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Sensorless Control of IPMSM Drive using EKF with Electromegnetic Noise Effect

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ABSTRACT

This paper proposes a new move toward to assess the performance of sensorless control of interior permanent magnet synchronous motor (IPMSM) drive along with electromagnetic noise effect by using EKF. Normally in rotary condition, rotor position and speed estimation of IPMSM drive are drawn through an Extended Kalman Filter (EKF) algorithm by measuring its voltages and currents of the stator. The main drawback in developing EKF is it may not proficient to consider the effect of electromagnetic noise which is mainly produced during the time of different speed ranges. Owing to this reason this may cause to vary the motor flux linkages which are significant to find the rotor position and speed by EKF method will give approximate results. To carry on this process, we present the simulation results for sensorless speed control of IPMSM drive by using EKF algorithm with the incorporation of a noise signal which is corresponding to the frequency of electromagnetic noise signal using MATLAB/Simulink software. The armature current, rotor position, and speed estimation are analyzed under this noise signal effect and the effectiveness of the EKF for sensor less control of IPMSM drive is observed.

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1. INTRODUCTION

Present years Permanent Magnet Synchronous Motor (PMSM) drives are extensively being used in the place of induction motor drives in many applications. This usage is due to numerous key features of PM motors, including robustness, efficiency, reliability, and shape adaptation to the working environment. Permanent magnet synchronous motors are extensively in high applications requiring performances with quieter operation. Generally, they exhibit low noise in comparison with other motors for various applications. The elevated performance applications require smooth operation hence demand low torque ripple. Though freely connected, the vibrations of a motor very often are related to its torque ripple contents and the demerits like reduced reliability, susceptibility to noise, additional cost to weight ratio and increased difficulty of the drive system. The rotor position and speed of the sensor less control of PMSM drive overcome over these demerits. The word “silent operation” should not misled for minimal cogging torque and ripple in torque only rather it should be inevitable for less vibration and noise. These are two separate factors. Lower ripple in the torque of PM motor results in smooth running of the motor, but it does not give guarantee for less vibration or noise. The electromagnetic radial forces when act on the stator cause vibration in a PM motor. The electromagnetic source is the vital source in low and medium size rating machines. Cogging torque, torque ripple and magnetic radial forces are the predominant electromagnetic sources of noise and vibration. According to quite a few research proposals, the decline of cogging torque and ripple in the torque can considerably minimize the vibration and acoustic noise [1-4]. So as to diminish mechanical vibrations, various studies are analyzed [5], [6]. In practical applications, control gains are restricted under resonant frequency band to suppress the source signal within mechanical one.

At higher and lower ranges of speed, the sensor less control of an IPMSM drive is procured by EKF algorithm. The parameters like, the line currents for EKF state variables and the line voltages for EKF command vector are measured. The voltages feeding to the motor have sinusoidal pulse width modulation (PWM) waveforms. We recommended to employ the fundamental voltage and current components. The basic current components are obtained by analog low pass filtering and the primary voltage components are obtained by sensing the digital switching of the inverter through PWM techniques. Generally magnetic fields are produced either by the flow of electric current or by the incidence of permanent magnetism. Transformers and motors and are examples of the previous, and the Earth's magnetic field is an occurrence of the latter. So as to develop the noise voltage in a conductor, magnetic lines of flux must be cut by the conductor. Electric machines worked on this function of basic principle. In the existence of an alternating field, such as that adjoining a 50/60 Hz power line, voltage will be induced into any stationary conductor as the magnetic field expands and collapses. Similarly, a noise voltage is being generated whenever a conductor moving through the Earth's magnetic field has in it as it cuts the lines of flux. These causes to change the flux linkages of the motor which may leads to change the estimation of rotor position and speed.

