorless Speed control of the Induction Motor (IM) in Direct Field Oriented Control (DFOC) modeling based on the mathematical model of the voltage and current parameter. The first is DFOC controlled modeling of IM, the second presents sensorless speed controller base on RF-MRAS, the third describes the model of the sensorless speed controller based on measured values directly from the induction motor as the voltage and current. The last is simulation results in the Matlab-Simulink environment. These results indicate that this proposed method can determine accurately, very quickly the speed of the induction motor and can be applied in the practice with high reliability, and low cost.*

Keywords

Direct Field Oriented Control, Induction Motor, Sensorless, Estimate Speed, Low Cost, Machine Model.

List of symbols

v_{sx}, v_{sy}	Components of stator voltage in $[x, y]$ system
i_{sx}, i_{sy}	Components of stator current in $[x, y]$ system
i_{rx}, i_{ry}	Components of stator current in $[x, y]$ system
T_e	The torque of induction motor
θ_e	Component of rotor flux angle
ω_e	Rotor electrical speed
ω_{sl}	Rotor slip speed
ω_0	Rotor speed
$\hat{\omega}_0$	Estimated rotor speed
S	Laplace operation
P	The number of poles
$P = P/2$	The number of pole pairs
$v_{s\alpha}, v_{s\beta}$	Component of stator voltage in $[\alpha - \beta]$ system
$i_{s\alpha}, i_{s\beta}$	Component of stator current in $[\alpha - \beta]$ system
$\psi_{R\alpha}, \psi_{R\beta}$	Component of rotor flux in $[\alpha - \beta]$ system
$\hat{\psi}_{R\alpha}, \hat{\psi}_{R\beta}$	Component of estimated rotor flux in $[\alpha - \beta]$ system
R_s, R_r	Stator resistance, rotor resistance
L_m, L_s	Magnetizing inductance, stator inductance
L_r, T_r	Rotor inductance, rotor time constant

1. Introduction

The controller of an induction motor without speed sensors have the advantage of low cost and high reliability, reduction of hardware, working in hostile environments, decreased maintenance requirements. The sensorless speed control method can be classified as follows:

1. The method with machine model such as open loop estimators, Model Reference Adaptive System (MRAS) [1]- [5], observes (Kalman filter, extended Kalman filter) [6]; Luenberger observer [7]; sliding mode observer.

2. Method without machine model is the estimators using intelligence algorithms such as Kalman filter techniques, Neural network, Fuzzy-logic based sensorless control [8]- [12], etc.

The model of reference adaptive system approach [3] is based on the comparison between the outputs of two machine models: the first one (reference model) does not contain the rotor speed, while the second one (adaptive model) uses the speed to estimate the machine flux. The outputs of the two models are compared to obtain an error signal. The error is the input of a proper adaptation mechanism to generate the estimated speed which is fed back to the adaptive model. This solution requires open-loop integration and drift problems could appear, this aspect is solved using a Low-Pass Filter (LPF) instead of an integrator. The Adaptive-Observers (AO) approach using the Luenberger observer [7] or the Kalman filter [6], gets accurate flux and speed estimates under detuned operating conditions. The key issue of the AO is the computation of their gain matrix to get stability and optimum filtering when both inputs and outputs are corrupted by noise. These solutions are still considered computationally intensive or difficult to tune, so the MRAS modeling is pretty complexity.

The estimators with using intelligence algorithms take much time so it needs a powerful processor such as a digital signal processor (DSP), which also means higher prices.

This paper proposes a simple and robust Sensorless speed of Direct Field Oriented Control (DFOC) scheme for low cost applications. The DFOC model improves motor exploitation (torque, power factor) and the drive efficiency. The proposed scheme is based on measured current and voltage of closed-loop DFOC speed controlled modeling. This algorithm is very effective for fast estimation and does not require high speed DSP (It also means reducing costs), but methods using soft-calculated algorithms have a longer response time and require a high-speed DSP and mean that the cost will be higher. The SS-DFOC scheme has been developed and implemented on a low-cost Chip-based controller with the induction motor drive for a primary vacuum pump, fan, etc is used in industrial applications.

