Sensorless Control Drive of Permanent Magnet Motor Based on a Simple On-line Parameter Identification Scheme

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Keywords

«Interior Permanent magnet synchronous motor IPMSM», «Extended electromotive force EEMF», «on-line parameter identification», «sensorless control».

Abstract

Interior Permanent Magnet Synchronous Motors (IPMSMs) are receiving increased attention for drive applications. To control IPMSM, position and speed sensors are indispensable because the current should be controlled depending on the rotor position. Several sensorless control schemes have been proposed. However, most of these methods use motor parameters to estimate rotor position, and hence position estimation error is caused by parameters variations. That is why, motor parameters are identified on-line under sensorless control.

In this paper, an effective and simple on-line parameter identification scheme is proposed to estimate the armature resistance and the q-axis inductance of IPMSMs. The identification method is developed based on the fact that, in practice both the d-axis inductance and the PM flux-linkage are constants. A sensorless control scheme based on the extended EMF using reduced-order observer and the proposed identification method are presented to maintain position estimation accuracy. Simulation results are included to prove the effectiveness of the overall control system under different operating conditions.

Introduction

Permanent Magnet Synchronous Motors (PMSMs) have been widely used in industrial applications because of their high power density, torque-to-inertia ratio, performance and efficiency. PMSMs have become widespread, and many studies on the PMSMs have been reported. Although rotor position and velocity can be used to achieve precise control of these motors, position sensors have several problems such as cost and durability. Therefore, many sensorless control methods have been proposed [1]-[21].

In this paper, an effective and simple on-line parameter identification method to the armature resistance and the quadrature-axis inductance is proposed and then applied to the well known sensorless control scheme based on the extended EMF. The proposed identification method is based on the fact that both the d-axis inductance and the PM flux-linkage can be considered constants in practice. Therefore, a reduced order system model of the IPMSM is concluded. This reduced system is of first order which can be easily implemented with less hardware. The mathematical model of the IPMSM using the EEMF in the rotating reference frame is utilized to estimate both rotor position and speed. The estimation position error is obtained from the EEMF by a lower-order observer [22]. This scheme corrects the estimated position and speed so that the estimation position error becomes zero. In addition, prior parameters measurements are not necessary using this proposed method. Also, the method can use any signal that satisfies the condition of persistent excitation [23]. Consequently, convenient signals for motor control can be used. Finally, the effectiveness of the proposed identification system is verified simulation results.

The paper is organized as follows: section II is a survey. Section III presents the EEMF model of IPMSM using a lower-order observer. The algorithm of the proposed on-line parameter identification method is detailed in section IV. Simulation results of the proposed identification method are demonstrated in sections V. Sensorless control along with parameter identification are discussed in section VI. Section VII presents conclusion of the paper.

Survey

Sensorless techniques to estimate rotor position and speed of IPMSM can be divided into two types; namely, 1) those using high-frequency voltage and current signals [2]-[12], and 2) those using the fundamental components of voltage and current signals [2], [7], [13]-[21].

The former methods use relations among three-phase currents [2], injection of high-frequency signals of voltages or currents [3], [4], [7], [8]-[11], special inverter pulse width modulation (PWM) patterns [5], and current response of step voltages [6]. These methods are effective at standstill and in low-speed ranges. The latter methods use detected terminal information on electromotive force (EMF); this method can be based on Kalman filtering [9], [10] or state observer [11]-[13], information on phase of flux [14], [15], difference of currents and voltages [21]-[23], and a sliding observer for flux estimation [20], [21] to estimate rotor position information. These methods are useful in middle, and high-speed ranges. However, these methods use motor parameters to estimate rotor position, and position estimation error is caused by parameters variations.

An IPMSM model is obtained using the EEMF [22]. Both EMF generated by permanent-magnets and EMF generated by rotor saliency are included in the EEMF term, position estimation using the EEMF can be realized for all kinds of synchronous motors. The sensorless control scheme based on the model with the EEMF in the stationary reference frame was proposed in [24], where approximation is not required.

As motor parameters are changed by magnetic saturation and temperature, on-line identification of these parameters is essential to enhance the performance of the proposed IPMSM sensorless schemes. To solve this problem, several parameter identification methods under sensorless control have been proposed [25]-[30]. Some methods identify motor parameters using special signals at standstill state [25] or under load conditions [31]. In these cases, it is difficult both to identify motor parameters under motor control and to respond to changes in these parameters. Other methods can identify parameters online [28], [29]. In [28], the stator resistance and the back EMF constant are identified, but inductances cannot be identified. Whereas, the online parameter identification method in [29] is complex, difficult and requires long time to be implemented due to the nonlinearity of the proposed second order IPMSM model. On the other hand, the identification method proposed in [29] does not use position and velocity to identify motor parameters; identified parameters are not affected by the accuracy of position estimation under sensorless control.

