Sensorless Torque and Speed Control of Traction Permanent Magnet Synchronous Motor for Railway Applications based on Model Reference Adaptive System

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Abstract

In recent years, by improving performance of magnet material and decreasing the cost, interest is growing in utilization of Traction Permanent Magnet Synchronous Motor (Traction PMSM) in propulsion systems. In this paper a speed sensorless control method for Traction PMSM, based on Model Reference Adaptive System (MRAS) is represented. In the proposed method the stator current is used to estimate the motor speed. The direct axis reference current (id) is considered to be zero for vector control. By implementing this assumption on stator current, only quadrature axis current (iq) is used for estimation the speed. Therefore the error would be simplified and the error controller, which is a PI controller, follows the rotor speed easily and causes the error to be zero. Stability analysis for proposed MRAS would be inspected and proved by Popov Hyperstability theory. Simulation results clearly show the suitable performance of the estimator in low and high speeds.

Key words: Traction PMSM, Vector Control, Speed Estimation, MRAS

1. Introduction

Currently, DC and induction motors are used as traction motors for railway vehicles, but in recent years PMSMs have received significant attention for use in railway due to their unique characteristics including lower energy consumption, higher efficiency, lower weight-to-power ratio, reliable operation, low noise production, robustness, etc. With the emergence progress in product of new permanent magnet materials, modern Traction PMSMs has been developed with high power and torque. Today, giant manufacturers of train are doing vast investigations on using PMSM in their products. In 2007 Toshiba has developed the world's first PMSM propulsion system in commercial service in Tokyo subway.

Vector control method needs the information about rotor position and speed. Insufficient space to install the sensor in some cases and also reduction in system costs raised the attention to sensorless speed control for PMSMs. Several methods have been presented for speed and position estimation, such as Back EMF position estimators [1], high frequency

signal injection [2], Advanced Kalman Filter [3], advanced Leonberger Observer, Sliding Mode Observer [4], etc. Each of methods have their own advantages and weak points. The methods based on MRAS, depending on the state variable considered for system, would have different estimation performances. Reference [5] uses reactive power to estimate the speed. In reference [6], the stator current of has been used to estimate the speed, but the error is complicated and PI controller is not able to estimate the speed easily.
In this paper, a speed estimation method based on MRAS has been presented which uses the stator current as a state variable for speed estimation. In the field oriented control, the direct axis reference current is considered to be zero. This assumption on MRAS simplifies the error and eventually causes the error controller to be able to estimate the speed easily and dynamically as well. The stability for proposed system has been examined using Popov Hyperstability theory.

2.Mathematic Model of PMSM

Voltage equations of PMSM in the synchronous rotating reference frame are:

$$\begin{cases} u_d = Ri_d + p\lambda_d - \omega\lambda_q \\ u_q = Ri_q + p\lambda_q + \omega\lambda_d \end{cases} \tag{1}$$

Where

$$\begin{cases} \lambda_d = L_d i_d + \lambda_{af} \\ \lambda_q = L_q i_q \end{cases} \tag{2}$$

Where u_d , u_q , i_d , i_q are the d-q axis stator voltages and currents, respectively; R is stator resistance; p is differential coefficient; λ_d , λ_q are the d-q axis stator magnetic flux, respectively; ω is electrical motor speed; L_d , L_q are the d-q axis stator inductances, respectively; λ_{af} is coupling flux linkage of rotor on stator.

The electromagnetic torque is given by:

$$T_e = \frac{3}{2} P\lambda_{af} i_q \tag{3}$$

Where P is the number of pole pairs.

3. Speed Estimation Methods based on MRAS

Model Reference Adaptive System theory is based on calculating an arbitrary state variable using two models. One of them is reference model, and another is comparative model. The unknown parameter would be estimated using the error between two models. Also the reference model has to be independent of estimated variable and in contrary; the comparative model should be dependent to the estimated variable. The error signal is given to the compare mechanism unit. The estimated variable (which is speed in this case) would be applied to the comparative model by compare unit output. This loop continues until the compare unit output finally equals the reference model output, and estimated variable reaches its final value. Stability of this system is examined using Popov Hyperstability criterion as well. This method is easy and needs simple computing. Fig. 1 shows the overall structure of MRAS.