2. THE MODEL OF IM IN DFOC CONTROL STRUCTURE

This part will present the Mathematical Base and speed controlled structure of induction motor with sensorless speed in Direct Field Oriented Control model.

2.1. The Mathematical Base of the Induction Motor

The equations of the induction motor model in $x-y$ the coordinates are expressed as follows [10,13]:

$$\begin{aligned} v_{sx} &= (R_s + sL_s)i_{sx} - L_s\omega_e i_{sy} \\ &\quad + sL_m i_{rx} - L_m\omega_e i_{ry} \qquad (1) \\ v_{sy} &= L_s\omega_e i_{sx} + (R_s + sL_s)i_{sy} \\ &\quad + L_m\omega_e i_{rx} + sL_m i_{ry} \qquad (2) \\ 0 &= sL_m i_{sx} - L_m\omega_{sl} i_{sy} \\ &\quad + (R_r + sL_r)i_{rx} - L_r\omega_{sl} i_{ry} \qquad (3) \\ 0 &= L_m\omega_{sl} i_{sx} + sL_m i_{sy} \\ &\quad + (R_r + sL_r)i_{ry} + L_r\omega_{sl} i_{rx} \qquad (4) \\ T_e &= (3/2)PL_m(i_{sy}i_{rx} - i_{sx}i_{ry}) \qquad (5) \end{aligned}$$

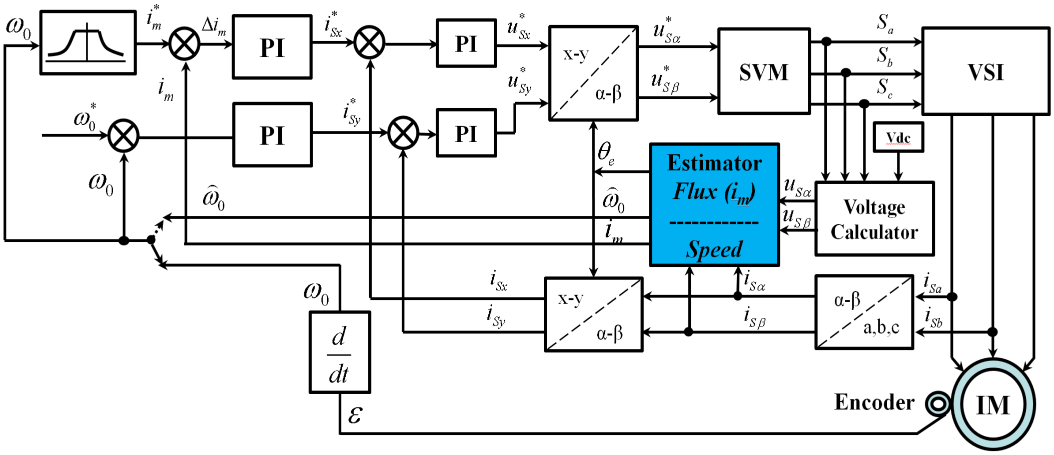

Fig. 1: The Sensorless Speed Direct Field Oriented Control (SS-DFOC) method block diagram.

2.2. The Speed Control Structure of the Induction Motor Drive

From the above equation system, we will construct the SS-DFOC control structure for induction motor drive as below Fig.1. [1,13].

