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Sensorless Adaptive Speed Control for PMSM Drives

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Abstract--**The simplified mathematical model of the permanent magnet synchronous motor is developed in this paper. Speed and torque controls of permanent magnet synchronous motors are usually attained by the application of position and speed sensors yet, speed and position sensors require the additional mounting space, reduce the reliability in harsh environments and increase the cost of the motor. Therefore, many studies have been performed for the elimination of speed and position sensors. Therefore, a V-I model based model reference adaptive control is proposed. A Model Reference Adaptive Control (MRAC) has been formed using parameter uncertainty cancellation to estimate the speed without using any sensor. Firstly, the speed estimation errors of a voltage and current model-based adaptive speed due to the parameter variation are analyzed. Consequently, an adaptation mechanism model is developed to cancel the effects of parameter variations on the estimated speed performance. Finally, the speed control with quantitative control performance considering the effect due to the feedback of estimated speed is presented. The results show that the MRAC is superior to the conventional PI controller in dynamic performance and steady precision. The effectiveness of the proposed controller is demonstrated by some simulation by using MATLAB/SIMULINK.**

***Keywords*—Model Reference Adaptive Control; Sensorless Speed Control; Permanent Magnet Synchronous Motor; Electric Machine**

I. Introduction

RECENTLY Permanent Magnet Synchronous Motor (PMSM) drives have received increased attention due to having several desirable features, such as, higher efficiency, higher power density, higher torque to inertia ratio etc. Vector controlled PMSM drive [1] has very high dynamic performance and are widely used in applications like machine tools, electric vehicles etc. Indirect vector controlled system requires the information of the speed: either from the speed encoder or from an estimator/ observer [2–4]. Elimination of the speed encoder is highly encouraged to increase the mechanical robustness of the system and to make the drive cheaper. This has made speed sensorless PMSM drive very attractive. Therefore, vector-control methods in the absence of any position or speed sensor have been investigated by many researchers [5,6,7]. In most of the methods the main proposed alternative is the estimation of the motor speed or position. In some methods (indirect methods) [8], first the estimation of velocity is performed and then the trigonometric values, which are required for the vector control, are calculated. In some other methods [9], the required trigonometric values are directly estimated from motor state equations. Estimation theory and especially Extended Kalman Filter method is extensively used in indirect methods [10].

Another method [11-14] is by using model references adaptive control. MRAC computes a desired state (called as the functional candidate) using two different models (i.e. reference and adjustable models). The error between the two models is used to estimate an unknown parameter (here speed is the unknown parameter). Hence, there is many more speed estimation techniques have been reported in literature such as Back-EMF based method [15,16], Artificial Intelligent (AI) [17-21], State observer based method [22] and etc. Out of all the techniques discussed so far, MRAC is widely accepted for speed estimation due to its simplicity and good stability. Also the method does not require any extra hardwire or signal injection or huge memory like EKF or ELO. Within the available MRAC-based methods, reactive power-based scheme [15] is not dependant on stator resistance and has definite advantages over the other methods.

In this paper, a mathematical model method of the vector controlled sensorless permanent magnet synchronous motors(PMSM) drives is introduced with the aid of the parameter identification using model reference adaptive control(MRAC). The traditional equivalent feedback system for speed identification is derived easily in case of the: induction motor because the rotor terminal voltages are equal to zero. But, instead of the simplicity of model equations, the application of MRAC in PMSM derives raises another problem because of the existence of the permanent magnet field. Also, this paper proposes the current detecting method on the synchronously rotating axis without position information, which is achieved indirectly by the measurement of the stator voltages and currents. The research proposed in this paper is using the V-I model based MRAC. The overall evaluation and investigation for modeling and simulation of sensorless technique for PMSM is using MATLAB/SIMULINK development tools environment.

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II. System Description and Modeling

Fig. 1 shows the block diagram of a PM synchronous motor control system investigated in this work. The system basically consists of three main parts: the motor, the plant which consists of inverter, current controller and the speed controller, and the model of adaptive control. The motor is driven by a current regulated voltage-source inverter (VSI) which generates three-phase variable-frequency stator currents. The magnitudes and frequencies of three-phase stator currents are determined by the adaptive speed-loop controller and the estimated shaft angular position which is computed from the voltage and current of the motor. Then, a speed estimator controller of sensorless PM synchronous motor drive system is proposed. The mathematical model of a PM motor can be described with Park's equations in the d-q coordinate system, which moves synchronously with the mover, by applying some coordinates transformations.

