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SENSORLESS SPEED CONTROL OF PERMANENT MAGNET SYNCHRONOUS MOTOR WITH HYBRID SPEED CONTROLLER USING MODEL REFERENCE ADAPTIVE SYSTEM

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Abstract- This article presents a hybrid controller which consists of a parallel connected fuzzy logic (FL) and PI speed controller for the sensorless speed control of Permanent Magnet Synchronous Motor (PMSM) using Model Reference Adaptive System (MRAS). The aim of the study to prevent speed overshot in startup time of the motor and provides a better dynamic response in transient states. In addition, this study, in order to eliminate distortions caused by sensors that MRAS sensorless control method, due to its simplicity and good stability has been preferred for the estimation of speed. A detailed simulation comparison between the novel and traditional designs is carried out closed loop sensorless methods of operation when a vector control drive is working under load and no load separately for the PI, FL and hybrid control.

Key Words- FL, PMSM, MRAS, PI, sensorless control.

1. INTRODUCTION

Permanent Magnet Synchronous Motors (PMSM) is an ideal candidate for high-performance industrial drives due to the outstanding features such as simple structure, high-energy efficiency, reliable operation and high power density.

Speed control of traditional PMSM drive systems is obtained by taking rotor position or speed information from shaft sensor such as an optical encoder or resolver. The use of these types of sensors increases system complexity, weight and the cost. Speed position sensorless systems overcome the shortcomings of the above, and improve system reliability, robustness and the dynamic performance.

A variety of techniques have been developed to eliminate the rotor position sensor in PMSM applications. In general sensorless control techniques of PMSM, Lunberger or Kalman filter observers, sliding mode control, MRAS estimators, high-frequency signal injection method, fuzzy logic and artificial intelligence, is on direct control of torque and flux [1-2-3-4-5-6].

This paper mainly focuses on designing the MRAS algorithm in order to estimate rotor speed. The purpose is to decrease the time to reach a speed reference of the PMSM system when the load torque changes suddenly. Also, this paper introduces a hybrid control for speed control of a PMSM drive. In the drive, a Fuzzy Logic (FL) and PI are connected in parallel. The aim of this study, is to obtain a controller that eliminates the over speed in startup and provides a fast and smooth dynamic response for the speed control of PMSM. Thus, the system is controlled by the FL to get fast dynamic response in transient state and also controlled by the PI to get smooth

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dynamic response in initial state. The performance of the proposed controller in verified by computer simulations.

2. MODELING OF THE PMSM

Figure 1 illustrates the block diagram of Field Oriented Control (FOC) scheme based PMSM drive used in this work. The drive consists of hybrid fuzzy-PI speed controller and MRAS to estimate of speed, SPWM, and PMSM. The MRAS scheme acts as the feedback sensor like the position/speed shaft sensor. It can work out the rotor's angular speed and produce the rotor's angular position by integrating the angular speed.

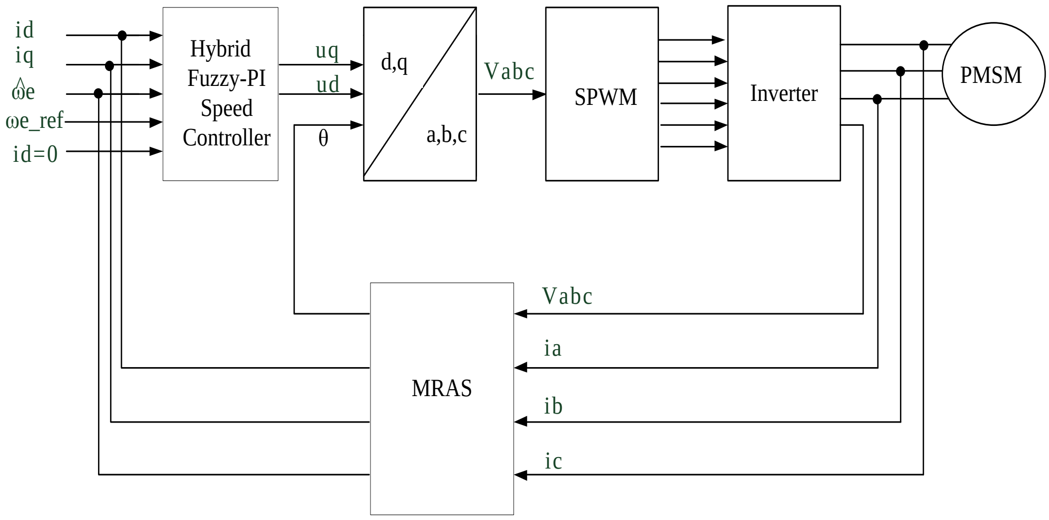
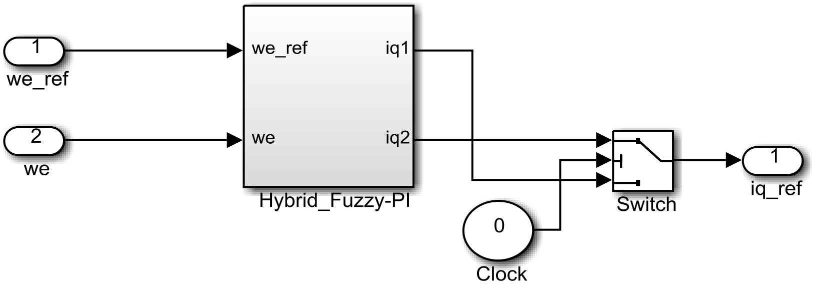


Figure 1. Sensorless speed control of PMSM with MRAS

3. DESIGN OF THE HYBRID CONTROLLER

The controller design for PMSM model plays an important role in the system performance. The PI control is used usually in the speed loop of PMSM closed loop control system. The adverse nonlinear nature of PMSM interior variables, the coupling characteristics and the external disturbances make it difficult to build the accurate mathematical model of controlled object and the controlled object often changes with the working condition. So, control algorithm of the conventional PI control strategy is easy to realize, so higher steady-state accuracy could be acquired and it could be widely used in engineering practice. But the expected control performance index could only be acquired through precise mathematical model and the system's dynamic response and anti-disturbance performance are not ideal enough [7]. The suitable control method is necessary in order to obtain good adjustment performances in various working conditions. But it is very difficult to identify system characteristics in real time and dynamic control parameters due to the complexity of PMSM servo system. Thus, the intelligent controller i.e. fuzzy controller is needed for improving the speed response and transient response.