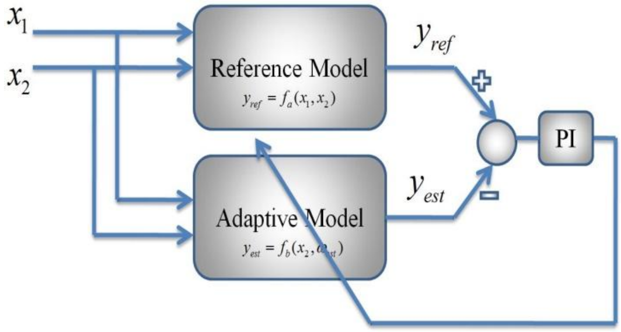


Fig. 1. Block Diagram of MRAS

Selecting the state variable as the output for both reference and comparative model enables us to develop different structures of MRAS. In some cases, the adaptive reference model is configured using stator flux, in other cases the stator currents has been used as state variables. Other structures using the reactive power as a state variable. For each state variable used in MRAS, a unique statement term of error criterion would be obtained which is applied to the compare mechanism in order to estimate the considered variable.

4. Estimator Stability Examination

If the stator current vector is considered as state variable, then according to machine equations, the stator current would be calculated as follows:

$$\frac{di_q}{dt} = \frac{1}{L_s}(u_q - Ri_q - \omega L_s i_d - \omega\lambda_{af}) \tag{4}$$

Estimated current is given by:

$$\frac{d\hat{i}_q}{dt} = \frac{1}{L_s}(u_q - R\hat{i}_q - \hat{\omega} L_s i_d - \hat{\omega}\lambda_{af}) \tag{5}$$

Finally, the error of estimated current can be achieved as:

$$\frac{d(i_q - \hat{i}_q)}{dt} = -\frac{1}{L_s}\left[R(i_q - \hat{i}_q) + (\omega - \hat{\omega})(L_d i_d + \lambda_{af})\right] \tag{6}$$

In the field oriented control, since the direct current is zero, the error would be obtained as follows:

$$\frac{d(i_q - \hat{i}_q)}{dt} = -\frac{1}{L_s}\left[R(i_q - \hat{i}_q) + (\omega - \hat{\omega})\lambda_{af}\right] \tag{7}$$

With the following definition for error, the state equation of error would be obtained consequently:

$$\varepsilon = (i_q - \hat{i}_q) \tag{8}$$

$$\varepsilon' = A\varepsilon - w \tag{9}$$

The criterion for the error value to gradually approach to zero, is based on the fact that error system state equations should be stable; in other word, all of the poles in state equations should be on the left side. The second criterion says the nonlinear feedback should hold true in the following inequality:

$$\eta(0,t_0) = \int_0^{t_0} v^T w dt \geq -\gamma^2 \tag{10}$$

In which, γ^2 is a positive real number. Assume that:

$$v = D\varepsilon \xrightarrow{(D=I)} v = \varepsilon \tag{11}$$

Finally the following term would be obtained after substitution of above terms in the Popov criterion.

$$\eta(0,t_0) = \int_0^{t_0} (i_q - \hat{i}_q)(\omega - \hat{\omega}) \frac{\lambda_{af}}{L_s} dt \tag{12}$$

Also considering PI controller for speed estimation, we would have:

$$\hat{\omega} = \int_0^t F_1(v,t,\tau) d\tau + F_2(v,t) + \omega(0) \tag{13}$$

Now, with insertion of above estimated speed in the Popov criterion, and solving the terms for Popov inequality, the following equation would be obtained for speed estimation:

$$\hat{\omega} = k_i \int_0^{t_0} (\hat{i}_q - i_q) \frac{\lambda_{af}}{L_s} dt + k_p (\hat{i}_q - i_q) \frac{\lambda_{af}}{L_s} + \omega(0) \tag{14}$$

And finally the estimated speed can be written as:

$$\hat{\omega} = k_i \int_0^{t_0} (i_q - \hat{i}_q) dt + k_p (i_q - \hat{i}_q) + \omega(0) \tag{15}$$

5. Simulation Results

Traction PMSM Vector Control without speed sensor using by MRAS method has been simulated using Matlab/Simulink. Results confirm the validity of proposed method. Table 1 shows the Traction PMSM parameters used in the simulation.

Rating of Traction PMSM	160 kW, 900 V, 750 RPM
Stator resistance	0.05 Ω
d-q axis inductance	$L_d = L_q$ =2. 5 mH

Total moment of inertia	2.2 kg.m^2
Friction factor	0.05558 N.m.s
Number of pole pairs	8
PM flux	λ_{af} = 0.3 V.s
Nominal torque	T_N = 1000 N.m

Table 1: specification of proposed Traction PMSM

The motor speed and load torque diagrams vs time are illustrated in fig. 2. The simulation time set to 6 s.

