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EXTENDED KALMAN FILTER BASED SENSORLESS CONTROL OF PMSM

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ABSTRACT

This paper proposes a sensorless control framework in view of expanded Kalman channel (EKF) for perpetual magnet synchronous engines (PMSM). The EKF conditions are worked in rotor transition arranged synchronous facilitate, so it can without much of a stretch be utilized for either non-notable or remarkable post engines. Latency and other workman parameters are not required in this spectator. Rotor speed and position can be assessed precisely and afterward a sensorless control framework is manufactured. The underlying rotor position and the workman parameters are not required in this framework. By some remuneration in eyewitness conditions, the spectator can be constantly steady and has just a single expected balance point. So the engine can start up from any obscure beginning positions.

Keywords «Permanent magnet motor», «Synchronous motor », «Vector control», « Sensorless control ».

INTRODUCTION

Changeless magnet synchronous engines (PMSM) are increasingly utilized on account of its high power thickness, expansive torque to inactivity proportion and high effectiveness. The rotor transition is produced by the lasting magnet on the rotor. So the rotor transition position is the same as the rotor electrical position. Also, the valuable rotor position is required for the elite control. Since repairman position sensor is normally excessively costly, builds the cost and abatement the soundness of the framework, workman sensorless control is turning into an examination concentrate now. Some sensorless control strategies have been proposed some time recently. By and large there are the strategies based on back electromotive power (EMF), show reference versatile framework (MRAS) (case in [1]) and state onlooker technique. The strategies in light of back EMF are straightforward however doesn't function admirably in low speed locale in light of the fact that the back EMF is too little contrasted and the commotion. The strategy in light of MRAS additionally can't get a delightful execution in low speed area and is extraordinarily relied upon the exactness of the reference display. The state onlooker strategy isn't appropriate for the nonlinear model and is difficult to know the input network. Additionally a few strategies in view of Kalman channel have been proposed, the greater part of which are established in the static two-stage facilitate, since the stator inductance of notable shaft engine is a variable of rotor position in static two-stage facilitate, these eyewitnesses can scarcely be utilized for notable post engines [2][3][4] . In this paper, another state spectator in view of stretched out Kalman channel is utilized to watch the rotor position and speed. The onlooker demonstrate is set up in the rotor transition arranged synchronous facilitate, so it can be utilized effectively in either notable or non-notable post engine in light of the fact that the stator inductances in synchronous facilitate are constantly steady. Expanded Kalman channel can illuminate nonlinear condition specifically by numeric emphasis. Kalman channel likewise thinks about the blunders of the parameters and the commotions in the estimation, so it is extremely hearty with the parameters' mistakes and estimation commotions. Additionally the introductory rotor position isn't essential for the start-up. By a legitimate remuneration in the spectator condition, the other sudden balance purposes of the onlooker are gotten off. The engine would startup be able to effectively from any obscure beginning position [5][6][7].

Observer based on extended Kalman filter

In rotor flux oriented synchronous coordinate (d,q axes), PMSM model is shown in (1).

$$\begin{cases} \frac{dI_d}{dt} = \frac{U_d}{L_d} - \frac{R \cdot I_d}{L_d} + \omega \cdot \frac{L_q}{L_d} I_q \\ \frac{dI_q}{dt} = \frac{U_q}{L_q} - \frac{R \cdot I_q}{L_q} - \omega \cdot \frac{L_d}{L_q} I_d - \frac{\psi_r}{L_q} \cdot \omega \\ \frac{d\omega}{dt} = 0 \\ \frac{d\theta}{dt} = \omega \end{cases} \qquad (1)$$

Here Id and Iq are the currents in d and q axes. R is stator resistance while Ld and Lq are the stator phase inductances in d and q axes. For non-salient motors, Ld is the same as Lq. Ud and Uq are stator voltages and R is stator resistance. ω is the rotor electrical angle speed and θ is rotor electrical angle (rotor flux angle). ψ r is rotor flux amplitude. Rotor speed is considered to change more slowly compared with other variables. State equations for PMSM can be written as (2).

$$\dot{x} = g(x,u) + w$$
$$y = C \cdot x + v \qquad (2)$$

Here $x = \begin{bmatrix} I_d & I_q & \omega & \theta \end{bmatrix}^T$ (3a)

