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Speed Control of Induction Motor with Sensorless Speed Measurement using Only Stator Variables

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Abstract: This paper proposes a new sensorless speed measurement algorithm through stator voltage and current variables for induction motors. The limitations of the mechanical/optical speed sensors can be overcome if the induction motor (IM) rotor speed can be evaluated from the input variables of the motor. In this proposed algorithm, rotor speed measurement is done by using stator currents and stator voltages represented in stationary (α-β) reference frame (SRF) fixed to the stator. The proposed method requires the computation of the time derivative of the rotor flux linkages which can be done easily using two successive samples of the rotor flux linkages. Mathematical model of IM is briefly explained to understand a physical structure of the proposed sensorless speed measurement algorithm. The performance of the IM is examined by applying the speed estimation algorithm for Direct Torque Control (DTC) using Space vector modulation (SVM) of IM drive. The analysis is done through simulation using MATLAB/SIMULINK.

Keywords: Space vector modulation, Sensorless speed estimation, Direct torque control.

1. INTRODUCTION

Precise speed computation is significant for control strategy and/or speed control of variable voltage variable frequency IM drive [1-4]. The rotor speed of the IM can be measured by using optical/mechanical speed sensors. Installation of speed sensor at the motor shaft is not feasible in some applications due to the retrofit situations and also due to increase in size, cost and hardware complexity of the drive system [5, 10]. In addition, frequent maintenance of the speed sensor is required, as well as system reliability is reduced. These drawbacks can be overcome if the speed of the IM can be evaluated from the input terminal variables of the motor [11].

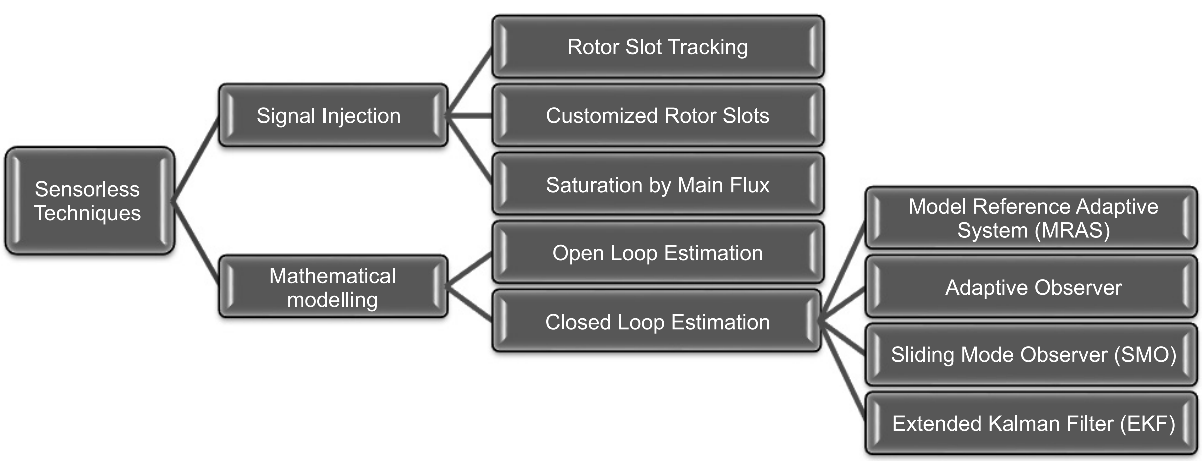

Figure 1: Classification of sensorless speed measurement techniques

Historically, two classes of sensorless speed estimation algorithms have developed for induction motors: computation using mathematical model of the IM and estimation through signal injection as shown in Figure 1

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[1, 12]. Signal injection techniques in *figure 1* require heterodyning demodulation methods to extract the rotor speed of the IM [1, 10]. In model based estimation techniques, rotor speed information is extracted by using voltage and current variables procured from the IM terminals [3]. In model based estimation techniques, modeling equations of the IM are used to compute the speed. Open loop rotor speed estimators mentioned in [4] requires the following (1) the transformation of the rotor voltage equation to a reference frame rotating with the speed of the stator flux, which increases the complexity of the algorithm, (2) the computation of the instantaneous electromagnetic torque and the rotor mechanical parameters for obtaining the rotor speed. Closed loop rotor speed techniques mentioned in Figure 1 are iterative process [6-9, 13-14], which may increase the complexity of the algorithm for estimation of rotor speed of IM. Apart from that, adaptation mechanisms are difficult to design in closed loop rotor speed estimation techniques [12].