The Proposed Parameter Identification Scheme

The flux-linkage of the permanent magnet (which is equal to K_E) is found to be constant. Similarly, the relationship between the d-axis flux ϕ_d and the d-axis stator current i_d is found to be almost linear. Therefore, the d-axis inductance L_d and the flux-linkage of the permanent magnet are considered constant. On the other hand, the stator resistance R_a varies practically with motor temperature, and the q-axis inductance L_q varies due to magnetic saturation. These deviations can lead to unreliable estimation of rotor position and speed. That is why; on-line identification of R_a and L_q is essential to enhance the performance of the IPMSM under sensorless control scheme. For this reason, an identification method is proposed to identify unknown L_q and R_a via a mathematical model using known values such as voltages, currents, and based on the fact that L_d and ϕ_f are practically constants.

The mathematical model can be concluded on a stationary reference frame or on an estimated rotating reference frame. In case of parameter identification under rotation conditions, the model on the estimated rotating reference frame is better than on the stationary reference frame because the model coefficients can be almost constant regardless of the rotation conditions [34]. Thus, the mathematical model of the IPMSM in the estimated rotating reference frame is given by transforming this model in the rotating d-q frame to the hypothetical γ-δ frame, and assuming L_d and ϕ_f are constants:

$$L_d p i_\gamma = v_\gamma - R_a i_\gamma + L_q \omega i_\delta \tag{1}$$

$$L_q p i_\delta = v_\delta - R_a i_\delta - \omega L_d i_\gamma - \omega K_E \quad (2)$$
$$L_q p i_\delta = u_\delta - R_a i_\delta \quad (3)$$
where, $u_\delta = v_\delta - \omega\left[L_d i_\gamma + K_E\right]$ (4)

Therefore, the main idea here is to use the machine equation in the q-axis (δ-axis) to identify the machine parameters R_a and L_q since the term u_δ contains constant parameters K_E and L_d.
Now, transforming (3) to a discrete state equation:
$$i_\delta(n+1) = A\, i_\delta(n) + B\, u_\delta(n) \quad (5)$$
where, $A = \left[1 - \frac{R_a \Delta T}{L_q}\right]$, $B = \left[\frac{\Delta T}{L_q}\right]$ (6)

and ΔT is the sampling period. Equation (5) is a first order discrete can be rewritten as:
$$y = \theta\, z \quad (7)$$
where, θ is the parameter matrix that includes the unknown motor parameters and is given by:
$$\theta = [A \quad B] \quad (8)$$
The scalar y represents the current output, i.e. $y = [i_\delta(n+1)]$ (9)

and the vector z contains the past input and output and is given by:
$$z = [\, i_\delta(n) \quad u_\delta(n)]^T \quad (10)$$
Using the relation of (7), the unknown parameter matrix θ can be derived from known vectors y and z by using the least square method. This method identifies the parameter matrix $\hat{\theta}$ such that the square of the prediction error reaches minimum [30], i.e. (11) is minimum.
$$\varepsilon_i = \left(y - \hat{\theta} z\right)^2 \quad (11)$$
To identify the parameter matrix $\hat{\theta}$ on-line, a recursive least square 'RLS' method is used [27]. The parameter matrix $\hat{\theta}$ is identified recursively using the following equations:
$$\hat{\theta}(k) = \hat{\theta}(k-1) + \left(y - \hat{\theta}(k-1)z\right)z^T P(k) \quad (12)$$
$$P(k) = \frac{1}{\lambda}\{P(k-1) - P(k-1)z(\lambda + z^T P(k-1)z)^{-1} z^T P(k-1)\} \quad (13)$$
where, λ is defined as the forgetting factor, the role of which is to delete past data, and P is the covariance matrix.
Thus, the identified motor parameters are derived from the elements of the parameter vector $\hat{\theta}$ as:
$$\hat{L}_q = \frac{\Delta T}{\hat{B}} \quad (14)$$
$$\hat{R}_a = \frac{(1-\hat{A})}{\hat{B}} \quad (15)$$