3. ESTIMATE SPEED OF IM BASE ON RF-MRAS MODEL

3.1. The Mathematical Equations of RF-MRAS Model

$$\psi_{R\alpha} = \frac{L_r}{L_m}\left(\int \left(u_{s\alpha} - \hat{R}_s i_{s\alpha}\right) \mathrm{d}t - \sigma L_s i_{s\alpha}\right) \quad (6)$$

$$\psi_{R\beta} = \frac{L_r}{L_m}\left(\int \left(u_{s\beta} - \hat{R}_s i_{s\beta}\right) \mathrm{d}t - \sigma L_s i_{s\beta}\right) \quad (7)$$

$$\hat{\psi}_{R\alpha} = \int \left(\frac{L_m}{T_r} i_{s\alpha} - \frac{1}{T_r}\hat{\psi}_{R\alpha} - \omega_0 \hat{\psi}_{R\beta}\right) \mathrm{d}t \quad (8)$$

$$\hat{\psi}_{R\beta} = \int \left(\frac{L_m}{T_r} i_{s\beta} - \frac{1}{T_r}\hat{\psi}_{R\beta} + \omega_0 \hat{\psi}_{R\alpha}\right) \mathrm{d}t \quad (9)$$

In this model, we only care about the speed of the motor, so the value of the stator resistor is known as given in the simulation (the value of the stator resistor is easily collected by ohm meter).

The signal of error is given by the following expression:

$$\xi = \hat{\psi}_{R\alpha}\psi_{R\beta} - \hat{\psi}_{R\beta}\psi_{R\alpha} \quad (10)$$

$$\hat{\omega}_0 = K_P \xi + K_I \int_0^t \xi \mathrm{d}t, \quad (11)$$

where $K_P > 0$, $K_I > 0$.

3.2. The RF-MRAS Model

The block structure of the model of reference adaptive system (RF-MRAS) with the adaptation method of the speed estimation is shown in Fig. 2. [3,13].

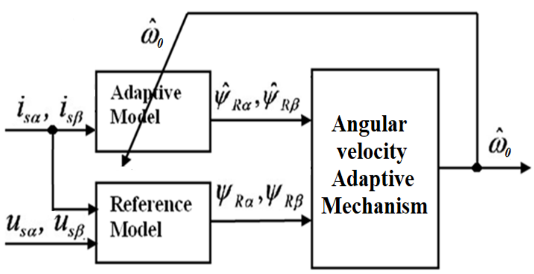

Fig. 2: The schemes of speed estimation use RF-MRAS model.

4. ESTIMATE SPEED OF IM BASE ON MACHINE MODEL (MM)

4.1. The mathematical equations of Machine Model

$$\frac{\mathrm{d}i_{s\alpha}}{\mathrm{d}t} = k_T(R_rL_s + L_rR_s)i_{s\alpha} - P\omega_0 i_{s\beta} - k_TR_r\psi_{s\alpha} - P\omega_0K_TL_r\psi_{s\beta} - K_TL_rV_{s\alpha} \quad (12)$$

$$\frac{\mathrm{d}i_{s\beta}}{\mathrm{d}t} = k_T(R_rL_s + L_rR_s)i_{s\beta} + P\omega_0 i_{s\alpha} - k_TR_r\psi_{s\beta} + P\omega_0K_TL_r\psi_{s\alpha} - K_TL_rV_{s\beta} \quad (13)$$

$$\frac{\mathrm{d}\psi_{s\alpha}}{\mathrm{d}t} = V_{s\alpha} - R_s i_{s\alpha} \quad (14)$$

$$\frac{\mathrm{d}\psi_{s\beta}}{\mathrm{d}t} = V_{s\beta} - R_s i_{s\beta} \quad (15)$$

Integrate the two sides of (14) and (15) we have

$$\psi_{s\alpha}(t) - \psi_{s\alpha}(0) = \int_0^t V_{s\alpha}\mathrm{d}t - \int_0^t R_s i_{s\alpha}\mathrm{d}t \quad (16)$$

$$\psi_{s\beta}(t) - \psi_{s\beta}(0) = \int_0^t V_{s\beta}\mathrm{d}t - \int_0^t R_s i_{s\beta}\mathrm{d}t \quad (17)$$

with $\psi_{s\alpha}(0) = 0, \psi_{s\beta}(0) = 0$, substitution of Equations (16) and (17) into Equations (12) and (13) separately, we obtain the following equations:

$$\frac{\mathrm{d}i_{s\alpha}}{\mathrm{d}t}i_{s\alpha} = k_T(R_rL_s + L_rR_s)i_{s\alpha} - P\omega_0 i_{s\beta} + k_TR_rR_s\int_0^t i_{s\alpha}\mathrm{d}t + PK_TL_rR_s\omega_0(\int_0^t i_{s\beta}\mathrm{d}t) - K_TL_rV_{s\alpha} - k_TR_r\int_0^t V_{s\alpha}\mathrm{d}t - PK_TL_r\omega_0\int_0^t V_{s\beta}\mathrm{d}t \quad (18)$$

$$\frac{\mathrm{d}i_{s\beta}}{\mathrm{d}t} = k_T(R_rL_s + L_rR_s)i_{s\beta} + P\omega_0 i_{s\beta} + k_TR_rR_s\int_0^t i_{s\beta}dt - PK_TL_rR_s\omega_0\int_0^t i_{s\alpha}\mathrm{d}t - K_TL_rV_{s\beta} - k_TR_r\int_0^t V_{s\beta}\mathrm{d}t + PK_TL_r\omega_0\int_o^t V_{s\alpha}\mathrm{d}t \quad (19)$$

The above integral equations may be written in the following concise forms.

$$\omega_0(-A_1X_1 - A_2X_2 - A_3X_3) = A_4X_4 + A_5X_5 + A_6X_6 + A_7X_7 + A_8X_8 \quad (20)$$

$$\omega_0(A_1Y_1 + A_2Y_2 + A_3Y_3) = A_4Y_4 + A_5Y_5 + A_6Y_6 + A_7Y_7 + A_8Y_8 \quad (21)$$

where

$$\begin{cases} X_1 = \int_0^t V_{s\beta}\mathrm{d}t; Y_1 = \int_0^t V_{s\alpha}\mathrm{d}t; A_1 = -Pk_TL_r \\ X_2 = i_{s\beta}; Y_2 = i_{s\alpha}; A_2 = -P \\ X_3 = \int_0^t i_{s\beta}\mathrm{d}t; Y_3 = \int_0^t i_{s\alpha}\mathrm{d}t; A_3 = Pk_TL_rR_s \\ X_4 = V_{s\alpha}; Y_4 = V_{s\beta}; A_4 = -k_TL_r \\ X_5 = \int_0^t V_{s\alpha}\mathrm{d}t; Y_5 = \int_0^t V_{s\beta}\mathrm{d}t; A_5 = -k_TR_r \\ X_6 = i_{s\alpha}; Y_6 = i_{s\beta}; A_6 = k_T(R_rL_s + L_rR_s) \\ X_7 = \int_0^t i_{s\alpha}\mathrm{d}t; Y_7 = \int_0^t i_{s\beta}\mathrm{d}t; A_7 = k_TR_rR_s \\ X_8 = \frac{di_{s\alpha}}{dt}; Y_8 = \frac{di_{s\beta}}{dt}; A_8 = -1 \end{cases} \quad (22)$$

Equations (20) and (21) are functions of the rotor speed, we can rewrite as

$$\omega_0 D_\beta = D_\alpha \quad (23)$$

$$\omega_0 Q_\alpha = Q_\beta \quad (24)$$

with

$$
\begin{aligned}
D_\beta &= -A_1X_1 - A_2X_2 - A_3X_3 \\
D_\alpha &= A_4X_4 + A_5X_5 + A_6X_6 + A_7X_7 + A_8X_8 \\
Q_\alpha &= A_1Y_1 + A_2Y_2 + A_3Y_3 \\
Q_\beta &= A_4Y_4 + A_5Y_5 + A_6Y_6 + A_7Y_7 + A_8Y_8
\end{aligned}
\tag{25}
$$

From (23) and (24) we calculate the angular velocity as follows:

$$\omega_0 = \frac{D_\alpha}{D_\beta}; \omega_0 = \frac{Q_\beta}{Q_\alpha} \tag{26}$$

However, we cannot use them to estimate the rotor speed directly because the sinusoidal variables D_β and Q_α may equal zero. In order to avoid division by zero, we can change as follows: squaring equations (23) and (24) adding the resulting equations.