Fuzzy logic control is a control algorithm based on a linguistic control strategy, which is derived from expert knowledge into an automatic control strategy. Fuzzy logic control doesn't need any difficult mathematical calculation like the others control system. While the others control system use difficult mathematical calculation to provide a model of the controlled plant, it only uses simple mathematical calculation to simulate the expert knowledge. Although it doesn't need any difficult mathematical calculation, but it can give good performance in a control system. Thus, it can be one of the best available answers today for a broad class of challenging controls problems. Taking into consideration the described advantages and disadvantages, the hybrid control is designed for the speed control of the PMSM as shown in Fig. 2. The controller consist of a FL, PI and clock-switch.



Figrue 2. Block diagram of the Hybrid speed controller

The input of the controller is speed error and the output of the controller is control current. The switch is set to run using PI controller at startup. When the system reaches to settling time the switch is second position and system operates as a fuzzy.

3.1. Design of the fuzzy logic controller

Various applications of FL have shown a fast growth in the past few years. Also FL has become popular in the field of industrial control applications for solving control, estimation, and optimization problems [8]. In this section, FL is proposed to replace the PI controller used for error minimization.
FL technique has been applied to solve optimization problems for induction motor drives [9-10]. It has been proposed to replace PI controllers in different error minimization applications [11-12]. Therefore, FL can replace the conventional PI controller to solve the optimization problem. The proposed FL is a Mamdani-type rule base where the inputs are the speed tuning signal ε_ω and its change $\Delta\varepsilon_\omega$, which can be defined as;

$$\Delta\varepsilon_\omega(k) = \varepsilon_\omega(k) - \varepsilon_\omega(k-1) \tag{1}$$

The structure of fuzzy logic system is shown in Figure 3.

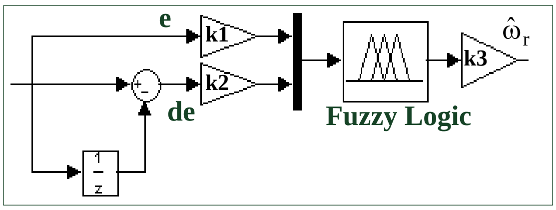


Figure 3. Structure of fuzzy logic controller

These two inputs are multiplied by two scaling factors *k1* and *k2*, respectively. The output of the controller is multiplied by a third scaling factor *k3* to generate the actual value of the rate of change of the optimized speed.

$$\hat{\omega}_r(k) = \hat{\omega}_r(k-1) + \Delta\hat{\omega}_r(k) \tag{2}$$

The choice of the values of the scaling factors greatly affects the performance of the FL. A trial and error technique is usually used to tune these gains to ensure optimal performance of the controller [13]. Each variable of the FL has seven membership functions. The following fuzzy sets are used: NB = negative big, NM = negative medium, NS = negative small, ZE = zero, PS = positive small, PM = positive medium and PB = positive big. The universe of discourse of the inputs -1.5 and 1.5, and outputs of the FL are chosen between −3 and 3 with triangular membership functions, as shown in Figs. 4 and 5. Table 1 shows the fuzzy rule base with 49 rules [13]. FL is modeled using the MATLAB fuzzy-logic toolbox GUI.

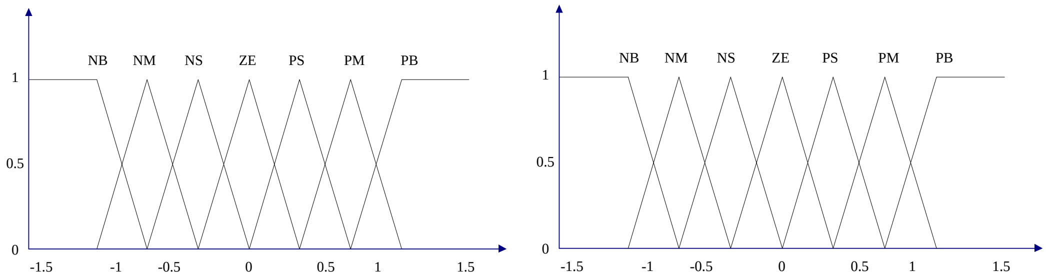


Figure 4. Membership functions of $\varepsilon_{\omega n}$, $\Delta\varepsilon_{\omega n}$

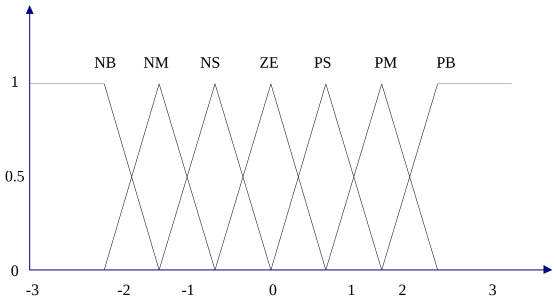


Figure 5. Membership functions of $\Delta\hat{\omega}_{rn}$

Table 1. Fuzzy logic rules for speed control

$\Delta\varepsilon_\omega$ \ ε_ω	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NM	NM	NS	NS	ZE
NM	NB	NB	NM	NM	NS	ZE	PS
NS	NM	NM	NM	NS	ZE	PS	PS
ZE	NM	NM	NS	ZE	PS	PM	PM
PS	NS	NS	ZE	PS	PM	PM	PM
PM	NS	ZE	PS	PM	PM	PB	PB
PB	ZE	PS	PS	PM	PM	PB	PB