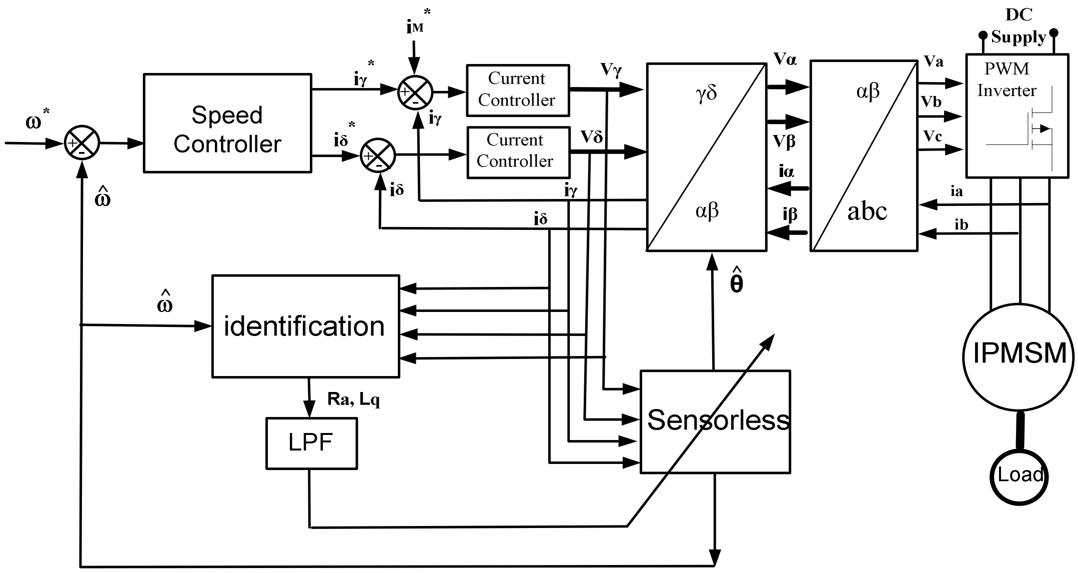


Fig. 1: Block diagram of EEMF sensorless control IPMSM drive scheme with the proposed on-line parameter identification system.

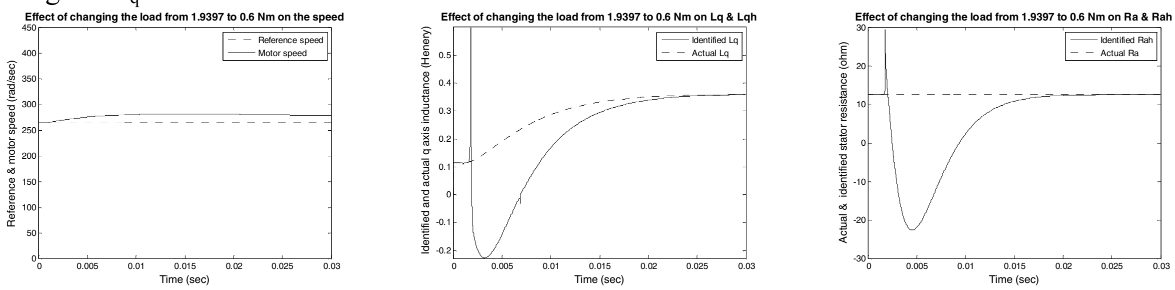
The identification system presented in [28], and [29] is based on a second order system of IPMSM which is more complex compared to the proposed scheme given by (5), (6) and (7). Therefore, the proposed identification method is simpler and requires less hardware to be implemented on-line, because of the reduced calculations. In addition, the unknown matrix in such case can be rapidly calculated and easily updated.

Parameter Identification Results

The simulink block diagram of the proposed on line parameter identification method, based on the reduced order system of the IPMSM using RLS algorithm is shown in Fig. 3, where equations (12) and (13) are updated each step in the identification block, using sampling time $\Delta T=10^{-6}$ sec.

Variation of L_q according to load change

Since the q-axis inductance L_q is a function of the q-axis current i_q due to magnetic saturation, and in turn since i_q is a function of the load torque, therefore, when the load torque varies, L_q also does. That is why, L_q has to be estimated due to every load torque change. Fig. 2 shows the on-line identification results under load changes from full load torque (1.9397Nm) to (0.6Nm), the reference speed is set to 264 rad/s. The simulation results demonstrate that the variation of load torque from 1.9397 Nm to 0.6 Nm has caused the variation of the q-axis current i_q from 1.82 A to 0.65 A. This in turn has caused the change of L_q from 0.1129 H to 0.347 H.