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \qquad (3b)$$

$$y = \begin{bmatrix} I_d \\ I_q \end{bmatrix} \qquad (3c)$$

Here w and v are random disturbances. In fact w is the process noise which stands for the errors of the parameters; v is the measurement noise which stands for the errors in the measurement and sample. The noise covariance matrixes are defined as follows:

$$Q = \mathrm{cov}(w) = E\{ww^T\} \qquad (4a)$$
$$R = \mathrm{cov}(v) = E\{vv^T\} \qquad (4b)$$

Extended Kalman filter can be built by the derivation below:

$$x(k+1) = f = x(k) + \dot{x} \cdot T_e = \begin{cases} I_d(k) + \left(\frac{U_d}{L_d} - \frac{R \cdot I_d}{L_d} + \omega \cdot \frac{L_q}{L_d} I_q \right) \cdot T_e \\ I_q(k) + \left(\frac{U_q}{L_q} - \frac{R \cdot I_q}{L_q} - \omega \cdot \frac{L_d}{L_q} I_d - \frac{\psi_r}{L_q} \cdot \omega \right) \cdot T_e \\ \omega(k) \\ \theta(k) + \omega \cdot T_e \end{cases} \qquad (5)$$

Define matrix F:

$$F = \frac{\partial f}{\partial x} = \begin{bmatrix} 1 - \frac{T_e}{\tau_d} & T_e \omega \frac{L_q}{L_d} & T_e \frac{L_q}{L_d} I_q & 0 \\ -\frac{L_d}{L_q} T_e \omega & 1 - \frac{T_e}{\tau_q} & T_e(-\frac{L_d}{L_q} I_d - \frac{K_e}{L_q}) & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & T_e & 1 \end{bmatrix} \qquad (6)$$

$\tau_d = L_d / R$, $\tau_a = L_a / R$ are stator constants.

Define matrix P as the error covariance of observation

$$P_k = E\{e_k^T \cdot e_k\} = \sum_{i=1}^{n} E\{[x_i - \hat{x}_i][x_i - \hat{x}_i]^T\} \qquad (7)$$

E{·} is the computation of expectation value.

Extended Kalman filter can be realized by iteration as follows:

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1. Compute the state ahead and the error covariance ahead.

$$\hat{x}_{k|k-1} = \hat{x}_{k-1|k-1} + \dot{x}\cdot T_c \quad (8a)$$
$$P_{k|k-1} = F_{k-1}P_{k-1|k-1}F_{k-1}^{T} + Q_{k-1} \quad (8b)$$

2. Compute the Kalman gain.

$$K_k = P_{k|k-1}\cdot C^{T}\cdot\left(C\cdot P_{k|k-1}\cdot C^{T} + R_{k-1}\right)^{-1} \quad (8c)$$

3. Update estimation with measurement.

$$\hat{x}_{k|k} = \hat{x}_{k|k-1} + K_k\left(y_k - C\cdot\hat{x}_{k|k-1}\right) \quad (8d)$$

4. Update the error covariance matrix.

$$P_{k|k} = \left[I - K_k\cdot C\right]\cdot P_{k|k-1} \quad (8e)$$

Based on extended Kalman filter, the sensorless control system is shown in Fig. 1. In this system, rotor flux oriented vector control is adopted. The d-axe current is controlled to be zero which can get the largest torque with the smallest phase currents. Since the terminal voltages of motor are hard to measure, the reference voltages are used in extended Kalman filter instead of the real voltages.

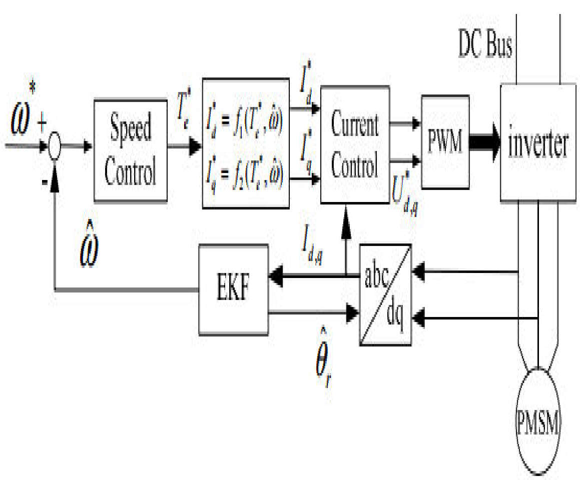

Fig. 1. Block diagram of the sensorless system

Start up ability analyse

Take non-salient PMSM motor as example, in real rotor flux oriented coordinate (γ −δ axes), PMSM model is:

$$\frac{dI_\gamma}{dt} = \frac{U_\gamma}{L} - \frac{R\cdot I_\gamma}{L} + \omega\cdot I_\delta; \quad (9a)$$
$$\frac{dI_\delta}{dt} = \frac{U_\delta}{L} - \frac{R\cdot I_\delta}{L} - \omega\cdot I_\gamma - \frac{K_e}{L}\cdot\omega. \quad (9b)$$