4. MRAS IN MOTOR CONTROL APPLICATIONS

In the MRAS method, the motor speed is estimated using a reference model and adaptive model. The reference model, which is independent of the rotor speed, calculates the state variable Ψ_r^s from the terminal voltage and current. Then the adaptive model, which is dependent on the rotor speed, estimates the state variable Ψ_r^r. The difference between these state variables is then used to drive an adaptation mechanism which generates the estimated speed $\hat{\omega}_r$. The generalized structure of MRAS is shown in Figure 3. The reference model and adaptive model have the same input. x and $\hat{x}$ are respectively the state variable of the reference model and adaptive model. Given performance index x is set by the reference model, which is compared with the corresponding performance of adaptive model $\hat{x}$. The difference value is the input of adaptation mechanism. The variable in adaptive model is modified by adaptation mechanism, in order to make its state variable $\hat{x}$ draw near x which also means the difference value approaches zero [14].

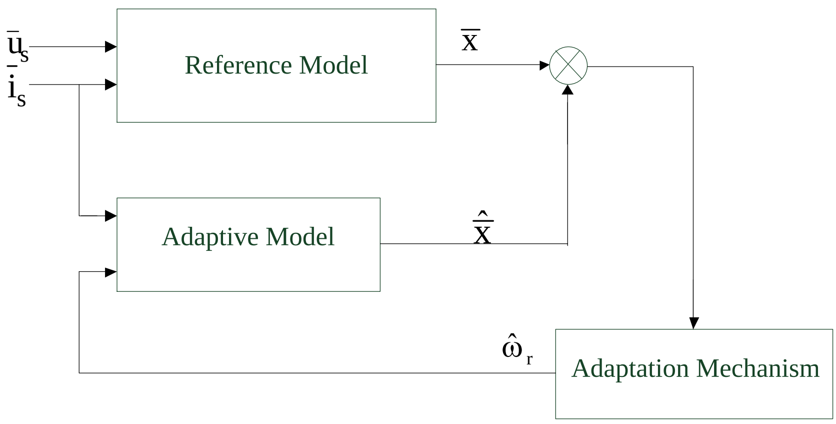


Figure 6. Generalized MRAS

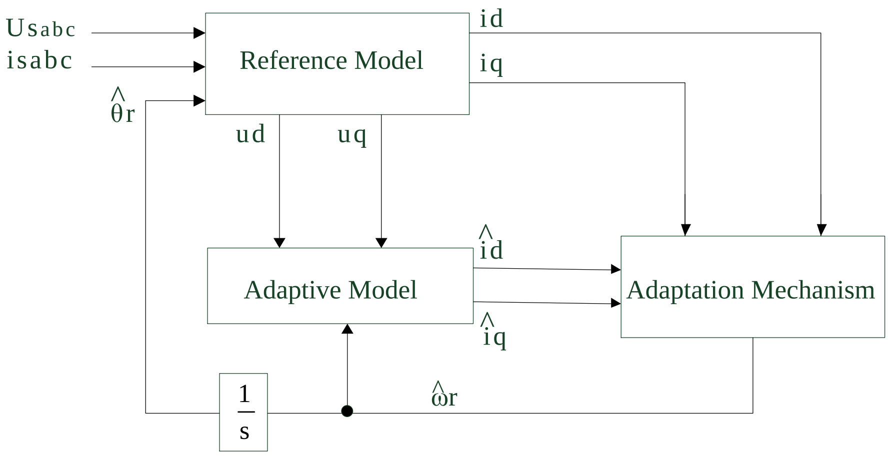


Figure 7. Structure of MRAS

This strategy selects PMSM itself as the reference model and its current model as the adaptation mechanism. MRAS sensorless control is mainly based on the model of the motor at the rotating reference plane. Stator voltage equations on rotating dq reference plane and flux equations are defined as follows [15].

$$u_d = R.i_d + L_d \frac{di_d}{dt} - \omega_r L_q i_q \tag{3}$$

$$u_q = R.i_q + L_q \frac{di_q}{dt} - \omega_r L_d i_d + \omega_r \psi_r \tag{4}$$

Where ud, uq are stator voltage component in d − q frame of axes; id, iq are stator current component; Ld, Lq are stator inductance; R is stator resistance; ψr is rotor flux; ωr is rotor speed [15].

$$\frac{di_d}{dt} = -\frac{R}{L_d}.i_d + \frac{\omega_r L_q}{L_d}.i_q + \frac{1}{L_d}u_d \tag{5}$$

$$\frac{di_q}{dt} = -\frac{\omega_r.L_d}{L_q}.i_d - \frac{R}{L_q}.i_q + \frac{1}{L_q}u_q - \frac{\omega_r \psi_r}{L_q} \tag{6}$$

We can write in matrix form;

$$\frac{d}{dt}\begin{bmatrix} i_d + \frac{\psi_r}{L_d} \\ i_q \end{bmatrix} = \begin{bmatrix} -\frac{R}{L_d} & \omega_r \\ -\omega_r & -\frac{R}{L_q} \end{bmatrix} . \begin{bmatrix} i_d + \frac{\psi_r}{L_d} \\ i_q \end{bmatrix} + \begin{bmatrix} \frac{1}{L_d} & 0 \\ 0 & \frac{1}{Lq} \end{bmatrix} . \begin{bmatrix} u_d + \frac{R.\psi_r}{L_d} \\ u_q \end{bmatrix} \tag{7}$$