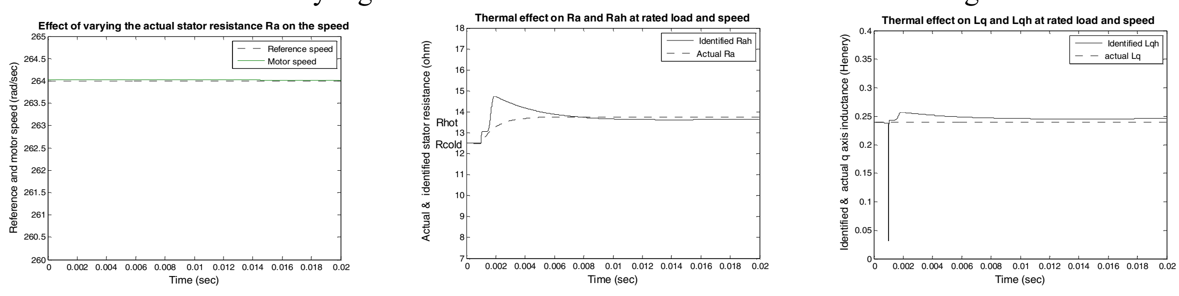
(a) (b) (c)

Fig. 2: Parameter identification results under load changes, at rated speed.

From the above figures, it is clear that the parameters were identified regardless of load change conditions, since $\hat{R}_a$ coincides with R_a and $\hat{L}_q$ follows exactly the variation of L_q. Thus, with the use of the identified parameters, position estimation under load changes can be realized in any sensorless control system.

Variation of stator resistance according to temperature change

Since the stator resistance R_a is temperature-dependent, it has to be identified on line in order to detect its variation with temperature. Fig. 3 shows the on-line identification results under heat during the operation of the IPMSM. The reference speed is set to 264 rad/s, and the load torque is set to its rated value (1.9397Nm). The actual stator resistance changes from 12.5 Ωto 13.75 Ω due to thermal effect. From the figures, it is clear that the identified resistance $\hat{R}_a$ follows exactly the variation of the actual stator resistance $R_a$caused by thermal changes and also, the identified inductance $\hat{L}_q$ coincides with the actual L_q in less than 0.025s. Therefore, both; the stator resistance and the q-axis inductance can be identified on line accurately regardless of load variation condition or thermal change.



(a) (b) (c)

Fig. 3: Parameter identification results under heat changes, at rated speed and torque.

Vector Control of IPMSM

The proposed identification method can be used in the vector control scheme of IPMSM. In this case a signal that satisfies the condition of persistent excitation [23] must be used. Therefore, a signal injection i_M^* is added to the q-axis current reference i_q^* to facilitate the identification of motor parameters. An *M*-sequence pseudo-random signals [31] are chosen for i_M^* .

