Laboratory implementation of electromagnetic torque based MRAS speed estimator for sensorless SMPMSM drive

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This Letter proposes a simple electromagnetic torque based model reference adaptive system (MRAS) speed estimator for sensorless surface mount permanent magnet synchronous motor (SMPMSM) drive. The proposed estimator is formed using instantaneous measured and estimated electromagnetic torque. The proposed estimator is implemented for 1.5 kW laboratory prototype SMPMSM drive using field programmable gate array ALTERA cyclone II. Experimental results demonstrate the efficacy of the proposed scheme under different test conditions viz. different low-speed regions and standstill at different load conditions with uncertainty in machine parameters. Results show that the estimator is stable in low-speed regions and exhibits robustness against uncertainties in machine parameters.

Introduction: In recent years, field oriented control (FOC) of PMSM drive [1, 2] has drawn attention from both academia and industry due to its high dynamic performance characteristics and have been widely used in many applications such as military, aerospace, automotive and household products. The performance of surface mount permanent magnet synchronous motor (SMPMSM) drive mainly depends on two aspects: (i) rotor position information and (ii) controller.

Rotor position information is required to implement FOC. Traditionally position sensor is used but it requires shaft extension, alignment and also increase the system cost. Therefore, sensorless rotor speed and position estimation is preferred because of its greater reliability, reduced hardware complexity and lower cost. Sensorless rotor speed and position estimation schemes are broadly grouped as: fundamental excitation methods, saliency and signal injection methods. In fundamental excitation method, the model reference adaptive system (MRAS) based methods discussed in [3, 4] for rotor speed and position estimation have drawn attention due to their simplicity. MRAS speed estimators based on stator current, stator flux, back electromotive force (back-EMF) and reactive power have been proposed for vector control of PMSM drive. The main drawback of these techniques is machine parameter sensitivity, which constrains its performance at standstill and low-speed regions. In this Letter, the electromagnetic torque based MRAS speed estimator is proposed to improve performance in the low-speed regions.

This Letter is organised as follows: the proposed electromagnetic torque based MRAS speed estimator is discussed and finally, experimental results are demonstrated to prove the robustness of the proposed estimator.

Structure of the proposed MRAS speed estimator: Fig. 1*a* shows the schematic of the proposed electromagnetic torque based MRAS speed estimator. In this work, the rotor speed is estimated from the difference between electromagnetic torques. Real system is considered as a reference model and it is independent with respect to estimated quantity, which provides T_e. The mathematical flux model is considered as the adjustable model and it includes estimated rotor speed, which provides $\hat{T}_e$. The error signal is obtained by comparing reference and estimated electromagnetic torque and it is processed through the proportional–integral (PI) controller to estimate the rotor speed and position. Fig. 1*b* shows the structure of FOC with the proposed electromagnetic torque based MRAS speed estimator for sensorless SMPMSM drive.

The stator d–q axes current can be described as

$$i_{qs} = \frac{1}{L_s}\int\{v_{qs} - R_s i_{qs} - \omega_r L_s i_{ds} - \omega_r \psi_m\} \tag{1}$$

$$i_{ds} = \frac{1}{L_s}\int\{v_{ds} - R_s i_{ds} + \omega_r L_s i_{qs}\} \tag{2}$$

Equations (1) and (2) can be written in matrix form as follows:

$$\frac{\mathrm{d}x}{\mathrm{d}t} = \begin{bmatrix} -\dfrac{R_s}{L_s} & \omega_r \\ -\omega_r & -\dfrac{R_s}{L_s} \end{bmatrix} x + \begin{bmatrix} \dfrac{1}{L_s} & 0 \\ 0 & \dfrac{1}{L_s} \end{bmatrix} u + \begin{bmatrix} 0 \\ -\dfrac{\psi_m}{L_s} \end{bmatrix} \omega_r \tag{3}$$

$$y = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} x \tag{4}$$

where $x = (\,i_{ds} \quad i_{qs}\,)^{\mathrm{T}}$, $u = (\,V_{ds} \quad V_{qs}\,)^{\mathrm{T}}$

The estimated stator current can be described as follows:

$$\frac{\mathrm{d}\hat{x}}{\mathrm{d}t} = \begin{bmatrix} -\dfrac{R_s}{L_s} & \hat{\omega}_r \\ -\hat{\omega}_r & -\dfrac{R_s}{L_s} \end{bmatrix} \hat{x} + \begin{bmatrix} \dfrac{1}{L_s} & 0 \\ 0 & \dfrac{1}{L_s} \end{bmatrix} u + \begin{bmatrix} 0 \\ -\dfrac{\psi_m}{L_s} \end{bmatrix} \hat{\omega}_r \tag{5}$$