U_γ and U_δ are stator voltages in γ-δ axes. I_γ and I_δ are stator currents in γ-δ axes.

Since the real rotor flux is not known in sensorless control, in the coordinate oriented by estimated rotor position (d-q axes), there are:

$$\begin{cases} U_d = U_\gamma\cos\gamma - U_\delta\sin\gamma \\ U_q = U_\delta\cos\gamma + U_\gamma\sin\gamma \end{cases} \quad (10a)$$

$$\begin{cases} I_d = I_\gamma\cos\gamma - I_\delta\sin\gamma \\ I_q = I_\delta\cos\gamma + I_\gamma\sin\gamma \end{cases} \quad (10b)$$

PMSM equations become:

$$\begin{cases} \frac{dI_d}{dt} = \frac{U_d}{L} - \frac{I_d}{\tau} + \omega\cdot I_q + \frac{K_e}{L}\cdot\omega\sin\gamma \\ \frac{dI_q}{dt} = \frac{U_q}{L} - \frac{I_q}{\tau} - \omega\cdot I_d - \frac{K_e}{L}\cdot\omega\cos\gamma \end{cases} \quad (11)$$

Here:

$\gamma = \theta - \hat{\theta}$ is rotor position error.

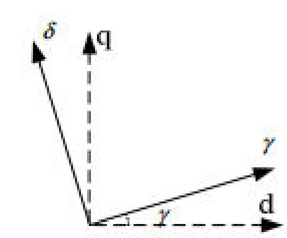

Fig.2. Real and estimated axes

In both coordinates, there always are:

$$\frac{d\theta}{dt}=\omega \quad (12)$$

Electromagnetic torque is:

$$T_{em}=p\cdot\psi_r\cdot I_\delta=p\cdot\psi_r(I_q\cos\gamma-I_d\sin\gamma) \quad (13)$$

Mechanical movement equation of PMSM is:

$$J\frac{d\Omega}{dt}=T_{em}-T_L(\Omega) \quad (14)$$

$T_L(\Omega)$ is load torque and it is a function of rotor speed.

If rotor electrical angle speed is used instead:

$$\frac{d\omega}{dt}=\frac{p^2\cdot K_e}{J}\cdot(I_q\cos\gamma-I_d\sin\gamma)-T_L(\omega) \quad (15)$$

In the observer proposed in (1), the third equation for rotor speed just relies on state feedback. If we just consider the other three equations, (superscript ^ stands for estimated variables)

$$\frac{d\hat{I}_d}{dt}=\frac{\hat{U}_d}{L}-\frac{\hat{I}_d}{\tau}+\hat{\omega}\cdot\hat{I}_q \quad (16a)$$

$$\frac{d\hat{I}_q}{dt}=\frac{\hat{U}_q}{L}-\frac{\hat{I}_q}{\tau}-\hat{\omega}\cdot\hat{I}_d-\frac{K_e}{L}\cdot\hat{\omega} \quad (16b)$$

$$\frac{d\hat{\theta}}{dt}=\hat{\omega} \quad (16c)$$

State observation errors are defined as:

$$\varepsilon=\begin{bmatrix}\varepsilon_d\\ \varepsilon_q\\ \gamma\end{bmatrix}=\begin{bmatrix}I_d-\hat{I}_d\\ I_q-\hat{I}_q\\ \theta-\hat{\theta}\end{bmatrix} \quad (17)$$

Using (10) (11) and (16), there are:

$$\frac{d}{dt}\varepsilon_d=\left(\omega\cdot I_q-\hat{\omega}\cdot\hat{I}_q\right)+\frac{K_e}{L}\cdot\omega\sin\gamma\ ; \quad (18a)$$

$$\frac{d}{dt}\varepsilon_q=-\left(\omega\cdot I_d-\hat{\omega}\cdot\hat{I}_d\right)-\frac{K_e}{L}\cdot(\omega\cos\gamma-\hat{\omega}). \quad (18b)$$

$$\frac{d}{dt}\gamma=\frac{d}{dt}\theta-\frac{d}{dt}\hat{\theta}=\omega-\hat{\omega} \quad (18c)$$