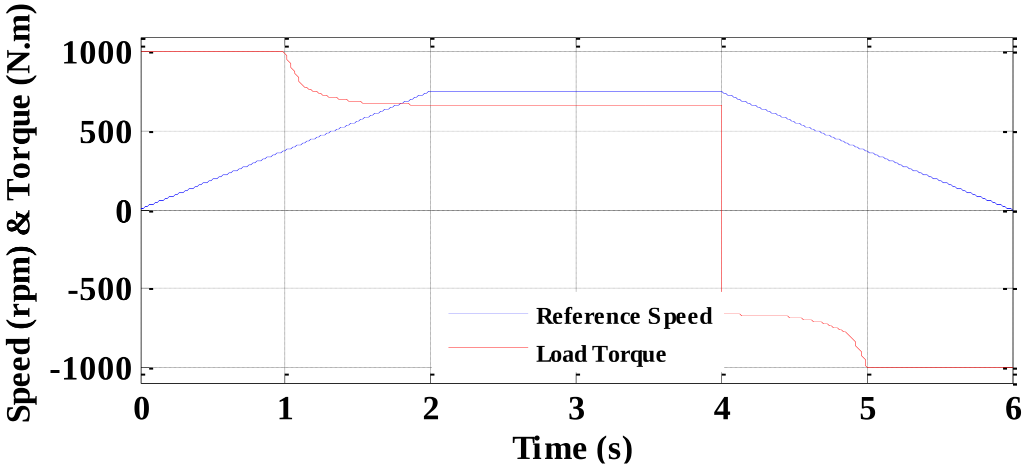


Fig. 2. Motor reference speed and load torque diagrams vs time

Train survey the distance between two stations in 3 general regions; the first one is positive acceleration (speed increasing), and the second one is constant speed, and the last one is negative acceleration (braking). In the beginning of this survey the load torque on axle of traction motor has its maximum value. With increasing the speed, load torque is decreased and finally in the braking region the load torque become negative. Reference, real and estimated speeds of traction motor are illustrated in fig. 3.

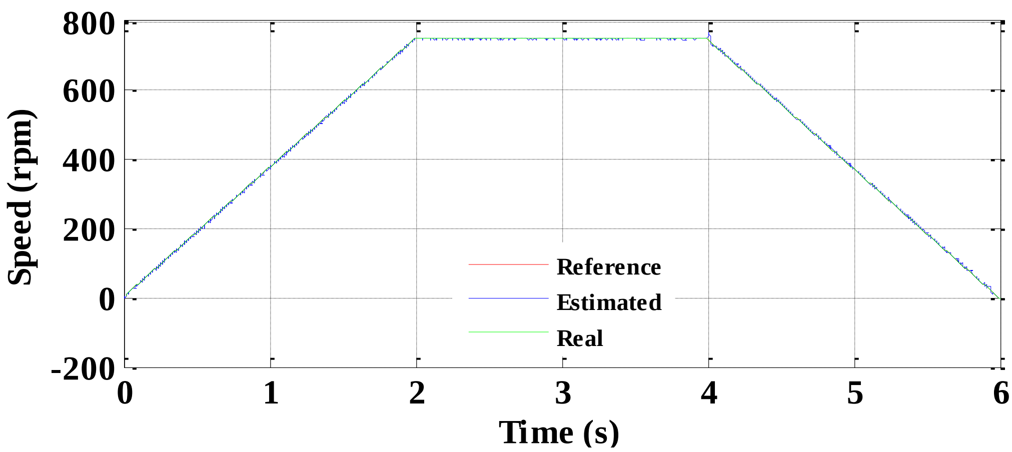


Fig. 3. Reference, real and estimated speeds of traction motor

Real speed follows the reference speed very well with proper adjustment of PI controllers coefficients. Furthermore as it clear in fig. 3 the estimated speed follows the real speed acceptable. The electromagnetic torque of traction motor and d-q axis currents are indicated in figs. 4 and 5, respectively.