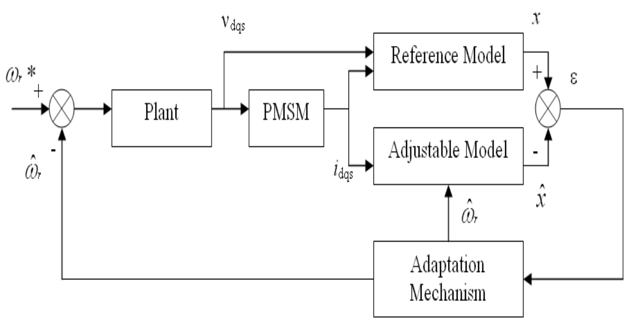


Fig. 1: Configuration of MRAC based vector controlled PMSM drive

III. MRAC-Based Speed Estimation

The basic idea of the model reference adaptive control is to create a closed loop controller with parameter from the motor model. Basically, adaptive control involves modifying the control law used by a controller to cope with the fact that the parameters of the system being controlled are slowly time varying or uncertain.

Fig. 2 shows the MRAC-based speed estimation scheme. It uses the outputs of two models: one independent of rotor speed (Reference Model) and the other dependant on rotor speed (Adjustable Model), to form an error signal. The adaptation mechanism is designed in order to improve stability and behavior of the adaptive system. The goals in the design were reducing the noise impact to control and influencing to the system transient response as little as possible.

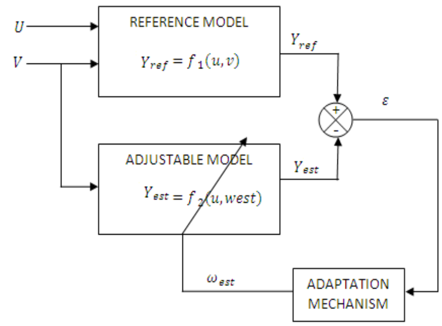


Fig. 2: Basic MRAC Structure

IV. Design of Speed Estimator

The equations of model reference adaptive control can be expressed as follows [20]:

$$\begin{bmatrix} v_{qs} \\ v_{ds} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R_s & 0 & \rho L_s & 0 \\ 0 & R_s & 0 & \rho L_s \\ \frac{-L_s R_s}{L_s} & 0 & \frac{R_s}{L_s}+\rho & -\omega_r \\ 0 & \frac{-L_s R_s}{L_s} & \omega_r & \frac{R_s}{L_s}+\rho \end{bmatrix} X \begin{bmatrix} i_{qs} \\ i_{ds} \\ \lambda_{qr} \\ \lambda_{dr} \end{bmatrix} \quad (1)$$

$$Te = \frac{3}{4} pLs(iqs\lambda dr - ids\lambda qr) = T_L + Bw_r + Jpw_r \quad (2)$$

Where,

$$p = \frac{d}{dt}$$

J = total mechanical inertia

B = total damping coefficient

The meanings of the other variables and parameters are clear from the literature [20]. From equation (1), the following voltage model and current model rotor flux equations can be derived [21]:

Reference Model:

$$\rho\lambda_{qrv} = L_s(v_{qs} - R_{Siqs})$$
$$\rho\lambda_{qrv} = L_s(v_{ds} - R_{Sids}) \quad (3)$$

Adjustable Model:

$$\rho\lambda_{qri} = -\frac{R_s}{L_s}\lambda_{qri} + \omega_r \lambda_{dri} + \frac{L_s R_s}{L_s} iqs$$
$$\rho\lambda_{dri} = -\frac{R_s}{L_s}\lambda_{dri} + \omega_r \lambda_{qri} + \frac{L_s R_s}{L_s} ids \quad (4)$$

$$\hat{\omega} = (k_p + \frac{k_i}{s})\varepsilon \tag{5}$$

The methodology of the conventional speed estimation approach [21] is briefly described in the following. The reference model is considered as the voltage model, and the adjustable model, which involves the rotor speed information, ω_r is the current model. If all the parameters and rotor speed employed in these two models are equal to their actual values, the estimated rotor fluxes based on equations (3) and (4) will coincide. In practice, a low pass filter is used instead of pure integration in the realization of equations (3) and (4) to avoid the problems caused by the initial condition offset and drifts [22].