$$\omega_0^2(D_\beta^2 + Q_\alpha^2) = D_\alpha^2 + Q_\beta^2 \tag{27}$$

Take the square root of both sides, we obtain the expression as:

$$\omega_0\sqrt{D_\beta^2 + Q_\alpha^2} = \sqrt{D_\alpha^2 + Q_\beta^2} \tag{28}$$

When the magnitude of the sinusoidal variables is larger than zero, the rotor speed may be estimated by:

$$\omega_0 = \frac{\sqrt{D_\alpha^2 + Q_\beta^2}}{\sqrt{D_\beta^2 + Q_\alpha^2}}$$

with $D_\alpha; D_\beta; Q_\beta; Q_\alpha$ are calculated from (25).

$$\omega_0 = \frac{\sqrt{(\sum\limits_{i=4}^{8} A_iX_i)^2 + (\sum\limits_{i=4}^{8} A_iY_i)^2}}{\sqrt{(\sum\limits_{i=1}^{3} -A_iX_i)^2 + (\sum\limits_{i=1}^{3} A_iY_i)^2}} \tag{29}$$

However, the above formula gives only the absolute value of the angular velocity. We need to identify its sign with the following inference: From (4.21) we have:

$$\text{sign} = \frac{D_\alpha D_\beta + Q_\beta Q_\alpha}{|D_\alpha D_\beta + Q_\beta Q_\alpha|} \tag{30}$$

The last formula uses to calculate the angular velocity as follows:

$$\omega_0 = \frac{D_\alpha D_\beta + Q_\beta Q_\alpha}{|D_\alpha D_\beta + Q_\beta Q_\alpha|} \cdot \frac{\sqrt{(\sum\limits_{i=4}^{8} A_iX_i)^2 + (\sum\limits_{i=4}^{8} A_iY_i)^2}}{\sqrt{(\sum\limits_{i=1}^{3} -A_iX_i)^2 + (\sum\limits_{i=1}^{3} A_iY_i)^2}} \tag{31}$$

In addition, we need to use the low pass filters at the input of the signals: $v_{s\alpha}, v_{s\beta}, i_{s\alpha}, i_{s\beta}$ and the output of signal: w_0 to eliminate the noise that can affect the accuracy of the estimated velocity.

The applications in real, the desired pass-band frequency is 100 Hz (628.3 rad/s), we need five Analog Filter Blocks.

The blocks have the following feature:

Design method: Butterworth, Filter type: Low-pass, Filter order =1, Pass-band cut frequency (rad/s) = 628.3 rad/s

Now, we build the speed estimation model as shown in Fig. 3.

4.2. The Machine Model

From equation (31) we proved. Now, we construct a model of estimation of speed as follows:

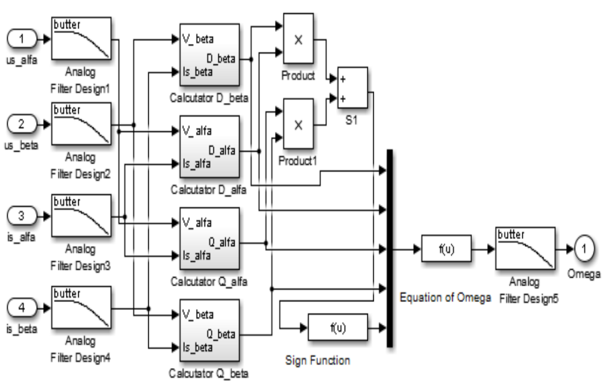

Fig. 3: The schemes of Speed Estimation base on Machine Model.

5. SIMULATION RESULTS

The induction motor is used for simulation in MATLAB-SIMULINK has the following basic parameters: $P = 0.735$ kW, U_{dc} =270 V, $P_p = 2$, R_S =2.1 Ω, R_r =2.51 Ω, L_m = 0.129 H, L_S = 0.137 H, L_r = 0.137 H, J=0.043 kg.m^2.