Thus, the system model can be simplified by using the equation state variables (i'_d ve i'_q) and the control variables (u'_d ve u'_q).

$$i'_d = i_d + \frac{\psi_r}{L_d}, i'_q = i_q, u'_d = u_d + \frac{R\psi_r}{L_d}, u'_q = u_q \tag{8}$$

After conversion, the current model of PMSM is defined as follows.

$$\frac{d}{dt}\begin{bmatrix} i'_d \\ i'_q \end{bmatrix} = \begin{bmatrix} -\frac{R}{L_d} & \omega_r \\ -\omega_r & -\frac{R}{L_q} \end{bmatrix} . \begin{bmatrix} i'_d \\ i'_q \end{bmatrix} + \begin{bmatrix} \frac{1}{L_d} & 0 \\ 0 & \frac{1}{L_q} \end{bmatrix} . \begin{bmatrix} u'_d \\ u'_q \end{bmatrix} \tag{9}$$

Equation (9) can then be shortened as;

$$pi' = Ai + Bu' \tag{10}$$

Speed information is included in the state matrix A, which is to be identified, and PMSM is the reference model. Estimated values are expressed in Eq. (11) which is the adjusted model.

$$\frac{d}{dt}\begin{bmatrix}\hat{i}_d^{'}\\ \hat{i}_q^{'}\end{bmatrix}=\begin{bmatrix}-\frac{R}{L_d} & \hat{\omega}_r\\ -\hat{\omega}_r & -\frac{R}{L_q}\end{bmatrix}\cdot\begin{bmatrix}\hat{i}_d^{'}\\ \hat{i}_q^{'}\end{bmatrix}+\begin{bmatrix}\frac{1}{L_d} & 0\\ 0 & \frac{1}{L_q}\end{bmatrix}\begin{bmatrix}u_d^{'}\\ u_q^{'}\end{bmatrix} \tag{11}$$

Equation (11) is then being shown as;

$$p.\hat{i}'=\hat{A}.\hat{i}'+B.u' \tag{12}$$

Defining the generalized error as $e=i'-\hat{i}'$, Equation (12) can then be obtained by subtracting equation (11) from the equation (9).

$$\begin{bmatrix}\frac{de_d}{dt}\\ \frac{de_q}{dt}\end{bmatrix}=\begin{bmatrix}-\frac{R}{L_d} & \omega_r\\ -\omega_r & -\frac{R}{L_q}\end{bmatrix}\cdot\begin{bmatrix}e_d\\ e_q\end{bmatrix}-J(\omega_r-\hat{\omega}_r)\cdot\begin{bmatrix}\hat{i}_d^{'}\\ \hat{i}_q^{'}\end{bmatrix} \tag{13}$$

Where $e_d=i_d^{'}-\hat{i}_d^{'}$, $e_q=i_q^{'}-\hat{i}_q^{'}$, $J=\begin{bmatrix}0 & -1\\ 1 & 0\end{bmatrix}$

Equation (13) also can be shown as;

$$\frac{de}{dt}=A_e e-W \tag{14}$$

Where

$$A_e=\begin{bmatrix}-\frac{R}{L_d} & \omega_r\\ -\omega_r & -\frac{R}{L_q}\end{bmatrix},\ W=(\hat{\omega}_r-\omega_r).J.\hat{i}_s^{'} \tag{15}$$

According to ultra-stability theory, the following conditions must be met in order to maintain the feedback system stable [16].

(1) Transition matrix $H(s) = (sI − A)^{-1}$ must be strictly positive real.

(2) Popov integral inequality is $\eta(0,t_1)=\int_0^{t_1} v^T w.dt \geq -\gamma_0^2$, in which, $\forall t1 \geq 0$, γ_0^2 is a finite positive constant independent of t1. So far, the MRAS is asymptotic stable.

The adaptive law is shown in (16), which is obtained by inverse solution to Popov integral inequality.

$$\hat{\omega}_r=\left(K_p+\frac{K_i}{s}\right).i_s\otimes\hat{i}_s=\left(K_p+\frac{K_i}{s}\right)\left(i_d^{'}\hat{i}_q^{'}-i_q^{'}\hat{i}_d^{'}\right)\hat{i}_q^{'} \tag{16}$$

Equation (17) is obtained by substituting equation (8) into equation (16).

$$\hat{\omega}_r = \left(K_p + \frac{K_i}{s}\right) \cdot \left(i_d \hat{i}_q - i_q \hat{i}_d - \frac{\Psi_r}{L} \cdot \left(i_q - \hat{i}_q\right)\right) \tag{17}$$

Where $\hat{i}_d, \hat{i}_q$ are obtained from the adjusted model, and i_d, i_q are obtained from the referenced model.

Adaptation mechanism consists of a PI controller as shown in the equation (17). PI controllers are widely used in industrial control systems applications. They have a simple structure and operation over a wide range can offer satisfactory performance. Therefore, a simple static gain linear PI controller is used the estimated rotor speed to produce the majority of adaptation designs in the literature for the MRAS speed observers.

5. FINDINGS

To prove the accuracy of the proposed hybrid control, computer simulation has been performed. The results are compared with the results obtained from PI and FL. The model of PMSM which are given in section 2 is used in the simulation. The parameters of the PMSM used in this study are given in Table 2.