In this proposed algorithm, rotor speed measurement is done by using stator currents and stator voltages represented in stationary (α-β) reference frame fixed to the stator. This method doesn't require the computation of instantaneous electromagnetic torque for determining rotor speed using the mechanical differential equations. The proposed method requires the computation of the time derivative of the rotor flux linkages which can be done easily using two successive samples of the rotor flux linkages. The speed of the IM is obtained directly without any iterations and therefore requires less computational time and better dynamic response.

The following sections of this paper are organized as follows: section II demonstrates the mathematical model of the IM to understand the physical basis for the speed measurement algorithm, section III explains the proposed sensorless speed measurement algorithm in IM's through stator voltage and current variables, section IV briefly describes the performance of the DTC IM drive using SVM with estimated speed feedback. In section V, the analysis of the IM drive system is done through MATLAB/SIMULINK software.

2. MATHEMATICAL MODELING OF IM

The fundamental modeling equations of the IM in SRF fixed to stator are given by [4]:

$$V_s = R_s I_s + p\lambda_s \tag{1}$$

$$0 = R_r I_r + p\lambda_r - j\omega_r \lambda_r \tag{2}$$

$$\lambda_s = L_s I_s + L_m I_r \tag{3}$$

$$\lambda_r = L_r I_r + L_m I_s \tag{4}$$

where V_s, λ_s, I_s, L_s, R_s, λ_r, I_r, L_r, R_r, L_m and ω_r are stator voltage space vector, stator flux linkage space vector, stator current space vector, stator self inductance, stator resistance, rotor flux linkage space vector, rotor current space vector, rotor self inductance, rotor resistance, mutual inductance and rotor speed in rad/sec respectively. Direct (α) and Quadrature (β) components of the above equations are realized by using the Clark transform.

3. ALGORITHM FOR MEASUREMENT OF ROTOR SPEED

Step 1: Sample the values of V_{as}, V_{bs}, V_{cs} and I_{as}, I_{bs}, I_{cs} on the IM stator input side. In case the stator neutral not available measure the line to line voltages V_{abs}, V_{bcs}, V_{cas} and using the transformation matrix the phase voltages are obtained

$$\begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 2 & 1 & 0 \\ 0 & 2 & 1 \\ 1 & 0 & 2 \end{bmatrix}\begin{bmatrix} V_{abs} \\ V_{bcs} \\ V_{cas} \end{bmatrix} \tag{5}$$

Step 2: Convert the stator voltages and stator currents to corresponding α-β variables [i.e., stationary reference frame fixed to stator]. (symmetrical 3-phase balanced system is assumed)

$$\begin{bmatrix} V_{\alpha s} \\ V_{\beta s} \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \end{bmatrix} \tag{6}$$

$$\begin{bmatrix} I_{\alpha s} \\ I_{\beta s} \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} I_{as} \\ I_{bs} \\ I_{cs} \end{bmatrix} \tag{7}$$

Step 3: From the modeling equations of IM calculate the values of $I_{\alpha r}$, $I_{\beta r}$ in terms of stator voltages & currents [i.e. from $V_{\alpha s}$, $V_{\beta s}$, $I_{\alpha s}$ and $I_{\beta s}$]

$$I_{\alpha r} = \frac{1}{L_m}\left[\int (V_{\alpha s} - R_s I_{\alpha s})\,dt - L_s I_{\alpha s}\right] \tag{8}$$

$$I_{\beta r} = \frac{1}{L_m}\left[\int (V_{\beta s} - R_s I_{\beta s})\,dt - L_s I_{\beta s}\right] \tag{9}$$