In this section, we will simulate three different speed levels: 100 rpm, 60 rpm and -40 rpm for both methods.

5.1. Estimate Speed of IM base on RF-MRAS Model

The following figures show the response of the estimated speed with the RF-RAS model, the error between the estimated speed and the actual speed (see Figs. 4-6).

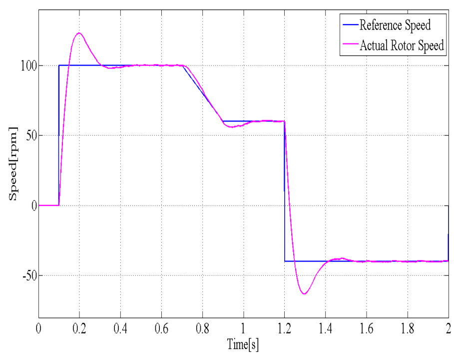

Fig. 4: Reference speed ω_{ref} (blue) and actual rotor speed ω_0 (magenta) of the IM drive.

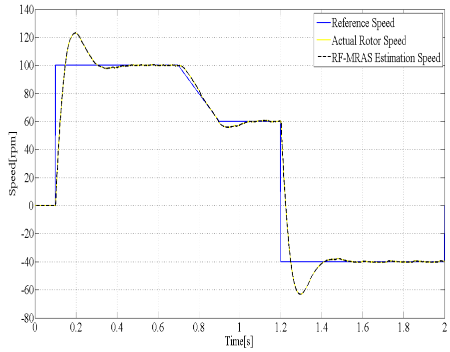

Fig. 5: Reference speed ω_{ref} (blue) and actual rotor speed ω_0 (yellow) and RF-MRAS estimated speed (black) of the IM drive.

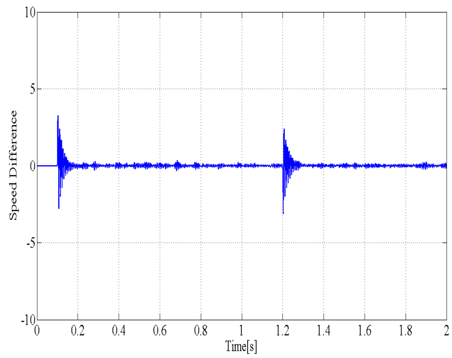

Fig. 6: The difference between real speed and RF-MRAS estimated speed.

5.2. Estimate Speed of IM base on the Machine Model (MM)

This part we also have the response of the estimated speed with the MM model, the difference between the estimated speed and the actual speed as follows: (see Fig.7)

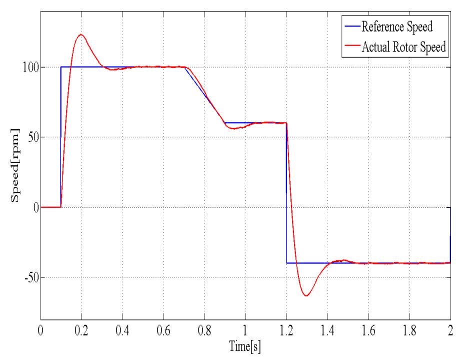

Fig. 7: Reference speed ω_{ref} (blue) and actual rotor speed ω_0 (red) of the IM drive.

In case we do not use a low-pass filter, the response we get is as follows: (see Fig. 8)

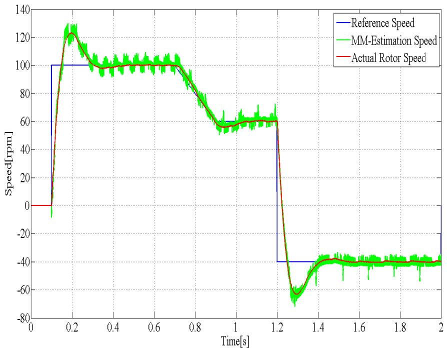

Fig. 8: Reference speed ω_{ref} (red), actual rotor speed ω_0 (red) and MM estimated speed (green) of the IM drive.