The equilibrium points of the system former will satisfy:

$$\frac{d}{dt}\varepsilon=0 \quad (19)$$

In the observer based on the equations former, besides the expected equilibrium point $\gamma = 0$, there is another equilibrium point:

$$\begin{cases}\hat{\omega}=\omega=0\\ T_{em}=p\cdot\psi_r(I_q\cos\gamma-I_d\sin\gamma)=T_L(\Omega)\end{cases} \quad (20)$$

Since the watched speed is zero, distinction between reference speed and input speed exists, the yield of speed controller (reference torque) will touch base at the most extreme confinement. Be that as it may, on this point, the electromagnetic torque measures up to stack torque while current Iq breaks even with wanted torque current. So the engine can't quicken any more and will remain in this wrong circumstance. Especially, when stack torque is simply grinding or piece torque which are most recognizable, the harmony point is $\gamma = \pm\pi/2$ where the real electromagnetic torque is zero albeit current Iq rises to the wanted esteem. On this point, since the rotor speed and electromagnetic torque are each of the zero, stack torque is additionally invalid. Under the impacts of the most extreme confinement in speed controller, the engine will remain in this circumstance. Practically speaking, when starting position mistake fulfill cos 0 γ > , the genuine electromagnetic torque has the same bearing with wanted torque, at that point PMSM can start up towards the coveted speed heading, and the engine will start up effectively. Something else, PMSM switches and the spectator will misunderstand a speed bearing and will join to the startling harmony focuses. This is confirmed by recreation in next segment. In [2], another balance focuses are proposed which doesn't fulfill (11). It's the joining issue of a few onlookers and these focuses don't exist in our spectator. The second sort of harmony focuses are for the most part controlled by the q-hatchet voltage condition, so we can include some pay in the second

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condition to break out this adjust. We change the condition to:

$$\frac{d\hat{i}_q}{dt}=\frac{\hat{U}_q}{L}-\frac{\hat{i}_q}{\tau}-\hat{\omega}\cdot\hat{i}_d-\frac{K_e}{L}\cdot\hat{\omega}+\frac{k\cdot Ri_q}{L} \qquad (21)$$

Here k is a coefficient positive. With the compensation, the unexpected equilibrium points can be avoided. In steady states, the compensation will be considered as a little error in stator resistance parameter. Its effects will be eliminated by the robustness of the system. Also when motor is started up successfully, the coefficient k can be decreased artificially and the compensation can be moved off finally.

Simulation results Simulations have been done in MATLAB Simulink to verify the performance of the extended Kalman filter. Motor parameters are shown in TABLE I. Table I Motor parametersSimulations have been done in MATLAB Simulink to verify the performance of the extended Kalman filter. Motor parameters are shown in TABLE I.

Table I Motor parameters

Stator resistance R	0.155 Ω
Stator inductance $L_d = L_q$	0.00125 H
Number of pole pairs p	4
Rotor magnet flux ψ_r	0.153 Web

In extended Kalman filter, matrixes Q and R in (4a) and (4b) are difficult to be known exactly because the disturbances w and v are not known. The only possible method is to adjust the values of Q and R by practical simulations or experiments. In simulation, we use the values as follows:

$$P=\begin{bmatrix}0.1&&&\\&0.1&&\\&&0.1&\\&&&0.1\end{bmatrix}\ Q=\begin{bmatrix}10&&&\\&10&&\\&&10&\\&&&10\end{bmatrix}\ R=\begin{bmatrix}1.0&\\&1.0\end{bmatrix}$$

Rotor speed and position estimation results are shown in Fig. 3 and Fig. 4. It shows that extended Kalman filter can observe rotor speed and position exactly. If there is some initial rotor position error, when this error is too large, the motor cannot start up and will converge to the unexpected equilibrium point. As shown in Fig. 5. With compensation as shown in (17), simulation results when there is a large initial position error (2 /3 π) is shown in Fig.6. The motor can start up successfully under the effects of compensation.