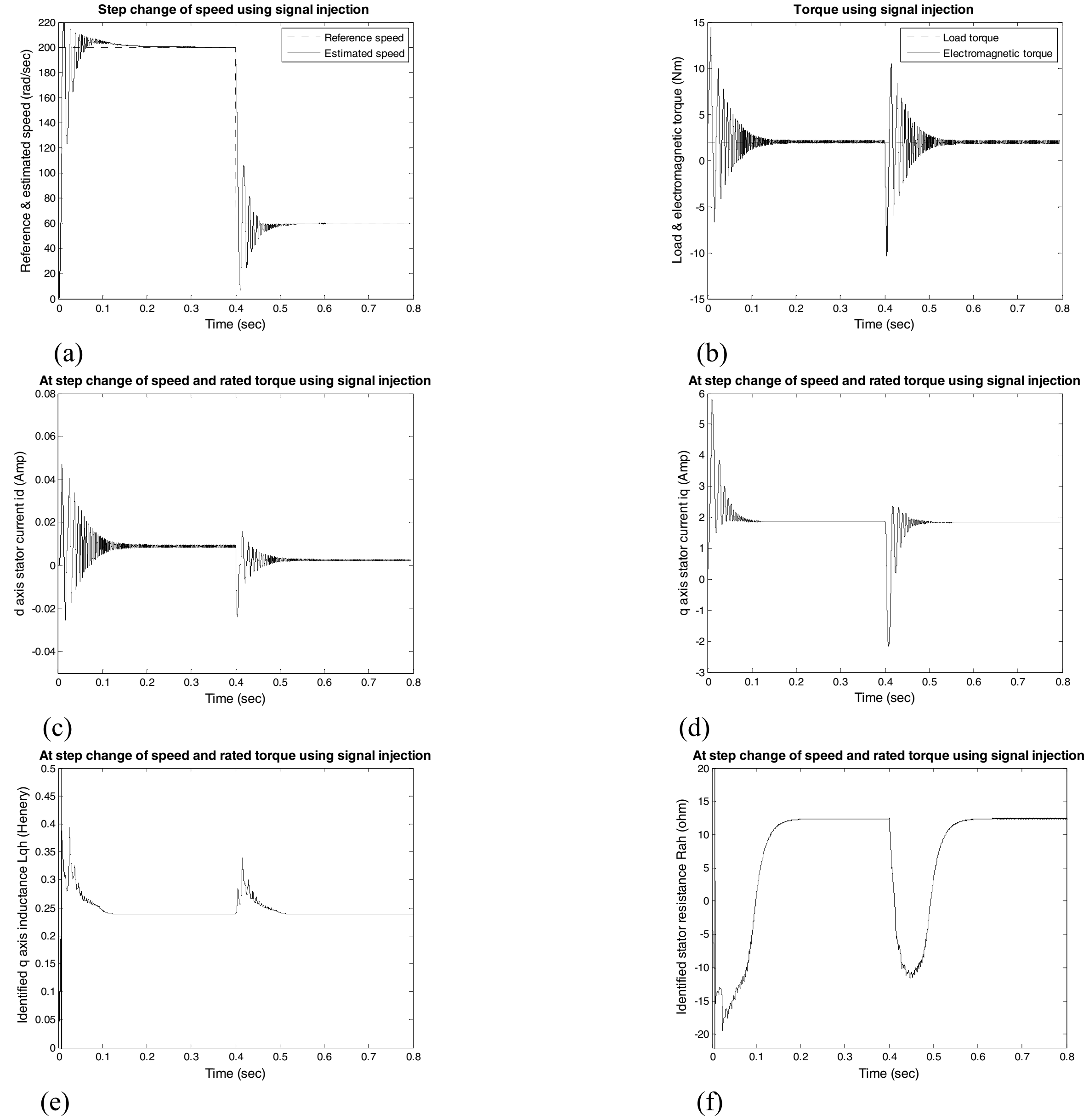


Fig. 4: Parameter identification results using signal injection i_M^*, at step change of speed and rated torque.

Fig. 4 shows the simulation results of the IPMSM vector controlled drive system when using signal injection i_M^* and the proposed identification scheme. The identification system is tested for a step change of speed from 200 rad/s to 60 rad/s at time t_1= 0.4s, and the load torque is set to its rated value. From the above figures, it is clear that the identified parameters; $\hat{R}_a$ and $\hat{L}_q$ reach their target (i.e. actual motor parameters R_a=12.5 Ω, and L_q= 0.2387 H in less than 0.2s, although the initial values of these parameters was set to zero. This ensure the accuracy and the validity of the proposed on line identification method which gives fast identification performance over the whole range of load and speed operation. In such case, motor parameters can be identified on-line; thus, prior parameter measurements for R_a and L_q are not necessary.

Extended EMF Model

Fig. 5 shows the space-vector diagram of IPMSM. The α-β frame is the stationary reference frame, the d-q frame is the rotating reference frame, and the γ-δ frame is the estimated rotating reference frame. The EEMF model can be summarized as follows [29]:
The mathematical model of the IPMSM in the d-q rotating reference frame is given by:

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} R_a + pL_d & -L_q\omega \\ L_d\omega & R_a + pL_q \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + K_E\omega \begin{bmatrix} 0 \\ 1 \end{bmatrix} \quad (16)$$

From the model in the stationary frame, it could be seen that, there are two terms including position information. One is the back EMF term generated by a permanent magnet, and the other is generated by rotor saliency. Thus, position estimation using information on both terms is complicated. To solve this problem, EEMF model is proposed as a mathematical model used in position estimation of synchronous motors. Equation (17) represents the EEMF model that is derived from (16) without approximation [24].