Table 2. The parameters of the PMSM

Features	Values
Rated power P_N(kW)	5
Rated voltage U_N(V)	300
Magnetic pole pairs p_n	4
Rated speed(r/min)	2300
Inertia (kg/m^2)	0,001469
Viscous damping coefficient (Nm.s)	0,0003035
Stator resistance R_s(Ω)	0,4578
Rotor flux linkageΨ_f (Wb)	0,171

Figures show simulation results of measured speed, estimated speed, electromagnetic torque, stator current components and estimated and measured angles with PI, fuzzy and hybird controller at step and variable speed reference (1000 rpm) under no load and load, respectively. As seen from the figure 8, consist of overshot at initial speed and long settling time about 0.018 sec. under no load. In figure 9 variable and inverse speed states examined. Variable reference speed response of motor has been better than step reference speed, but unable to prevent overshot. In figure 10 shows PI controller response with variable reference signal of PMSM under load (10 Nm). As seen from the figure, the speed response of PI controller in transient state has been very poor and speed changes between 1250 rpm and 750 rpm. This is not an acceptable range for sensitive applications. Also estimated speeds with MRAS have given a very good response at every condition.

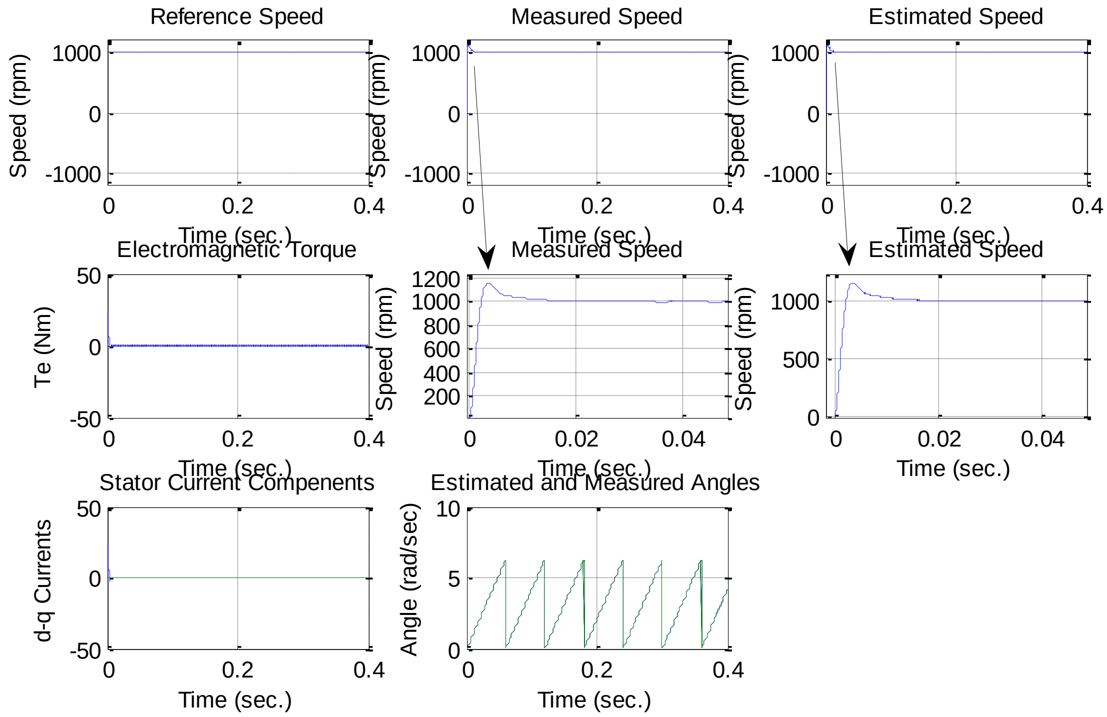


Figure 8. PI controller response with step reference signal of PMSM under no load

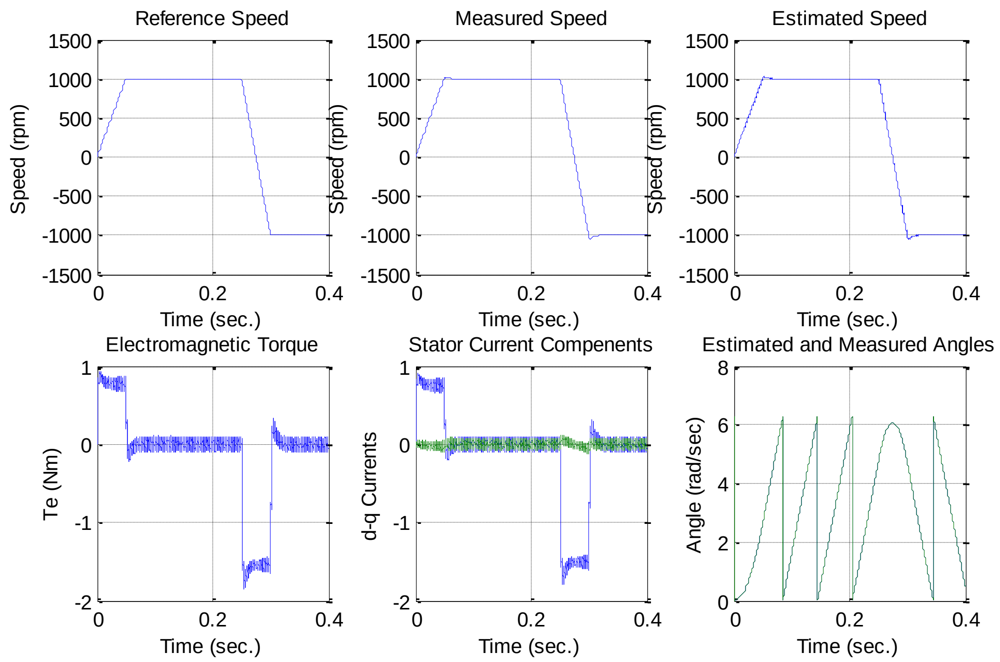


Figure 9. PI controller response with given reference signal of PMSM under no load