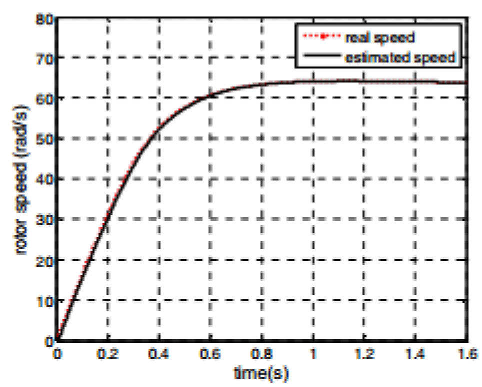

Fig. 3. Estimated and real rotor speed

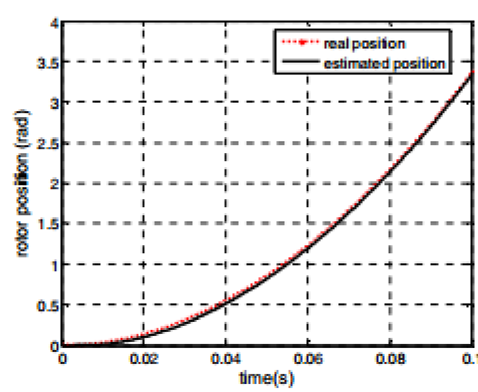

Fig. 4. Estimated and real rotor position

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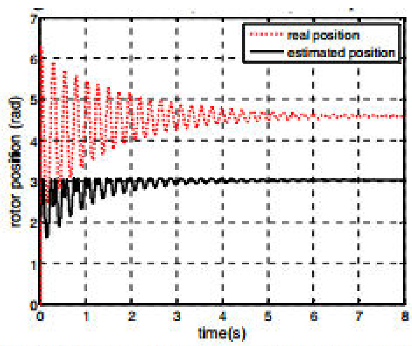

Fig.5. Failure start up when initial position error is too large (simulation)

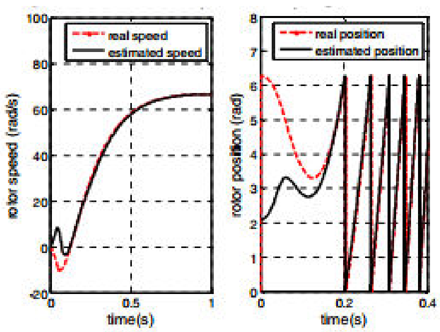

Fig. 6. Success start-up with compensation (simulation)

Simulations also show that with the same load torque and mechanic inertia, the coefficient of compensation has no relations with the initial position error. With the same value of k, result of start up without initial position errors is shown in Fig. 7. To test the start up ability with load torque, simulation result with an electromotive torque of 5Nm is shown in Fig. 8.

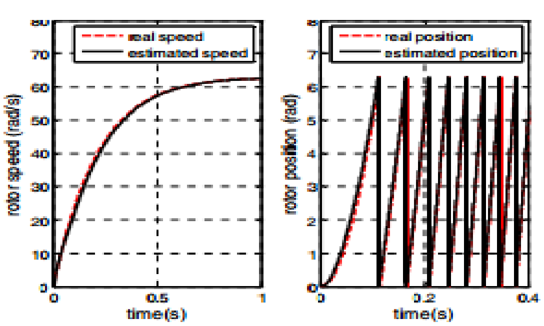

Fig. 7. Start-up with compensation and no initial position error

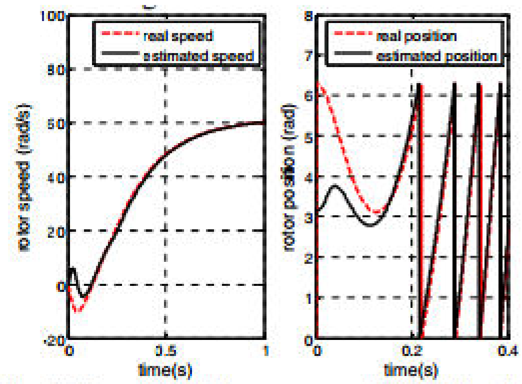

Fig. 8. Start-up with compensation and load torque

Simulations also show that the system can start up when there is a block torque and in steady state, the compensation has very little effects in rotor speed and position estimation.