$$\hat{y} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \hat{x} \tag{6}$$

where $\hat{x} = (\,\hat{i}_{ds} \quad \hat{i}_{qs}\,)^{\mathrm{T}} = \hat{y}$

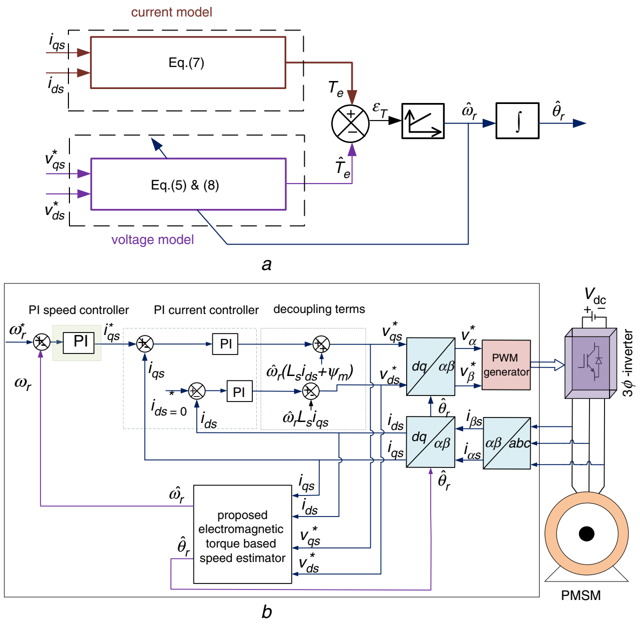


Fig. 1 *Proposed configuration*

a Structure of electromagnetic torque based MRAS speed estimator
b Control diagram of sensorless SMPMSM drive with the proposed electromagnetic torque based MRAS speed estimator

Electromagnetic torque is given as

$$T_e = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\{\psi_m i_{qs}\} \tag{7}$$

Estimated electromagnetic torque is expressed as

$$\hat{T}_e = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\{\psi_m \hat{i}_{qs}\} \tag{8}$$

Mechanical dynamics of the PMSM can be expressed as

$$T_e - T_L = J\frac{\mathrm{d}\omega_r}{\mathrm{d}t} \tag{9}$$

In (9), any perturbation either in load torque (T_L) or speed (ω_r) introduces variation in the electromagnetic torque (T_e) until both the torques, i.e. load torque and electromagnetic torque becomes equal. Similarly, any change in the load torque or estimated rotor speed introduces variation in estimated electromagnetic torque until the estimated electromagnetic torque become equal to load torque. So, in (9), the rotor speed and electromagnetic torque are replaced by their estimated values and expressed as

$$\hat{T}_e - T_l = J\frac{\mathrm{d}\hat{\omega}_r}{\mathrm{d}t} \tag{10}$$

By subtracting (10) from (9), the following expression is obtained:

$$e_T = T_e - \hat{T}_e = J\frac{d(\omega_r - \hat{\omega}_r)}{\mathrm{d}t} \tag{11}$$

By subtracting (8) from (7), the electromagnetic torque error is obtained as

$$\varepsilon_T = T_e - \hat{T}_e = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\{\psi_m(i_{qs} - \hat{i}_{qs})\} \tag{12}$$

To ensure the system stability, the steady-state error (ε_T) should be maintained approximately zero. The estimated rotor speed can be obtained as follows:

$$\hat{\omega}_r = \int_0^t k_1(T_e - \hat{T}_e)\mathrm{d}t + k_2(T_e - \hat{T}_e) + \hat{\omega}_r(0) \qquad (13)$$

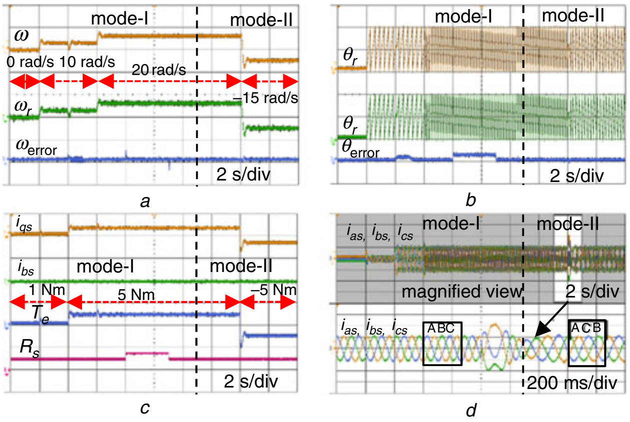
The estimated rotor position is achieved by integrating the estimated speed

$$\hat{\theta}_r = \int \hat{\omega}_r \mathrm{d}t \qquad (14)$$

Thus, the proposed electromagnetic torque based speed estimator is formed according to (13) and (14). It performs well at standstill, low-speed regions and robust with respect to machine parameter variations. Also, there is no design complexity involved as it eliminates computation of stator flux [1, 2, 4], back-EMF and programmable low-pass filters.