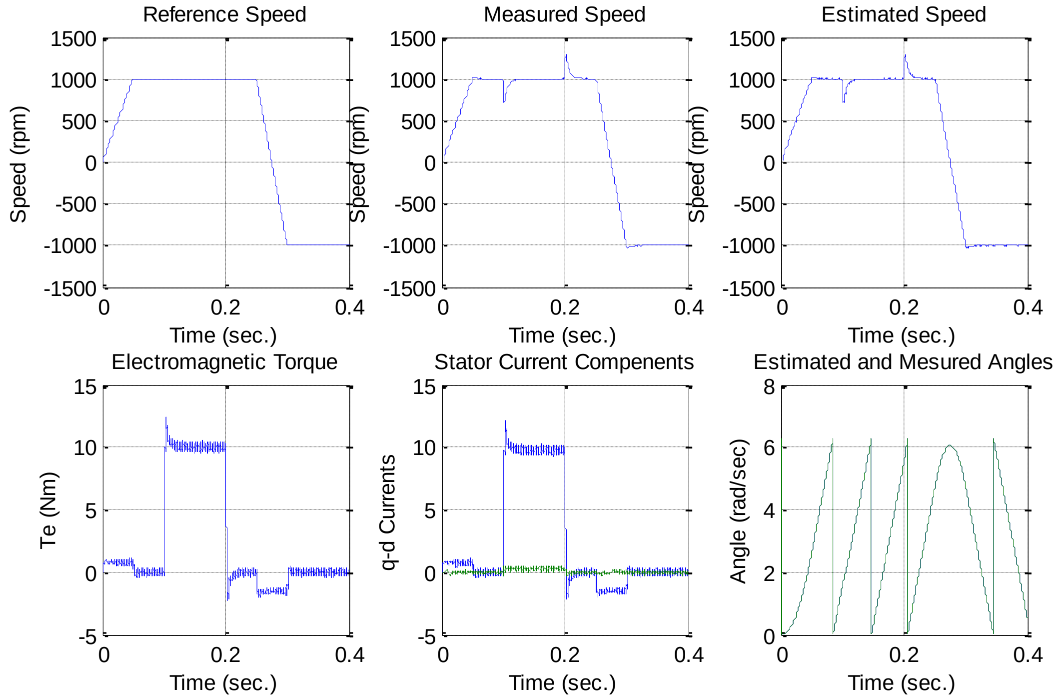


Figure 10. PI controller response with given reference signal of PMSM under load

Figs 11, 12 and 13 show values while the motor is running under the same conditions as in figs. 8, 9 and 10. As seen from the figure 11, consist of overshot and settling time less than PI controller at initial speed under no load. In figure 12 variable and inverse speed states examined. Variable reference speed response of motor has been better than step reference speed, but unable to prevent overshot. In figure 13 shows fuzzy logic controller response with variable reference signal of PMSM under load (10 Nm).

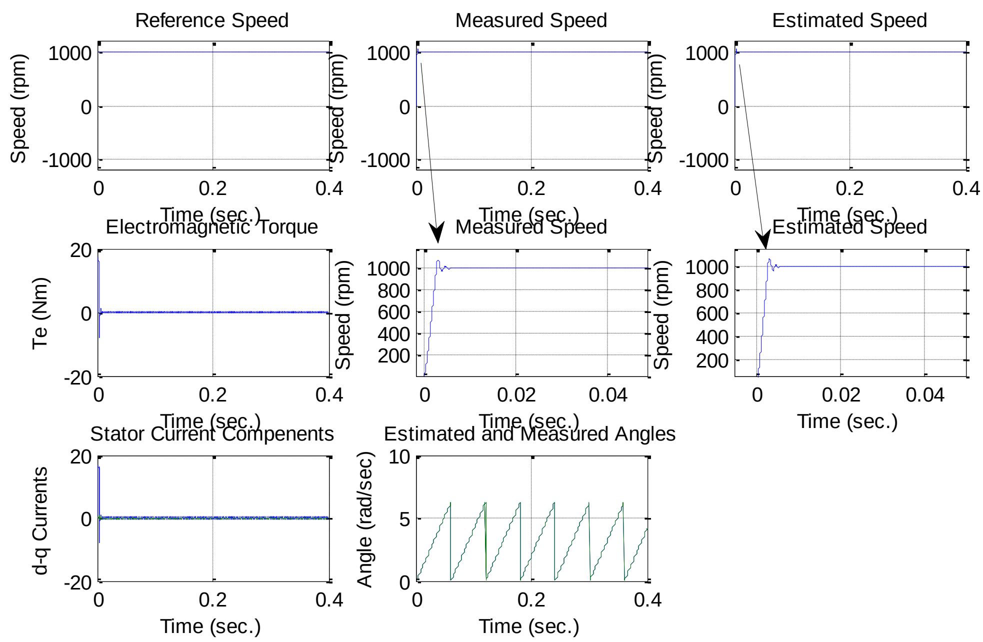


Figure 11. Fuzzy logic controller response with step reference signal of PMSM under no load

As seen from the figure, the speed response in transient state has been better than PI controller and speed changes between 1010 rpm and 990 rpm. This is an acceptable range for sensitive applications.