Experiment results

Experiments have been done on a platform with the DSP C6711 as the controller. The parameters of the motor are the same as Table 1.In fact, the parameters can be varied in a large field.

$$P=\begin{bmatrix}0.1 & & & \\ & 0.1 & & \\ & & 0.1 & \\ & & & 0.1\end{bmatrix}$$

$$Q=\begin{bmatrix}0.1 & & & \\ & 0.1 & & \\ & & 0.1 & \\ & & & 0.1\end{bmatrix} \quad R=\begin{bmatrix}0.1 & \\ & 0.1\end{bmatrix}$$

The estimated and real speeds when the motor rotor mechanical angle speed is accelerated from 2π rad/s to 2π rad/s are shown in Fig.9. If a load torque impact is used in the rotor, rotor speed during dynamic state is shown in Fig. 10. It can be seen that in both steady and dynamic

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states, the estimated speed by EKF observer can also track the real rotor speed very well.

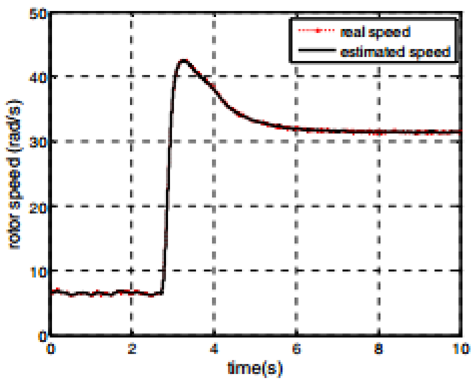

Fig. 9. The estimated and real speeds during acceleration

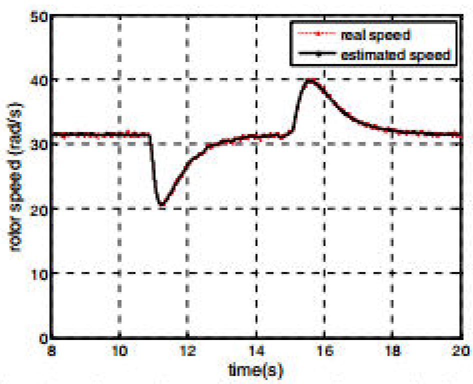

Fig.10. The estimated and real speeds during load impact

When there are some errors in the initial position, the estimated and real positions during start up periods are shown in Fig. 11 and Fig. 12. The initial value of the estimated position is always zero while the real position is random.

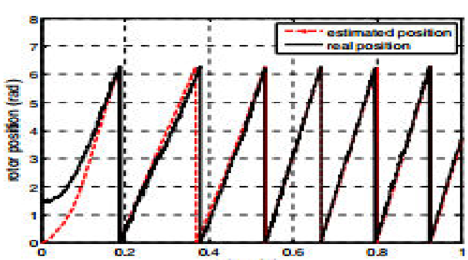

Fig. 11. Start-up with little initial position error (experiment)

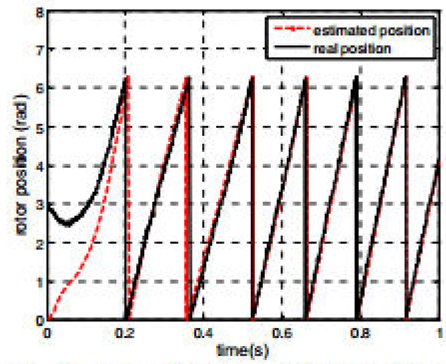

Fig. 12. Start-up with large initial position error (experiment)

It can be seen that the engine can start up from any obscure introductory position. The broadened Kalman channel can track the genuine rotor position rapidly amid start up periods. Furthermore, there is few turns around or vibrations. Clearly the underlying position measure or estimation in our framework isn't required. Insteady state, there are some relentless state blunders between the genuine and evaluated rotor positions. That is since we utilize the reference voltages rather than the terminal voltages, the voltage blunders caused the position estimation mistake.

CONCLUSION

This paper proposed a sensorless control framework in light of expanded Kalman channel for the PMSM. The Kalman channel can evaluate the correct rotor speed and rotor position while the underlying position and technician parameters are not required. By legitimate remuneration in q-hatchet condition, just anticipated harmony point is kept. At that point the engine can start up at any obscure introductory positions and it isn't important to assess the underlying position before start up. The broadened Kalman channel is set up at rotor motion situated synchronous tomahawks, so it can be effectively utilized as a part of either non-notable or remarkable engines. The issue is that the covariance networks of clamors must be dictated by analyze since the commotions and unsettling influences are not known by and by.

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