Step 4: The values of rotor flux components are derived from the following equations

$$\lambda_{\alpha r} = L_r I_{\alpha r} + L_m I_{\alpha s} \tag{10}$$

$$\lambda_{\beta r} = L_r I_{\beta r} + L_m I_{\beta s} \tag{11}$$

Step 5: The derivates of flux linkages $\lambda_{\alpha r}$ & $\lambda_{\beta r}$ are calculated using following equations

$$þ\lambda_{\alpha r}(t) = \frac{\lambda_{\alpha r}(t) - \lambda_{\alpha r}(t-\Delta t)}{\Delta t} \tag{12}$$

$$þ\lambda_{\beta r}(t) = \frac{\lambda_{\beta r}(t) - \lambda_{\beta r}(t-\Delta t)}{\Delta t} \tag{13}$$

Step 6: From the rotor equation of the IM, speed is calculated as follows

$$\omega_r = \sqrt{\frac{\left(R_r I_{\alpha r} + þ\lambda_{\alpha r}\right)^2 + \left(R_r I_{\beta r} + þ\lambda_{\beta r}\right)^2}{\lambda_{\alpha r}^2 + \lambda_{\beta r}^2}} \tag{14}$$

4. DTC-SVM INDUCTION MOTOR DRIVE

There are various types of DTC-SVM schemes that have been presented in the literature [15-19]. The type of DTC-SVM control scheme is depending on the torque control and applied flux algorithm. Primarily, DTC computes the reference stator voltage vector and then it is realized by SVM algorithm. In DTC-SVM control schemes, the control algorithm is based on averaged values, whereas space vector modulator calculates the switching signals for the inverter. Among the various control schemes, a DTC-SVM control scheme with closed-loop flux control and torque control in stator flux cartesian coordinates [19] is selected for simulation studies and the control strategy is shown in Figure 2.

In the control scheme of Figure 2, electromagnetic torque $(\hat{T}_e)$ and flux linkage $(\hat{\lambda}_s)$ are computed by using stator currents and stator voltages expressed in SRF fixed to stator. The computed values of flux linkage $(\hat{\lambda}_s)$ and electromagnetic torque $(\hat{T}_e)$ are then compared with reference values of flux linkage $(\hat{\lambda}_s)$ and electromagnetic torque $(\hat{T}_e)$ respectively and the error is used as input to corresponding PI controllers. The outputs of the PI torque controller and PI flux controller can be interpreted as the required stator voltage components V_{sq}, V_{sd} in the stator flux oriented coordinates (*d*-*q*). These DC voltage commands are then converted into SRF, the commanded values $V_{s\alpha}$, $V_{s\beta}$ are delivered to SVM which computes the switching signals for the inverter according to given in [20]. The reference value of torque (T_e) is computed from the actual rotor speed and reference rotor speed. The reference value of stator flux is computed from the speed reference.

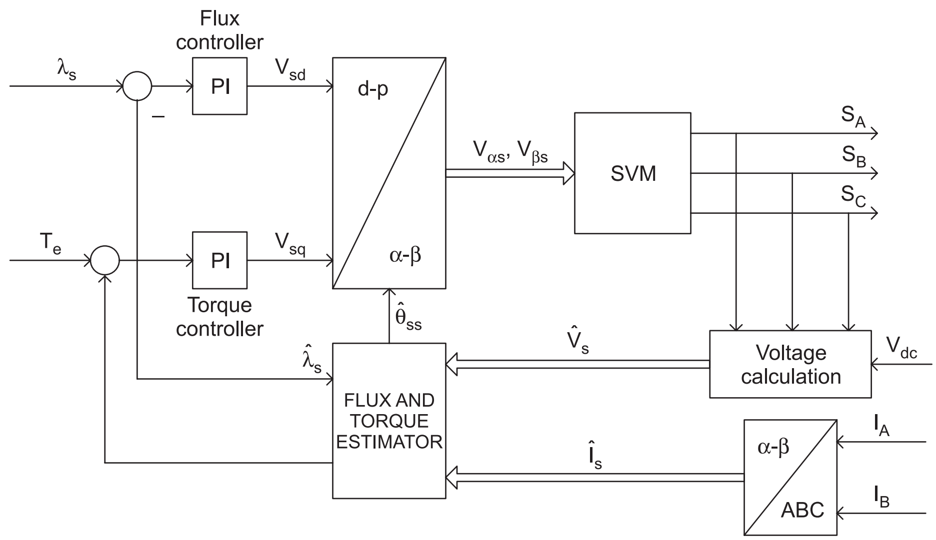

Figure 2: DTC-SVM control strategy in stator flux Cartesian coordinates

5. RESULTS

The rotor speed obtained by the proposed method for the IM whose parameters are given in Table 1 is applied to DTC-SVM control scheme.