An estimation error defined by $\varepsilon = \lambda_{drv}\lambda_{qri} - \lambda_{qrv}\lambda_{dri}$ is derived when the speed used in the current model is not identical to the actual one without any influence of parameter variation. A tuning signal for the adjustable model is generated from the regulation of this error through a PI controller as in fig.3. This design is based on the basic design of MRAC structure. The adaptation mechanism is designed using Popov's hyper-stability theory to derive the estimated speed as in equation (5). From equation (3) and (4), the different motor parameters are employed in the V- and I-models in this estimation mechanism. Hence the parameter uncertainties will lead to the contribution to the error, ε and result in speed estimation error. The error signal is then passed through an adaptation mechanism to estimate rotor speed.

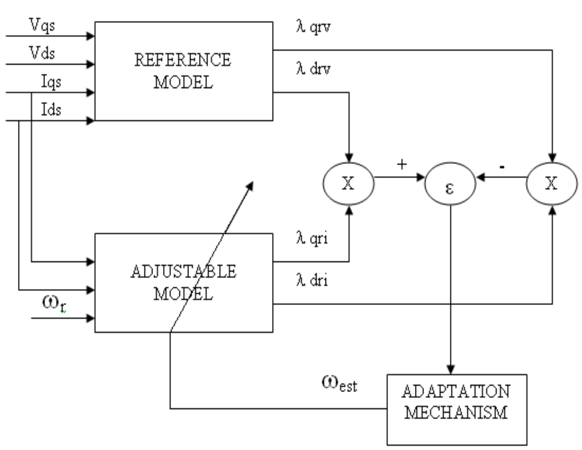
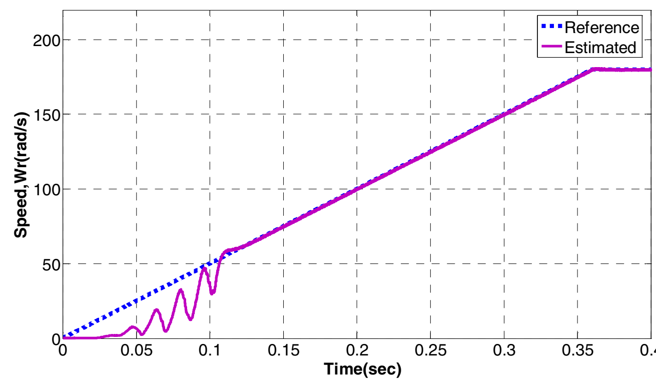


Fig. 3: Configuration of proposed scheme speed estimator

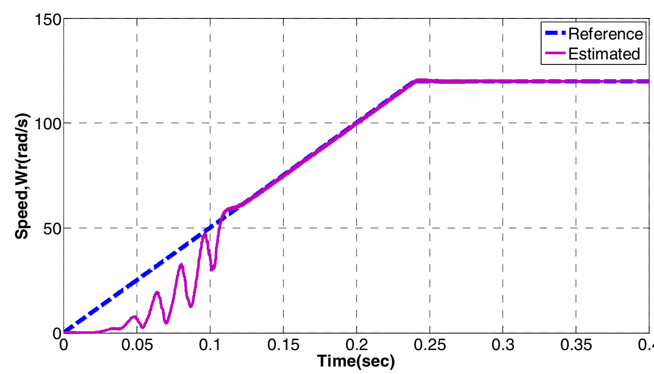
V. Simulation Result

The proposed speed estimation algorithm for PMSM drive has been simulated in MATLAB/SIMULINK under the following operating conditions. Table 1 shows the specification of the permanent magnet synchronous motor used in the simulation. The response to step changes in speed commands are studies for four arbitrarily selected speed commands: at rated speed, 180(rad/s), two third of rated speed, 120(rad/s), one third of rated speed, 60(rad/s) and one sixth of rated speed, 30(rad/s). Comparisons of the drive behavior of speed control are performed by overlapping and zooming speed responses of the types illustrated in figs 4, 5, 6, 7, and 8.

Fig. 4(a), (b), (c) and (d) show the speed responses during transient and in the no load condition. As shown in fig. 4, this system used a ramp type speed reference so that the system could be able to estimate the rotor speed. For high speed response, it takes 0.1s to reach the stable condition while for low speed condition it takes 0.13s to reach the stable condition. Based on the observation, the proposed sensorless control algorithm has a good response in the low and high speed.