1.1 The Mechanism of Electromagnetic Noise Generation

The usual electromagnetic force, which consists of dissimilar frequencies spectrum and various division of rotation force waves generated by the mutual action of stator and rotor and acting on the interior surface of stator core, is the main source of motors vibration and electromagnetic noise. According to Maxwell’s law, the instantaneous value of standard electromagnetic force per unit area can be expressed as :

$$p_r\,(\theta,t) = \frac{b^2(\theta,t)}{2\mu_0} \tag{1}$$

where μ_0 is the permeability of vacuum and $b(\theta,\ t)$ is the air gap flux density, which was superposed by stator flux and rotor flux, and can be expressed as:

$$b\,(\theta,t) = b_\nu(\theta,t) + b_\mu(\theta,t) = \sum_\nu B_\nu Cos(\nu\theta - \omega_1 t - \emptyset_{\nu r}) + \sum_\mu B_\mu Cos(\mu\theta - \omega_1 t - \emptyset_{\mu r}) \tag{2}$$

where $b\nu(\theta,\ t)$, $b\mu(\theta,\ t)$ respectively, represent the instantaneous value of flux density formed at stator side and rotor side which changes with respect to position angle and time. Then substitute equation (2) into equation (1), the following equation can be obtained:

$$p_r\,(\theta,t) = \frac{1}{2\mu_0}\{\sum_\nu B_\nu^2 Cos^2\,(\nu\theta - \omega_1 t - \emptyset_{\nu r}) + \sum_\mu B_\mu^2 Cos^2\left(\mu\theta - \omega_1 t - \emptyset_{\mu r}\right) + 2\sum_{\nu1,\nu2} B_{\nu1}B_{\nu2}Cos\,(\nu_1\theta - \omega_1 t - \emptyset_{\nu1r})XCos\nu_2(\nu_2\theta - \omega_1 t - \emptyset_{\nu2r}) + 2\sum_{\mu1,\mu2} B_{\mu1}B_{\mu2}Cos\left(\mu_1\theta - \omega_1 t - \emptyset_{\mu1r}\right)XCos\left(\mu_2\theta - \omega_1 t - \emptyset_{\mu2r}\right) + 2\sum_{\nu,\mu} B_\nu B_\mu Cos\,(\nu\theta - \omega_1 t - \emptyset_{\nu r})XCos\left(\mu\theta - \omega_1 t - \emptyset_{\mu r}\right)\} \tag{3}$$

According to equation (3), the typical electromagnetic force which is acting on the stator tooth consists of five parts and the force waves with large amplitude and low order are the major sources. In PMSM, the electromagnetic force waves which are generated by the interaction between stator and rotor harmonic magnetic flux density (the fourth part) and the interaction of various harmonic magnetic flux density induced by permanent magnets (the fifth part), are the major sources of electromagnetic noise[7].

In normal radiation, the electromagnetic noise power which is generated by electromagnetism acting on stator teeth can be expressed as:

$$W = 2\rho c\pi^2 f_r^2 Y^2 S_0$$

where ρ is the sound of medium density, c is the velocity of sound in medium density, fr is the frequency of electromagnetic force wave, and S_0 is the vibrating area in vertical direction of the sound wave propagation. Y is the displacement of vibration under stator electromagnetic force and it is given by $Y = P'/K - \omega_r^2 M$ by neglecting the damping. Where P' is the amplitude of electromagnetic force wave acting on stator teeth.$K$is the stiffness of stator system.$M$is the mass of fixed system. ω_r is the angular frequency of electromagnetic force wave.

Several on-line parameter estimation methods such as the extended kalman filter (EKF), recursive least square (RLS), and model reference adaptive system (MRAS) have been proposed for sensor less control of PMSM drive[8-10]. Among these, the most successful estimator is Extended Kalman Filter in terms of the least square for estimating the states of nonlinear systems, which is very suitable for implementation in systems with sensors affected by noise. It processes all the available measurements in spite of of their accuracy, to provide quick and truthful assessment of the target variables, and also attain a fast convergence. Besides, the EKF serves to be suitable for the state estimation of a PMSM. In this proposal, the Extended Kalman Filter (EKF) based on an on-line recognition method is proposed to estimate speed and position of the rotor by measuring direct axis and quadrature axis currents of the IPMSM. Finally, the simulation results show the validity of the estimator. But it does not include the electromagnetic noise effect while estimating the speed and position of the rotor [11].

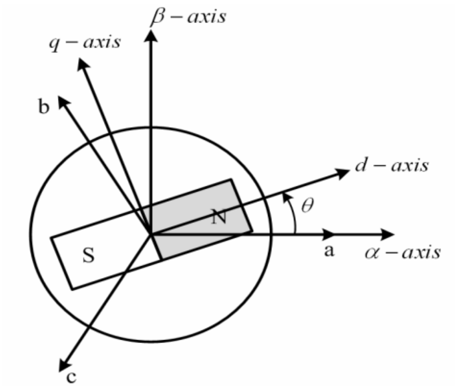

Figure 1. IPMSM Coordinate systems

2. MATHEMATICAL MODEL OF IPMSM

Explaining research chronological, including research design, research procedure (in the form of algorithms, Pseudocode or other), how to test and data acquisition [1]-[3]. The description of the course of research should be supported references, so the explanation can be accepted scientifically [2], [4].