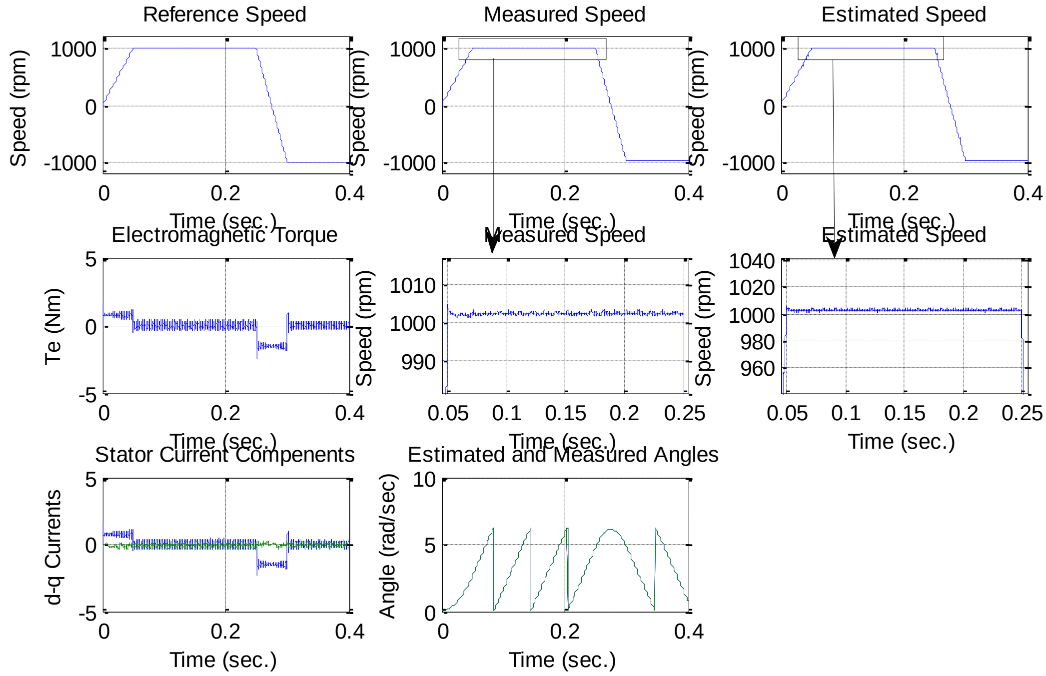


Figure 12. Fuzzy logic controller response with given reference signal of PMSM under no load

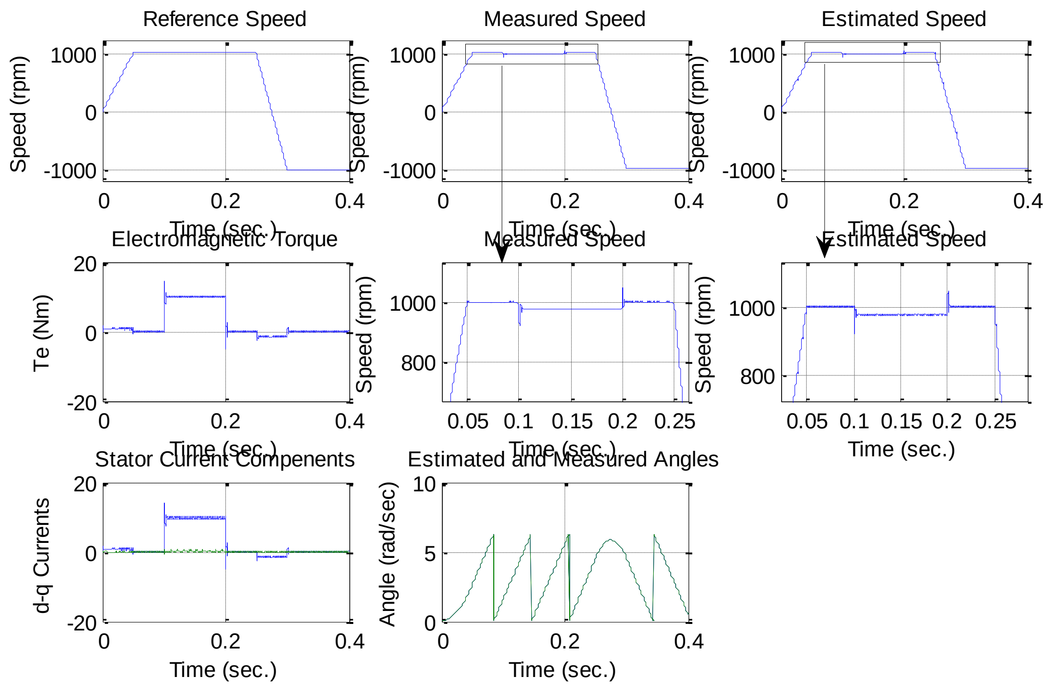


Figure 13. Fuzzy logic controller response with given reference signal of PMSM under load

Figs 14, 15 and 16 show values while the motor is running under the same conditions as in figs. 8, 9, 10, 11,12 and 13. As seen from the figure 14, 15 and 16 consist of no overshoot, better settling time and better transient state response.

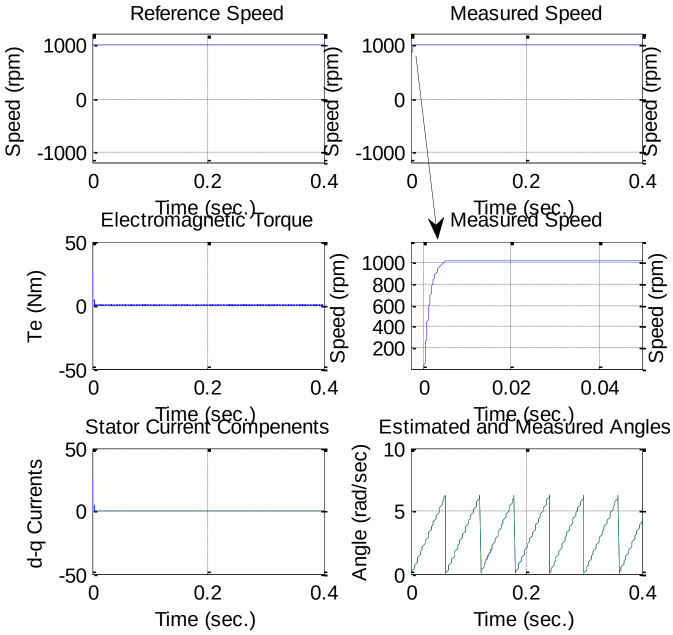


Figure 14. Hybrid controller response with step reference signal of PMSM under no load