(a)



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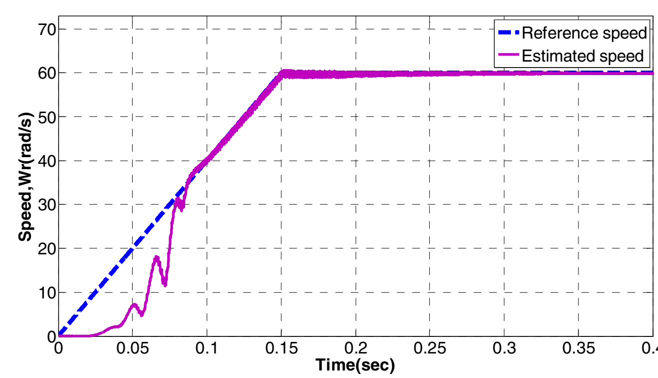

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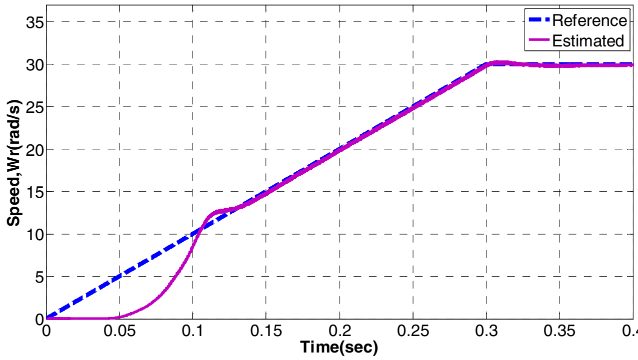
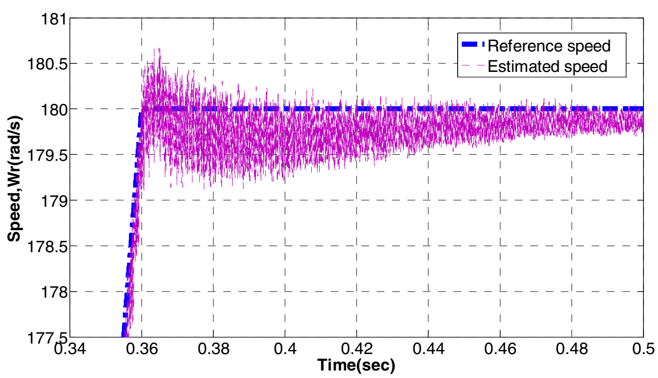


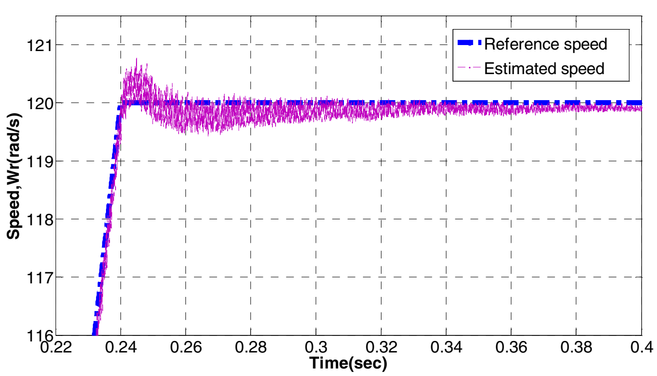
(d)

Fig. 4: Comparison of speed responses obtained during start-up by reference and estimated speed for four different speeds: (a) at rated, 180(rad/s) (b) at 120(rad/s) (c) at 60(rad/s) (d) at 30(rad/)

Fig. 5(a), (b), (c) and (d) is focusing on overshoot before reached the steady state condition for selected speed: at rated speed, 180(rad/s), at 120(rad/s), at 60(rad/s) and at 30(rad/s). As shown in fig. 5, at the high speed response, the overshoot is in a very small value and reached the steady state condition at 0.38s while for the low speed response, there is an overshoot and this discrepancy can be overcome by proper adjustment of PI speed controller gains.