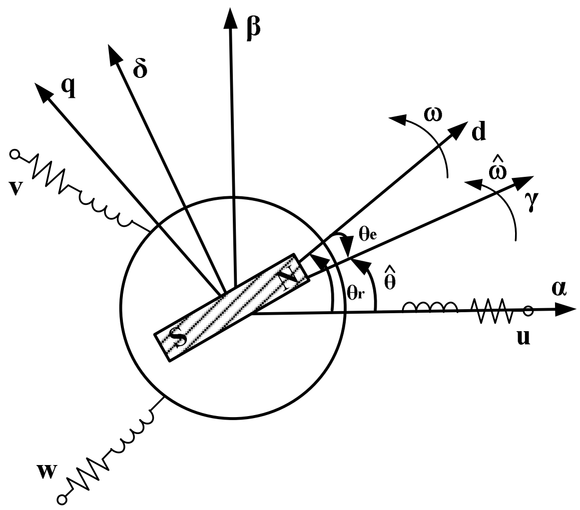


Fig. 5: Space-vector of IPMSM.

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} R_a + pL_d & -L_q\omega \\ L_q\omega & R_a + pL_d \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} 0 \\ E_{ex} \end{bmatrix} \quad (17)$$

where, $E_{ex} = \omega\left[\left(L_d - L_q\right)i_d + K_E\right] - \left(L_d - L_q\right)\left(pi_q\right)$ (18)

The second term of (17) is called an EEMF. Transforming (17) into the γ-δ frame, which lags by θ_e from the d-q reference frame, to get:

$$\begin{bmatrix} v_\gamma \\ v_\delta \end{bmatrix} = \begin{bmatrix} R_a + pL_d & -L_q\omega \\ L_q\omega & R_a + pL_d \end{bmatrix} \begin{bmatrix} i_\gamma \\ i_\delta \end{bmatrix} + \begin{bmatrix} e_\gamma \\ e_\delta \end{bmatrix} \quad (19)$$

where, $\begin{bmatrix} e_\gamma \\ e_\delta \end{bmatrix} = E_{ex} \begin{bmatrix} -\sin\theta_e \\ \cos\theta_e \end{bmatrix} + (\widehat{\omega} - \omega)L_d \begin{bmatrix} i_\gamma \\ i_\delta \end{bmatrix}$ (20)

From the model of (19), the state-space equation for estimating the EEMF is obtained when it is assumed that the differentiation of the time of the EEMF is zero [22].

$$p\begin{bmatrix} i_\gamma \\ e_\gamma \end{bmatrix} = \frac{1}{L_d}\begin{bmatrix} -R_a & -1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} i_\gamma \\ e_\gamma \end{bmatrix} + \frac{1}{L_d}\begin{bmatrix} 1 \\ 0 \end{bmatrix} v_{\gamma 1} \quad (21)$$

$$p\begin{bmatrix} i_\delta \\ e_\delta \end{bmatrix} = \frac{1}{L_d}\begin{bmatrix} -R_a & -1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} i_\delta \\ e_\delta \end{bmatrix} + \frac{1}{L_d}\begin{bmatrix} 1 \\ 0 \end{bmatrix} v_{\delta 1} \quad (22)$$

Where, $v_{\gamma 1} = v_\gamma + L_q\omega i_\delta$ (23)

$v_{\delta 1} = v_\delta - L_q\omega i_\gamma$ (24)

The input voltages are compensated in order to eliminate the cross coupling between the γ- and δ-axis as shown in (23) and (24). Thus, the state-space equation is decoupled and becomes simple by a least-order observer.

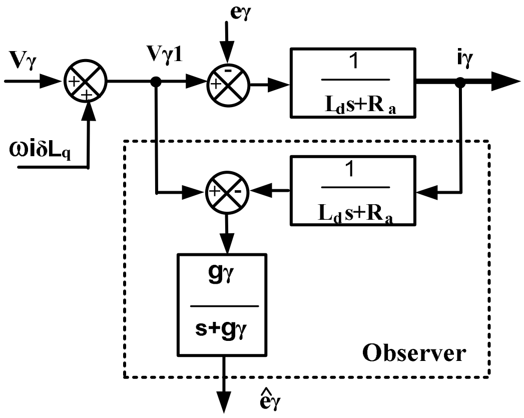


Fig. 6: Equivalent block diagram of least-order observer for estimation of EEMF.