Table 1
Induction motor parameters

Parameter	*Value*	*Parameter*	*Value*
Output Power, P_0	3000 Watts	Rotor Resistance, R_r	1.84 Ω
Line to Line Voltage, V_{LL}	380 Volts	Stator Inductance, L_s	0.17 H
Frequency, f	50 Hz	Rotor Inductance, L_r	0.17 H
No. of Poles, P	4	Mutual Inductance, L_m	0.16 H
Stator Resistance, R_s	1.85 Ω	Moment of Inertia, J	0.007 kg-m^2

The speed response of the IM with step change in speed reference is shown in Figure 3. The speed of the motor traces the reference speed within permissible limits. Figure 4 shows the variation of speed of the motor and the speed obtained by proposed method for the above operating condition of the motor. Figure 5 shows the error between actual speed and predicted speed using the proposed method. The steady state error is found to be less than 0.85%.

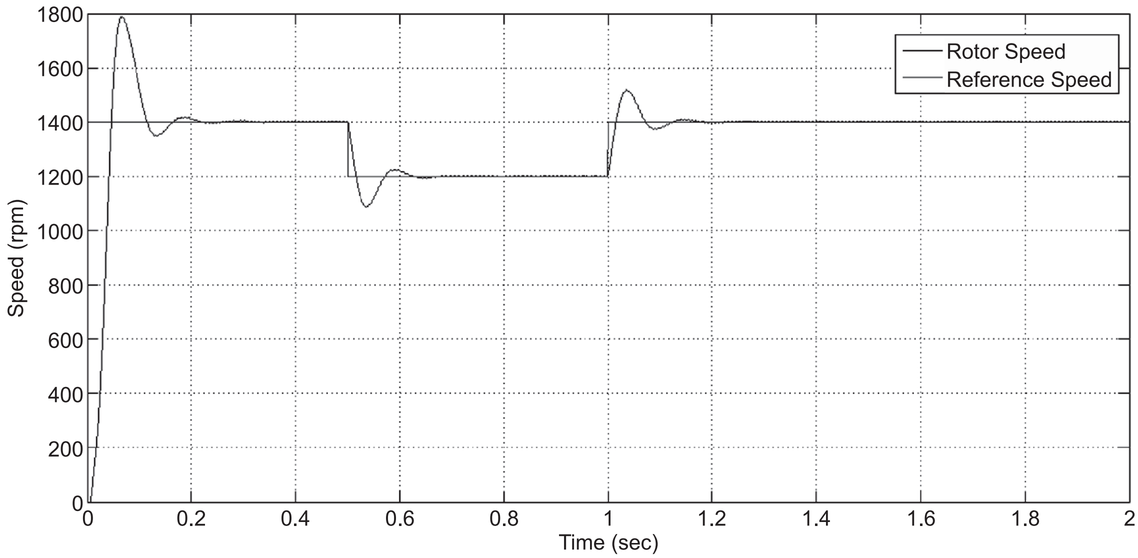

Figure 3: Comparison between rotor speed and speed reference

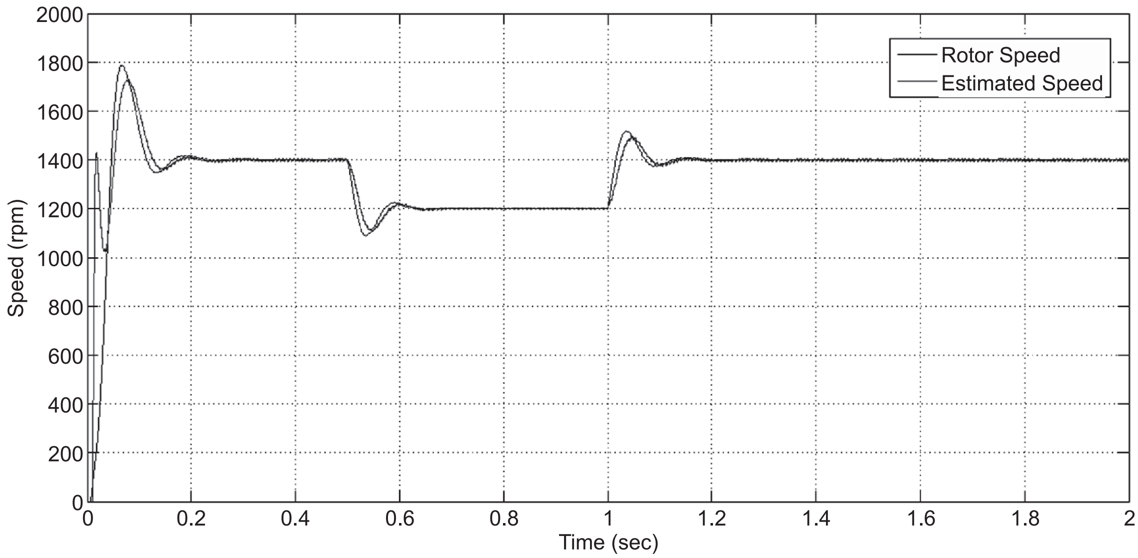