(a)



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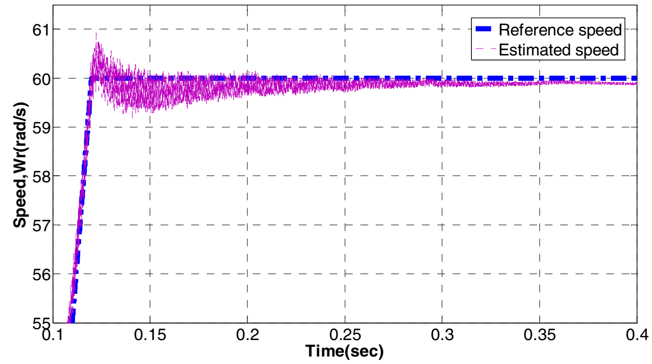

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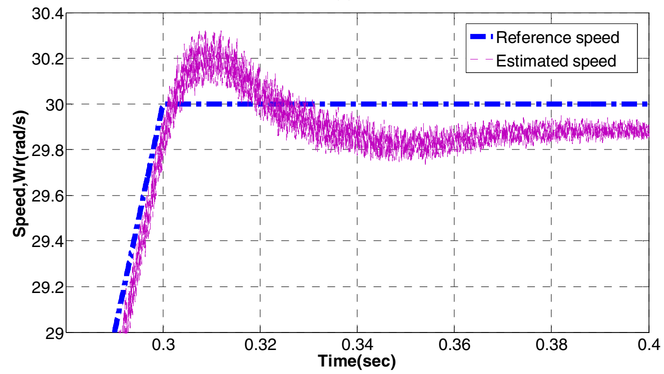
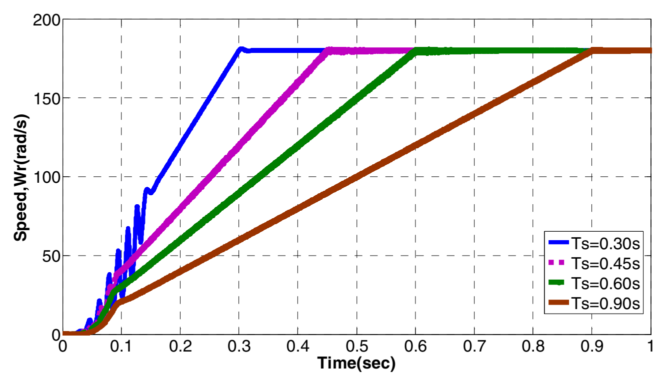


(d)

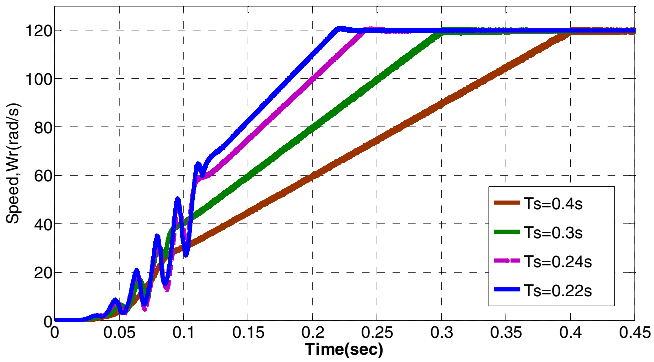
Fig. 5: Comparison of speed responses before reached steady state condition for four different speeds: (a) at rated, 180(rad/s) (b) at 120(rad/s) (c) at 60(rad/s) (d) at 30(rad/s)

Fig. 6(a), (b), (c) and (d) show the comparison of different slope for ramp type speed reference. For the high speed response, the highest slope gives more disturbances during start up compared to the lowest slope. The optimum slope for the high speed response is at settling time, T_s=0.45s.

For the low speed response, it gives a slow speed response before it reached to the steady state condition and there are disturbance for each of the slopes.



(a)



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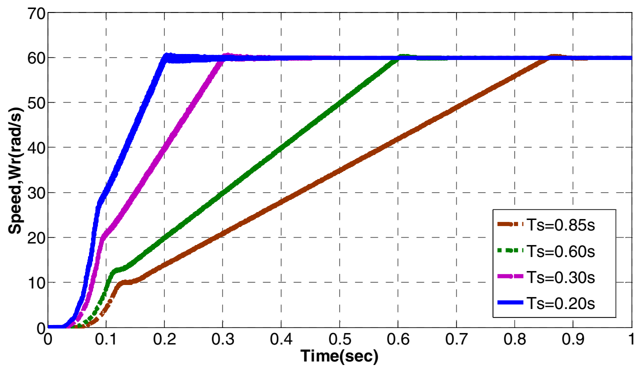
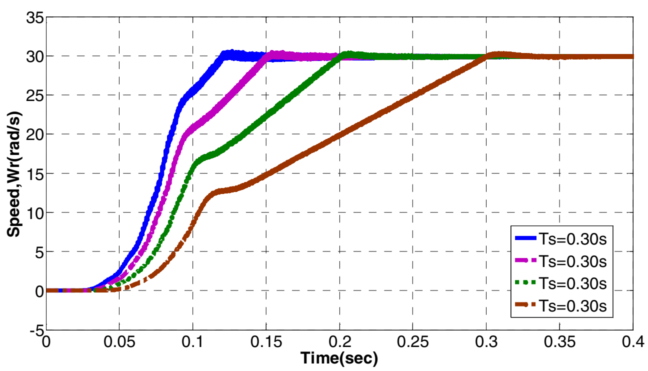