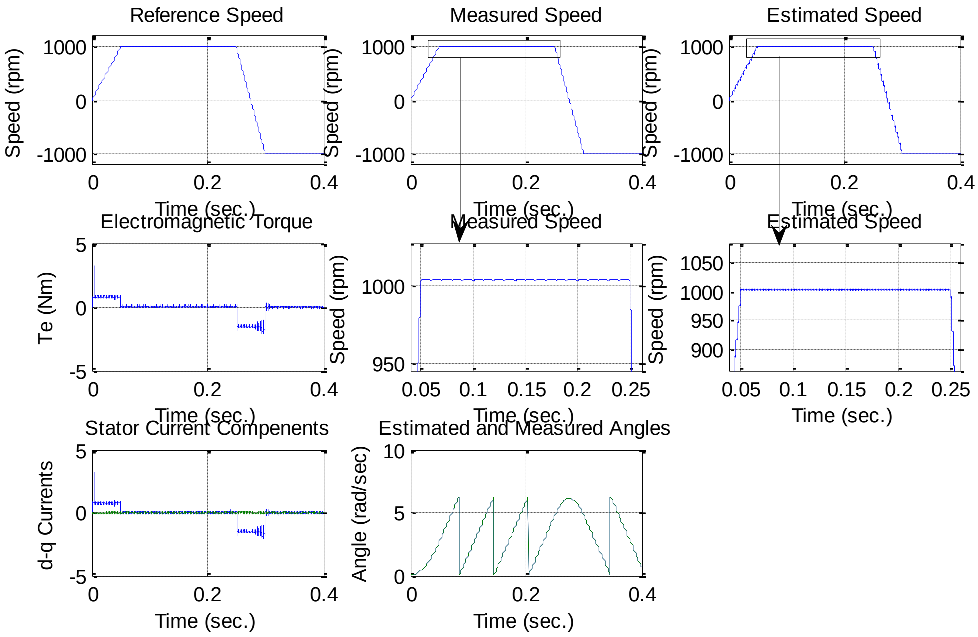


Figure 15. Hybrid controller response with variable reference signal of PMSM under no load

The results show that the hybrid control is less sensitive to reference signal changes and external load disturbance than that of PI and fuzzy logic.

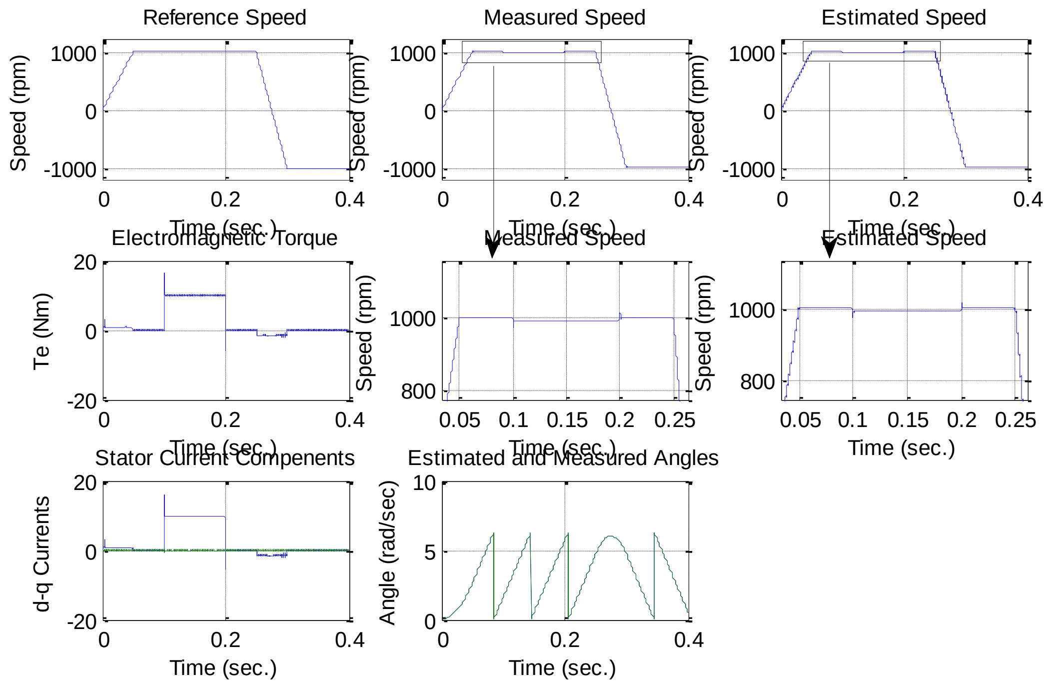


Figure 16. Hybrid controller response with variable reference signal of PMSM under load

6. CONCLUSIONS

In this paper, sensorless control was carried out on PMSM based on MRAS and proposed a novel hybrid speed controller to replace the classical fixed gain PI controller. A detailed comparison between the two schemes has been carried out using field oriented vector control PMSM drive. Simulation of hybrid controller shows better transient response as well as better load torque disturbance rejection in closed loop sensorless modes of operation.

7. ACKNOWLEDGMENT

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