The coordinate system of IPMSM is shown in Figure1 in three different coordinates. Each coordinate transformation is expressed as:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = T' \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad \text{where } \mathrm{T} = \tfrac{2}{3}\begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3/2} \\ -1/2 & -\sqrt{3/2} \end{bmatrix} \tag{4}$$

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = P \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad \text{where } \mathrm{P} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \tag{5}$$

The voltage equation of an IPMSM in the stationary reference frame for an analysis of the stator current is defined as follows:

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = R_s \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} + P \begin{bmatrix} L - \Delta L \cos 2\theta & -\Delta L \sin 2\theta \\ -\Delta L \sin 2\theta & L + \Delta L \cos 2\theta \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} + \emptyset_f \begin{bmatrix} \cos\theta \\ \sin\theta \end{bmatrix} \tag{6}$$

where $\mathrm{L} = \frac{L_q + L_d}{2}$ and $\Delta L = \frac{L_q - L_d}{2}$

While v_α, v_β and i_α, i_β are the α-axis and β-axis voltages and currents respectively. Ld and Lq are d-axis and q-axis inductance, $\emptyset_f$ is the permanent magnet flux linkage, p is the differential operator and θ is the rotor position[12], [13]. The voltage equation in rotating reference frame can be obtained by:

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} R_s + pL_d & -\omega_r L_d \\ \omega_r L_d & R_s + pL_q \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} 0 \\ \omega_r \emptyset_f \end{bmatrix} \tag{7}$$

where ω_r is the speed of the rotor in radian per second.

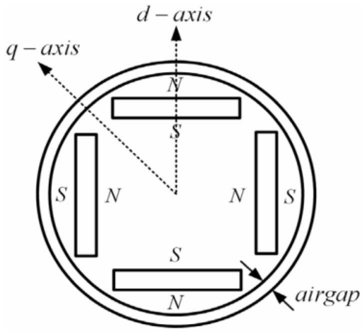

Figure 2. Rotor structure of an IPMSM

The magnetic path of an IPMSM is dissimilar from that of an SPMSM since the relative permeability of a permanent magnet is almost equal to the air. This feature causes an effect to produce an air-gap on the d-axis. Because the permanent magnets of the SPMSM are attached to the rotor surface, hence it makes d-axis inductance is equal to q-axis inductance. Conversely in the IPMSM, d-axis inductance is dissimilar from q-axis inductance depending on the position of permanent magnets. As shown in Figure 2, the q-axis inductance is bigger than the d-axis inductance because permanent magnets are on the d-axis path where the magnetic flux occurs. The reluctance torque is produced by magnetic saliency from the difference of inductance. Consequently, the torque generated in the IPMSM consists of two parts termed as magnetic torque and the reluctance torque and is given by[14]:

$$T_e = \frac{3}{2}\frac{P}{2}\left[\emptyset_f i_q + \left(L_d - L_q\right)i_d i_q\right] \tag{8}$$

where P is the number of magnetic poles. In equation (8), there are the terms of d-axis and q-axis reference currents that generate the same torque. When the reference current is specified as the stator current, the torque can be derived as equation (6). In such a case, the reference d-axis and q-axis currents are generated by the angle of the stator current.

$$T_e = \frac{P}{2}\frac{3}{2}\left[\emptyset_f I_s \sin\theta + \frac{(L_d - L_q)}{2} I_s^2 \sin 2\theta\right] \tag{9}$$

where θ is the stator current angle in the synchronous reference frame, and I_s is the stator current vector.