(c)



(d)

Fig. 6: Comparison of speed responses obtained during start-up by reference and estimated speed for four different speeds: (a) at rated, 180(rad/s) (b) at 120(rad/s) (c) at 60(rad/s) (d) at 30(rad/s)

From the simulation, reverse operation is tested to the PMSM drive. Fig. 7 shows the forward operation at start-up and reverse operation at 1.5s while Fig. 8 shows the reverse conversion of the system. It obviously shows that both designs perform nearly similar performances. The system shows that there are no overshoot and undershoot, the settling time of both designs are the same and negligible of steady state error. Based on the analysis from the above result, it shows that the proposed sensorless control algorithm has good speed responses in the low and high speeds.

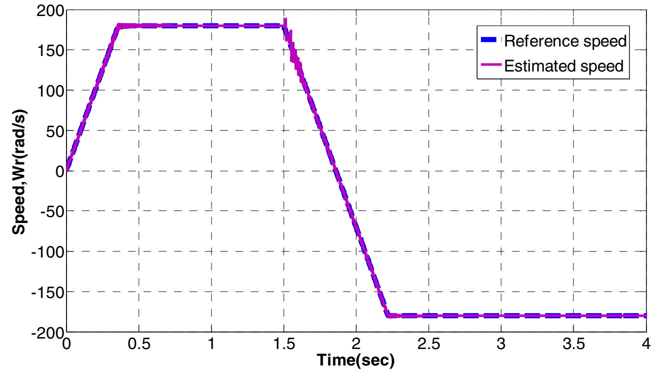


Fig. 7: Comparison of speed response obtained during forward and reverse operation by reference and estimated speed at rated speed command

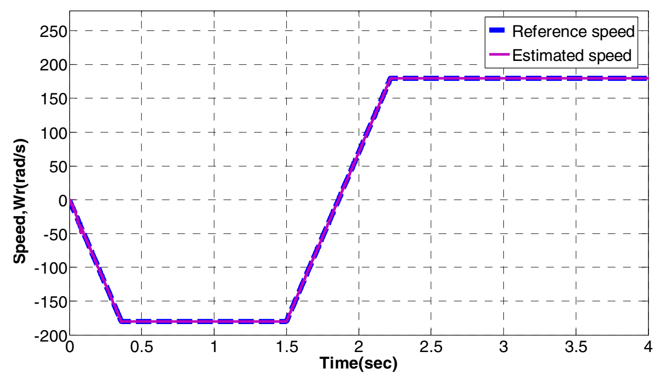


Fig. 8: Comparison of speed response obtained during reverse and forward operation by reference and estimated speed at rated speed command

VI. Conclusion

The vector controlled drives of PMSM are proposed without using speed sensor. A model reference adaptive controller based speed estimation technique has been presented in this paper which been proved in the simulation that it has a good adaptation with parameters variation. Basically, the rotor estimated speed is generated from the adaptation mechanism using the cancellation of error between the estimated quantities obtained in the two models of voltage and current. The simulation results indicate that the proposed algorithm shows good speed response in the low and high speeds. Finally, the proposed algorithm shows a better performance in the parameter variation compared to the conventional algorithm of sensorless speed control for PMSM drives.

VII. APPENDIX

The technical data of the PMSM used in the simulations are as in Table 1.

TABLE I.
MOTOR SPECIFICATIONS

NO.	Motor Specifications	
1.	Peak Torque, Nm	10
2.	Rated Torque, Nm	1.7
3.	Rated Current, A	2.7
4.	Peak Current, A	10
5.	Rated Speed, rad/s	180
6.	Pole Pair Number	3
7.	Inertia, kgm^2	0.000256
8.	Resistance, Ω	2.67
9.	Inductance, mH	11.5
10.	Magnet Flux, Vs/rad	0.1210
11.	Rated Frequency, Hz	150
12.	DC Link Voltage, V	320

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