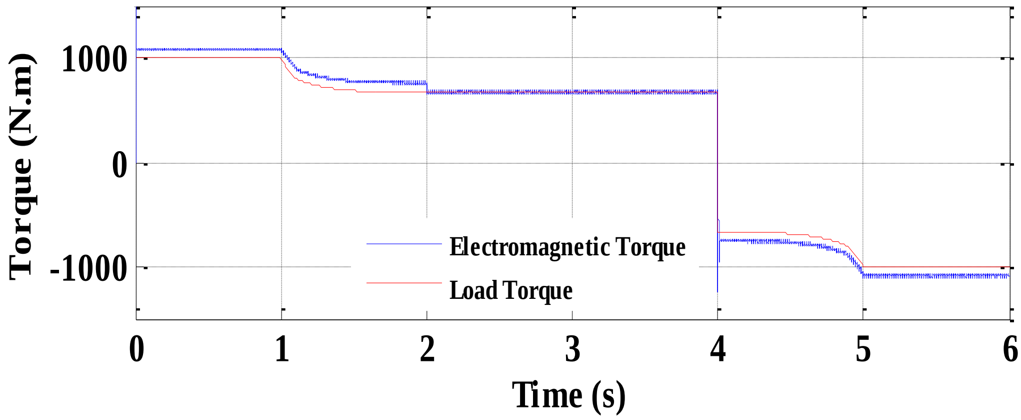


Fig. 4. Load and electromagnetic torques

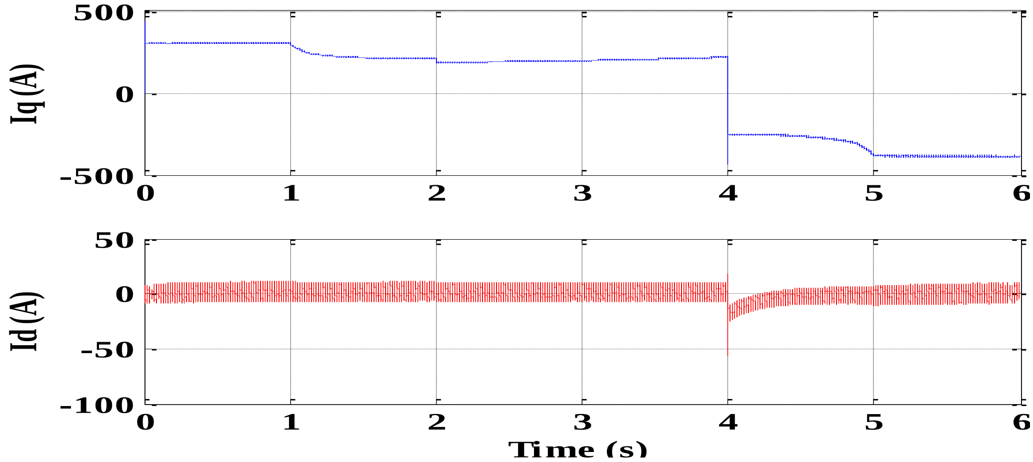


Fig. 5. Direct and quadrature axis currents

As we expected the direct axis current almost zero and the quadrature axis current follows electromagnetic torque with constant ratio. Fig. 6 shows the system's speed step response, the reference step speed of 750 rpm has been applied in 0.1s to drive; also the torque equal to 500 N.m is applied to the motor. The estimated speed, reference speed and real speed of motor are shown in Fig. 6. As it can be seen, the estimated speed follows the real speed very well. Also the d-q currents are shown in fig. 7.