Experimental results and discussion: The proposed scheme is implemented on 1.5 kW SMPMSM (360 V, 2.9 A, 1500 rpm, 50 Hz) drive using ALTERA Cyclone II field programmable gate array controller. Three-phase inverter (SEMIKRON make, 750 V, 30 A, 20 kHz) is used for control of SMPMSM. The motor stator current is sensed through LAH 25-NP and it is given to signal conditioning circuit consisting of OP-AMP (OPA 227P). The actual rotor speed and position is obtained by encoder (1024 PPR), which is used for comparison. The experimental studies are conducted for different case studies (157 to −157 rad/s), in this Letter only step change in low-speed regions at 50% load with uncertainty in the stator resistance is presented.

Fig. 2 shows the performance of the proposed method during low-speed variations and it is characterised into two modes, which are mode I: low-speed variations in the forward motoring with uncertainty in the stator resistance and mode II: forward to reverse motoring operation in the low-speed region.



a *b* *c* *d*

Fig. 2 *Experiment results for step change in low-speed regions at 50% load-with uncertainty in the stator resistance*

a Measured, estimated rotor speed and rotor speed error.
Scale: (ω_r, $\omega_{r(\text{est})}$ = 30 rad/s/div), (ω_{error} = 2 rad/s/div)
b Measured and estimated rotor position and rotor position error.
Scale: (θ_r = 180°/div), ($\theta_{r(\text{est})}$ = 180°/div), (θ_{error} = 6°/div)
c *q–d* axes stator current and electromagnetic torque. Scale: (i_{qs} = 6 A/div), (i_{ds} = 1 A/div), ($\hat{T}_e$ = 10 Nm/div), (R_s = 2.4 Ω/div)
d Three-phase stator current. Scale: (i_{as}, i_{bs}, i_{cs} = 2 A/div)

Mode I: In this case, different low-speed regions are considered, i.e. 0, 10, 20 rad/s. Initially, motor started with 10% of rated load then 50% of load is applied at 10 rad/s to analyse the performance of the proposed estimator with respect to load variations. Further to verify the robustness of the proposed speed estimator, at 20 rad/s the stator resistance value is increased and decreased by a step of 50% from the nominal value. Fig. 2*a* shows the actual, estimated speed and speed estimation error of the proposed estimator. It is observed that estimated speed follows the actual speed and further it is found that the maximum estimated speed error is ±1 rad/s at the speed of 20 rad/s during load removal condition. Fig. 2*b* shows the actual, estimated position, estimated position error for the proposed estimator. It is inferred that, estimated position follows the actual position during variation in the speed. It is found that the maximum estimated position error is 2° at the speed of 20 rad/s with 50% of rated load during uncertainty in resistance. The dynamic response of *q–d* axes stator current, estimated electromagnetic torque and uncertainty in the stator resistance are shown in Fig. 2*c*. It is clearly seen that, during load variation the *d–q* axes stator current is perfectly decoupled. Further it is noted that the estimated electromagnetic torque is directly proportional to the *q*-axis stator current. For better clarity the three-phase current response is shown in Fig. 2*d*. It is inferred that for constant load the three-phase current is maintained constant during speed variation.

Mode II: In this case, simultaneous variation in the speed (+20 to −15 rad/s) and load (5 to −5 Nm) is considered. The following observations are made for the proposed estimator during forward motoring to reverse motoring operation: (i) the performance of the proposed estimator has smooth tracking response during low-speed region; (ii) the maximum speed and position error are found to be 0.5 rad/s, ±0.5°, respectively, during transients; (iii) from the magnified view of stator current, it is found that during forward motoring mode the stator current sequence is ABC which are 120° apart from each other and during reverse motoring mode the stator current sequence is changed to ACB.

Table 1 summarises the performance of the proposed electromagnetic torque based MRAS speed estimator along with stator current based MRAS speed estimator and back-EMF based speed estimator under different speed ranges with parameter uncertainty. It is noted that the proposed estimator performs well for entire speed range which include low-speed regions with parameter uncertainty.

Table 1: Comparison of worst-case transient error

	Proposed scheme		Stator current based MRAS scheme [2]		Back-EMF based scheme [1]	
	Speed error (%)	Position error (deg)	Speed error (%)	Position error (deg)	Speed error (%)	Position error (deg)
High speed (100–157 rad/s with 50% uncertainty in *Ls*)	6.3	6	8	10	10	12
Medium speed (50–100 rad/s)	5.2	5	6	7.2	7.6	8
Low speed (<20 rad/s with 50% uncertainty in *Rs*)	4	4	*	*	*	*

These methods are not able to follow the actual speed and position in low-speed regions.

Conclusions: A simple and robust electromagnetic torque based MRAS rotor speed estimator for SMPMSM drive is proposed in this Letter. The proposed estimator is simple and no design complexity is involved as it eliminates computation of stator flux, back-EMF, programmable low-pass filters. Experimental results demonstrate the effectiveness of the proposed estimator for the step change in low-speed regions at 50% load with uncertainty in the stator resistance. The worst-case transient error for the proposed estimator is found to be maximum of ±6.3 rad/s (speed error), 6° (position error) for overall tests considered.

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One or more of the Figures in this Letter are available in colour online.

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