Figure 4: Comparison between rotor speed and estimated speed of Induction motor

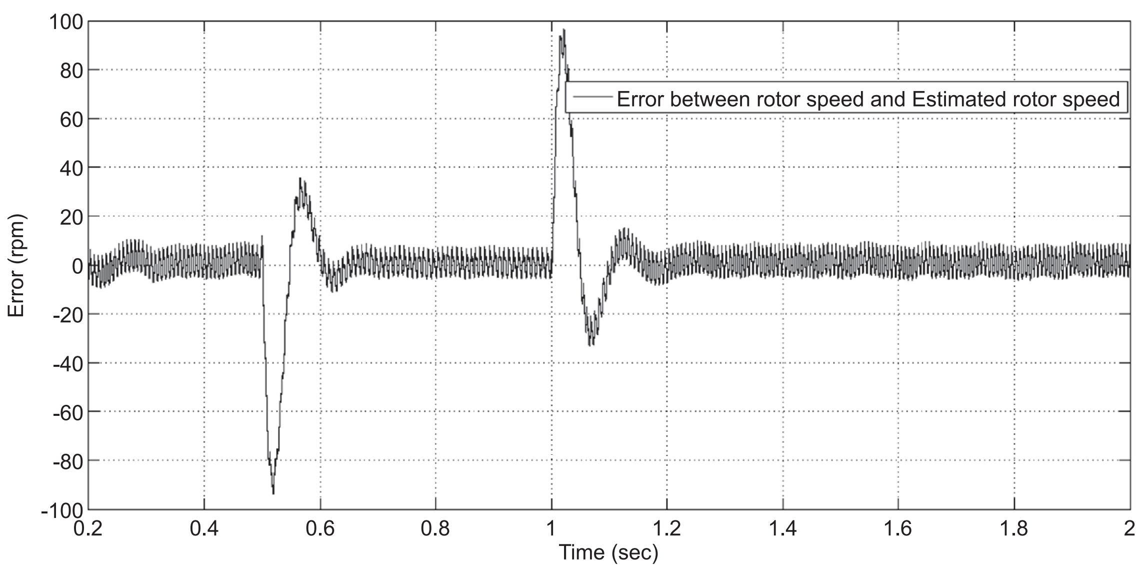

Figure 5: Relative error between estimated rotor speed and rotor speed

6. CONCLUSION

In this paper, sensorless speed estimation technique for induction motors through stator voltage and current variables is proposed. This method doesn't require the computation of instantaneous electromagnetic torque for determining rotor speed using the mechanical differential equations. The rotor speed is obtained directly without any iterations and therefore requires less computational time and better dynamic response. The performance of the IM is examined by applying the speed estimation algorithm for DTC using SVM of IM drive. The actual speed of the motor traces the reference speed irrespective of the load torque within permissible limits and the steady state error between actual speed and predicted speed using the proposed method is found to be less than 0.85%.

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