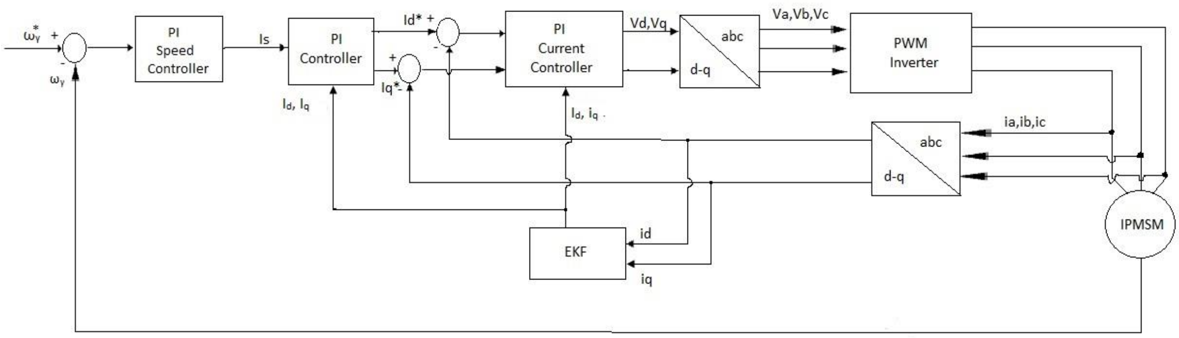

Figure 3. Configuration of the IPMSM drive system with parameter estimation

3. EXTENDED KALMAN FILTER FOR PARAMETER ESTIMATION

An EKF has been used for broad range speed applications in drive control and on line parameter estimation. In spite of this, the EKF is helpful for a PMSM because it has high-performance in the noisy condition and wide range speed control. Thus, it is frequently used to get the angular speed from noisy mechanical measurements, estimate the rotor position in a mechanical sensor less control application and differentiate the machine parameters. In this section, the latter application will be given a special attention for an IPMSM. The proposed EKF provides estimated d-axis and q-axis inductances L_d and L_q respectively [15-17].

3.1. IPMSM State Space Model

Eq. (7) can be redefined as follows:

$$v_d = R_s i_d + L_d \frac{di_d}{dt} - \omega_r L_q i_q$$
$$v_q = R_s i_q + L_q \frac{di_q}{dt} + \omega_r L_d i_d + \omega_r \emptyset_f \quad (10)$$

The system model should be in the form of the state equation to be used in the EKF. The state equations can be expressed as follows:

$$\dot{x}(t) = f\big(x(t)\big) + G\,V(t) + \sigma(t)$$
$$y(t) = Hx(t) + \mu(t) \quad (11)$$

where V = $[v_d \quad v_q]^T$ and y = $[i_d \quad i_q]^T$ are input and output vectors. X = $\left[i_d i_q ab\right]^T$ is a state system vector (a=$1/L_d, b = 1/L_q$). σ(t) and μ(t) are uncorrelated zero-mean white Gaussian noises with covariance **Q** and **R** respectively. σ(t) is system noise that includes the system disturbances and model inaccuracies, while μ(t) represents the measurement noise. The system matrices **f(x(**t**))**, **G** and **H** are defined as:

$$\text{f(x(t)} = \begin{bmatrix} a(-R_s i_d) + \frac{a}{b}\omega_r i_q \\ b\big(-R_s i_q - \omega_r \emptyset_f\big) - \frac{b}{a}\omega_r i_d \\ 0 \\ 0 \end{bmatrix} \quad (12)$$

$$\text{G} = \begin{bmatrix} a & 0 \\ 0 & b \\ 0 & 0 \\ 0 & 0 \end{bmatrix}, \qquad \text{H} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \quad (13)$$

$$\text{F(x(t))} = \frac{\partial x}{\partial t}\bigg| at\ x = x(t) = \begin{bmatrix} -aR_s & \frac{a\omega_r}{b} & v_d - R_s i_d + \frac{\omega_r i_q}{b} & -\frac{a\omega_r i_q}{b^2} \\ -\frac{a\omega_r}{b} & -bR_s & \frac{b\omega_r i_d}{a^2} & v_q - R_s i_q - \omega_r\left(\emptyset_f - \frac{i_d}{a}\right) \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \quad (14)$$

The prediction of the state covariance requires the online computation of the Jacobean matrix **F**, defined as (14).