Fig. 6 shows the equivalent block diagram of least-order observer for estimating e_γ, where g_γ represents the gain of the observer. Assuming that the error between the estimated speed $\hat{\omega}$ and the actual speed ω is sufficiently small, the EEMF is estimated as follows [22]:

$$\begin{bmatrix} \hat{e}_\gamma \\ \hat{e}_\delta \end{bmatrix} = E_{ex} \begin{bmatrix} -\sin\hat{\theta}_e \\ \cos\hat{\theta}_e \end{bmatrix} \tag{25}$$

Thus, the estimated position error $\hat{\theta}_e$ can be derived as follows:

$$\hat{\theta}_e = \tan^{-1}\left(-\frac{\hat{e}_\gamma}{\hat{e}_\delta}\right) \tag{26}$$

The estimated speed is compensated by compensator $G_e(s)$ as shown in Fig. 7. The estimated position $\hat{\theta}$ follows the actual one by (27), when the proportional and integral compensator is selected as Ge(s) [22]

$$\hat{\theta} = \frac{K_{ep}s + K_{ei}}{s^2 + K_{ep}s + K_{ei}}\theta \tag{27}$$

where, K_{ep} and K_{ei} are proportional and integral gains.

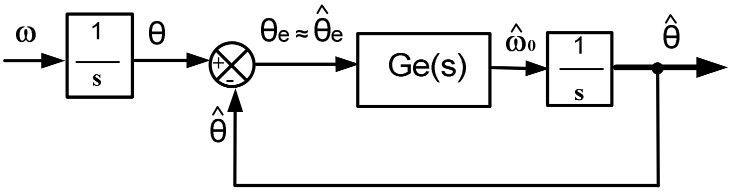


Fig. 7: Equivalent block diagram of position and speed estimator.

Sensorless Control under Load Change

Sensorless control with on-line parameter identification was realized using the system shown in Fig. 1. Although the estimation system was based on the EEMF model, the proposed parameter identification system can be applied to any estimation system that uses motor parameters. The block diagram of Fig. 1 consists of three main systems; vector control, sensorless drive control, and proposed parameter identification system. In which, three-phase current signals and voltage references are transformed to two-phase signals on the stationary reference frame, and these signals are transformed to corresponding current and voltage on the estimated rotating reference frame. From these current and voltage signals, motor parameters are identified as in the proposed parameter identification system. Then, it is appropriate for sensorless control to use the identified parameters after they have passed through a low-pass filter because they tend to include fluctuations. The decay time constant of the low-pass filter must be appropriately decided for each parameter. The decay time here was set to 0.02s for the inductance parameter and 0.01s for the resistance parameter. Using these identified parameters, the proposed observer estimates the EEMF, which in turn, estimates the position and velocity. The error between the command speed and the estimated speed is applied to a PI controller to output reference currents. Then, the injection signal i_M^* is added to the δ-axis current reference. The error between the command and the measured currents is applied to PI controllers to output the reference voltages.

The ratio of the amplitude of M-sequence signals to the rated current is about 5%, and the frequency of the injection signal i_M^* is about 3 KHz. Of course, it is not necessary to inject this signal when the parameters need not to be identified.

Fig. 8 shows the simulation results of EEMF sensorless control IPMSM drive scheme with on-line parameter identification system.