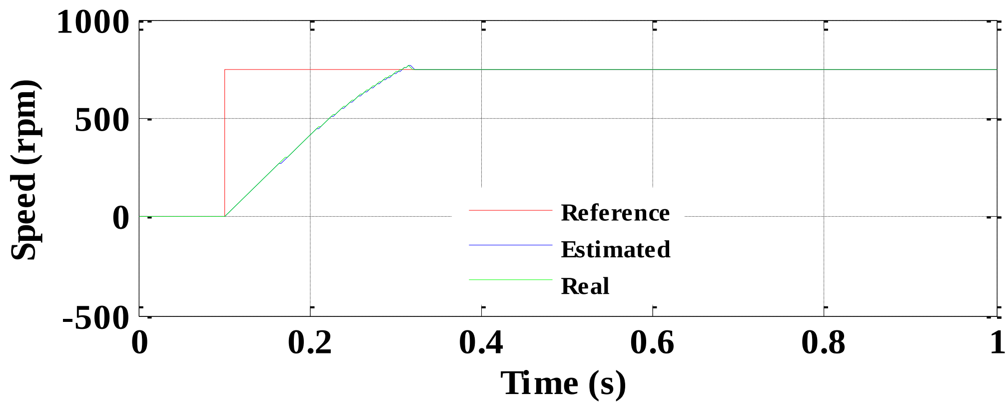


Fig. 6. Speed Step Response alongside the Estimated Speed

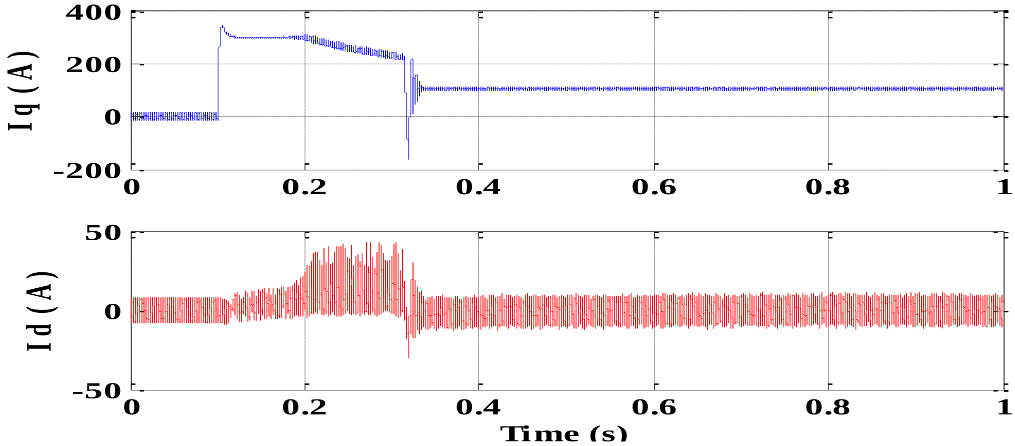
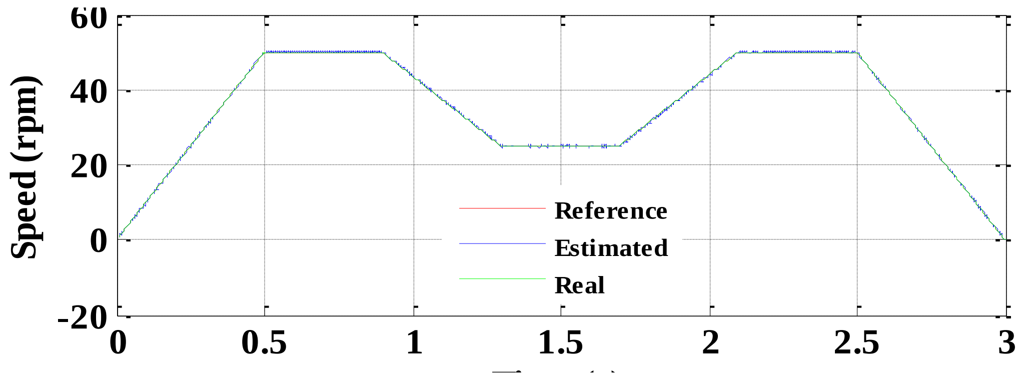


Fig. 7. Direct and quadrature currents

Motor performance at zero speed and speed estimation error has been shown in Fig. 8.



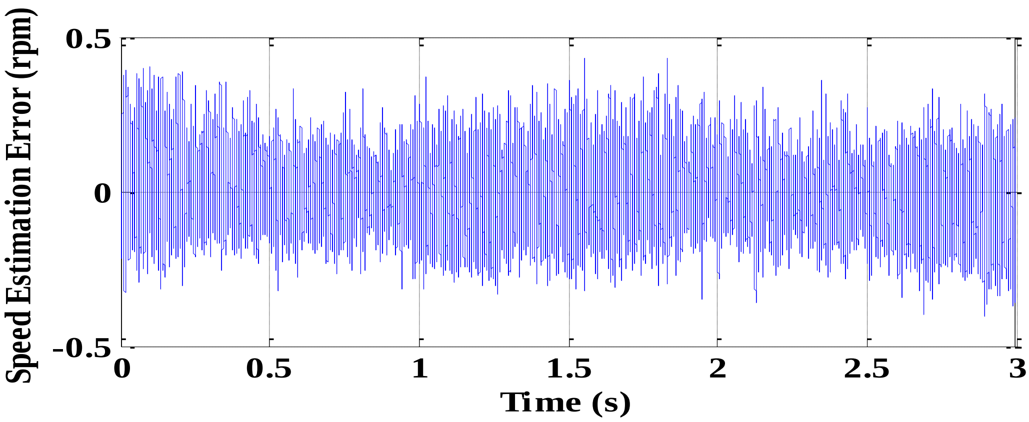


Fig. 8. Operation of Speed Estimator and Estimation Error in Zero Speed

5. Conclusion

A sensorless vector control of Traction PMSM, which uses stator current as state variable for speed estimation, is presented in this paper. In proposed method the direct axis reference current (id) is considered to be zero and only quadrature axis current (iq) is used for estimation the speed. This assumption lead to error simplification and caused the speed estimator have a suitable performance. In proposed method the estimated speed follows the real speed very well, furthermore the estimator perform well at low speeds.

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