In case we use the low-pass filter in the model, the response we get is as shown below: (see Figs. 9-10)

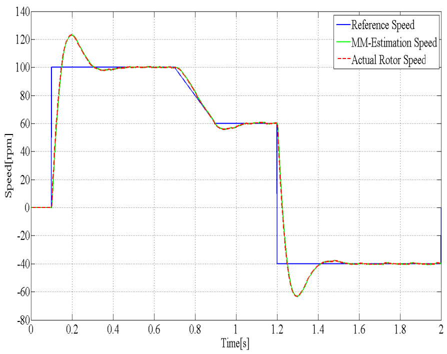

Fig. 9: Reference speed ω_{ref} (blue), actual rotor speed ω_0 (red) and MM estimated speed (green) of the IM drive.

From the above simulation results, we find that when there is no low-pass filter, the response of the speed is ripple (Fig. 8.) but when using a low-pass filter the accuracy of the MM method is good at many different speeds (Fig. 9.), at the speed is near zero, the error is still quite large [1] and [9]. Comparing the MM method to the RF-MRAS model, we find that its characteristics are approximately equal.

In addition, we also obtain the response of the stator current and rotor flux during the operation as follows: (see Figs. 11-12)

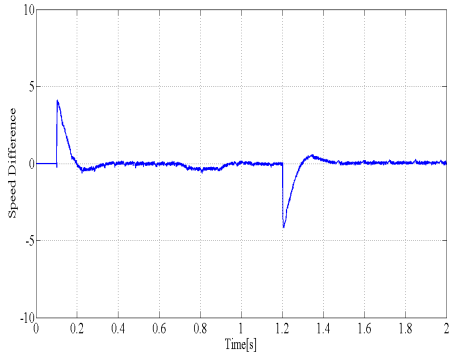

Fig. 10: The difference between real speed and MM estimated speed.

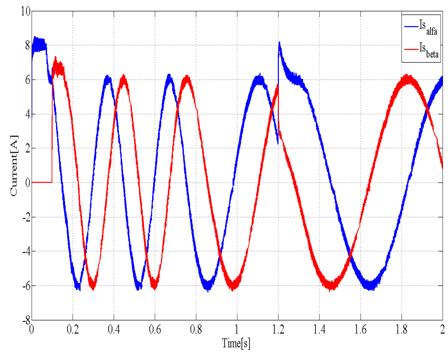

Fig. 11: The components of the stator current: Is_α (blue) and Is_β (red).

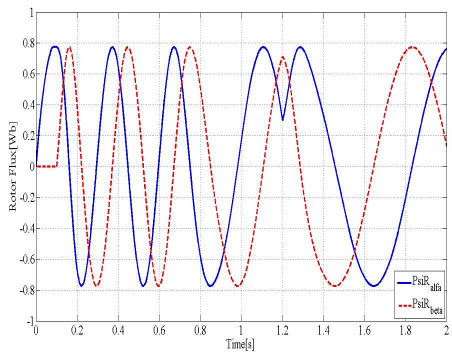

Fig. 12: The components of the rotor flux: PsiR_α (blue) and PsiR_β (red).

With the response of the current and flux at 1.2 seconds, the speed of the induction motor changing direction leads to a sudden change in its response.

6. CONCLUSIONS

This paper presents a method; for estimating the speed of an induction motor; based on a machine model (MM). It achieves accuracy at many different speed levels, but it is limited at near zero speed. Its characteristics are compared to the RF-MRAS model, its advantage is that the convergence time is faster than RF-MRAS model because it calculates directly the current and voltage measured from the induction motor. RF-MRAS model is adaptive so they need time to converge. Also on the hardware, it does not need a high speed DSP as intelligent estimation methods: Genetic Algorithm (GA), Artificial Neural Network (ANN) [8] and [9], Fuzzy logic [10] etc and thus reduces the cost of implementation. They can be applied in places where no need to operate at near zero speed such as fans, pumps, etc or other applications using V/Hz technology in the past.

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