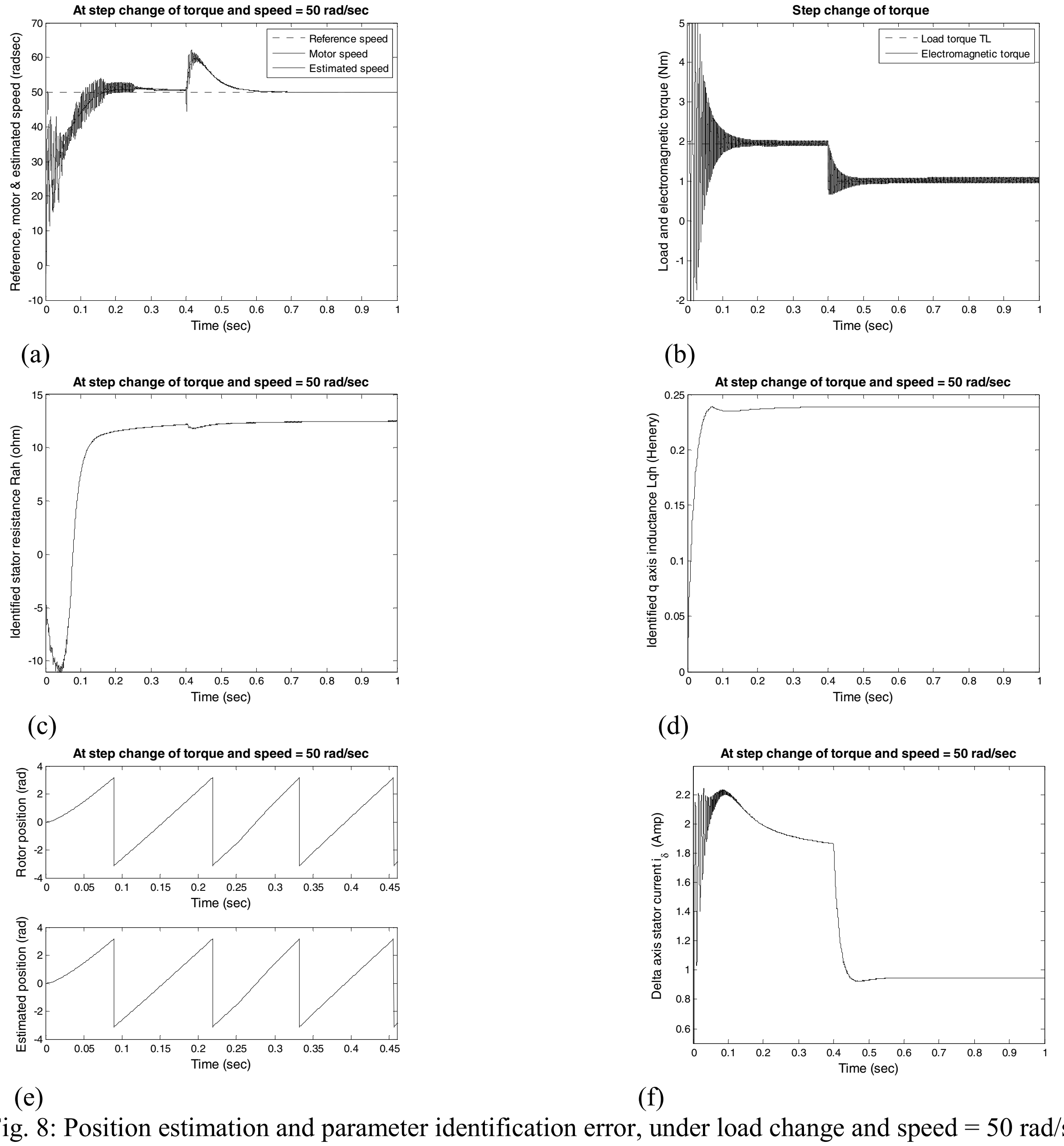


Fig. 8: Position estimation and parameter identification error, under load change and speed = 50 rad/s.

It is clear from the above figures that appropriate motor parameters were identified, and the estimated position coincided exactly with the rotor position. In addition, the estimated speed followed the profile of the rotor speed accurately, irrespective of load change conditions. Thus, the sensorless IPMSM drive system will have adequate performance in order to obtain the necessary position and speed information for replacing a shaft sensor. Moreover, the accuracy of the estimated position which depends on the motor parameters will be improved due to the presence of the identification system that can measure the motor parameters on line.

Therefore, the proposed sensorless drive system with the proposed on-line identification scheme gives fast and accurate transient performance over a wide range of speed and torque operation.
It can be noted that, with the use of the identified parameters, position estimation under load change was realized.

Conclusion

In this paper, an on-line parameter identification method is proposed and then applied to the well known sensorless control scheme based on the EEMF, as a countermeasure. The objective of the parameter identification is to identify motor parameters used in position estimation to maintain accuracy of the sensorless control system, since any motor parameter change can generate a position estimation error.
The proposed identification method injects high frequency signals and identifies varying motor parameters on-line; the position estimation system uses these identified parameters to estimate rotor position accurately. The proposed method has several advantages:

1- Motor parameters can be identified on-line; thus, prior parameter measurements are not necessary.
2- The proposed method can use any signal that satisfies the condition of persistent excitation [25] and special band pass filter are not necessary.
3- The proposed method is based on reducing the order of the IPMSM model in the hypothetical frame into a first order system which is very simple and easy to be implemented practically with less hardware.
4- Since in practical case, L_d and ϕ_f are maintained constants, and L_q and R_a varied due to magnetic saturation and temperature. The proposed identification system will be used to identify and measure on-line L_q and R_a only. Therefore, the unknown parameter matrix will be simple and can be easily updated compared to the complex unknown parameter matrix proposed in [28] and [29].
5- Due to the reduced calculation, the proposed identification system requires less hardware to be implemented compared to the other systems proposed in [28] and [29], which use a non-linear model of IPMSM.

The simulation results have shown that the proposed on-line identification method can provide fairly good identification performance over a wide range of load conditions and thermal changes. It can also be incorporated into any sensorless speed control scheme. Therefore, with the use of the identification parameters, position estimation under load changes can be realized accurately.

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