3.2. Extended Kalman Filter

The complete structure of the EKF algorithm consists two steps which are termed as prediction step and innovation step. The first step performs a prediction of both quantities based on the previous estimates $\widehat{X_k}|k-1$and the meanvoltage $\langle V_{k-1}\rangle$ actually induced to the system in the period from tk-1 to tk. The next step performs the predicted state estimate and its covariance matrix using a feedback correction scheme that receives the measured motor currents

The common EKF algorithm is expressed in the following two stages:

1) Prediction step

$$\widehat{X_k}|k-1 = \widehat{X_k}|k-1 + \left[f\big(\widehat{X_{k-1}}|k-1\big) + G\langle V_{k-1}\rangle\right]T_s$$

$$P_k|k-1 = P_{k-1}|k-1 + (F_{k-1}P_{k-1}|k-1 + P_{k-1}|k-1\,F_{k-1}^T)T_s + Q$$

2) Innovation step

$$\widehat{X_k}|k = \widehat{X_k}|k-1 + \left[K_k\big(y_k - H\widehat{X_k}|k-1\big)\right]$$

$$P_k|k = P_k|k-1 - K_k H P_k|k-1$$

3) Kalman gain

$$K_k = P_k|k-1H^T(HP_k|k-1\ H^T+R)^{-1}$$

For the on-line application of the Kalman filter, time constraints are crucial; where most of the matrices hold numerous null elements, all the calculations have been made explicitly, reducing computational time.

An important step in the design of Kalman filter is the choice of initial values for the covariance matrices **Q** And **R** as they influence the performance, convergence and stability. The matrix **Q** is related to the system noise. The rise in the value of the elements of **Q** will likewise raise the Kalman gain, resulting in quicker filter dynamics but with worse the steady-state performance. On the other hand, the matrix **R** is related to the measurement noise. Increasing the values of the elements of **R** will assume that the current measurements are largely influenced by noise and thus less dependable. Therefore, the Kalman gain will decrease, yielding worse transient response. The diagonal initial state covariance matrix $\mathbf{P}_0$ represents variances or mean-squared errors with regard to the initial condition. Varying $\mathbf{P_0}$ yields the different amplitude of the transient, while both transient duration and steady state conditions will be unchanged [18].

In this paper, the initial values of covariance matrix **P** and system matrix **Q** and **R** have been chosen with a trial and error procedure to get the best tradeoff between filter Stability and convergence time. As the value of **Q** increases, Kalman gain also increases, which causes variation of estimation values. Likewise, EKF is strongly affected by measurement noise as **R** increases. **P** is selected based on [19], [20] because it is nothing to do with steady-state condition. In conclusion, to obtain the high performance of proposed EKF, matrices are chosen as follows:

$$P=\begin{bmatrix}1&0&0&0\\0&1&0&0\\0&0&300&0\\0&0&0&300\end{bmatrix};\ Q=\begin{bmatrix}0.1&0&0&0\\0&0.1&0&0\\0&0&10&0\\0&0&0&10\end{bmatrix};\text{ and }R=\begin{bmatrix}0.5&0\\0&0.5\end{bmatrix};$$

4. DISCUSSION OF SIMULATION RESULTS

The overall proposed system is shown in Figure 3. The current and speed controls are included in the drive system. The estimated speed by EKF is used for the current controller to calculate the gain of the current controller. Figure 4 shows the actual and estimated speed of the motor which can be attained almost equal to 157 radians per second and Figures 5 – 7 gives results for armature current, rotor position and torque that are developed in the rotor. It shows the presentation of EKF with and without electromagnetic noise effect as shown from Figures 8 - 13. After summarizing the simulation results, the analysis of armature current at a load torque T_L of 5 N-m. has been observed and the electromagnetic noise affects in the armature current in rotating reference frame models I_d and I_q , may play an important role to find the flux linkages, rotor position and speed of the motor. This may cause present ripples in the armature current and torque of the fundamental component.

Table 1.Motor specifications:

Stator Resistance	0.349Ω
d-axis Inductance	13.16Mh
q-axis Inductance	15.60Mh
Number of poles	4
Flux Linkage	0.554Wb
Rated Power	1.54 Kw
Rated Current	9.8A
Rated Speed	1500r.p.m.

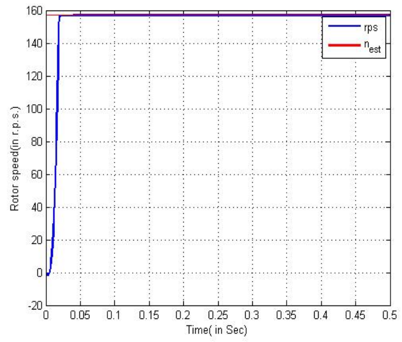

Figure 4. Estimated and actual speed by using Kalman filter

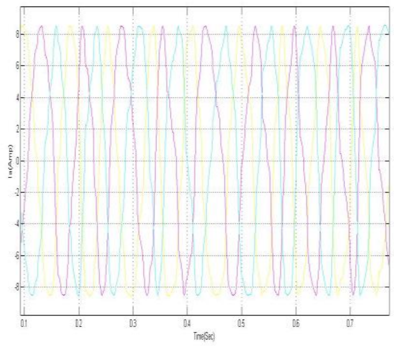

Figure5. Armature Current with Noise Signal

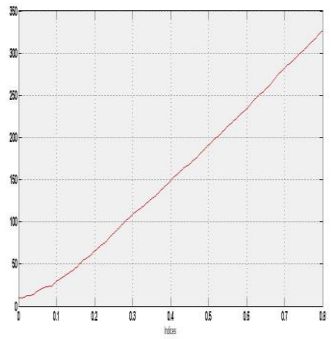

Figure 6. Rotor position

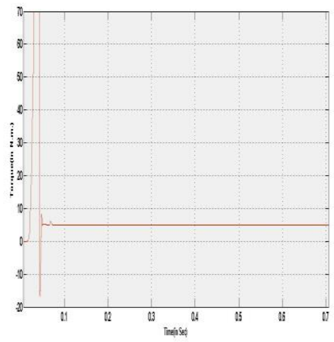

Figure 7. Torque developed in the Motor

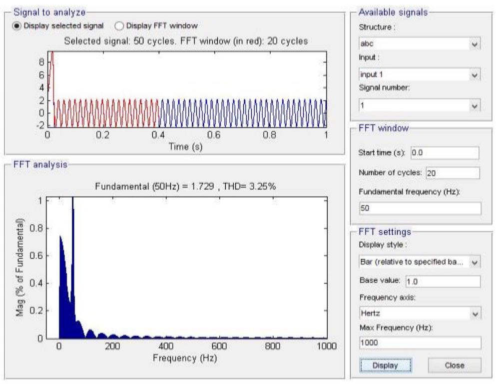

Figure 8. Iabc without Noise signal

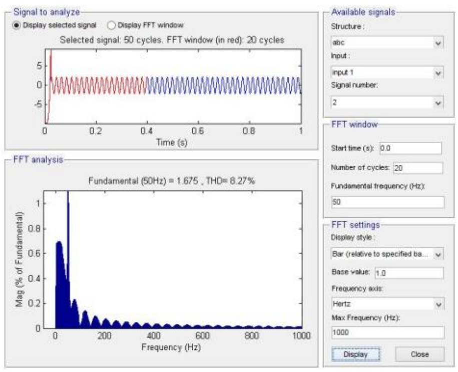

Figure 9. Id without Noise signal

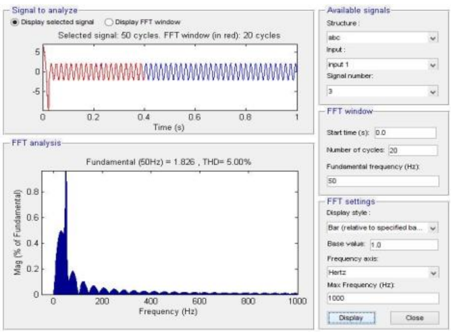

Figure 10. Iq without Noise signal

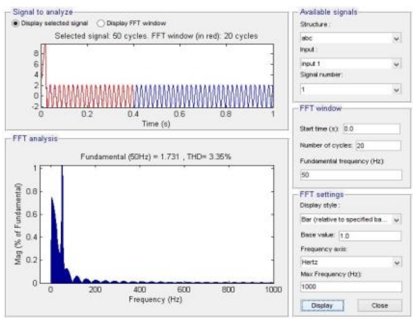

Figure 11. Iabc with Noise signal

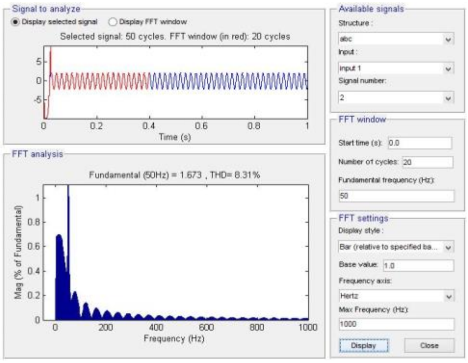

Figure 12. Id without Noise signal

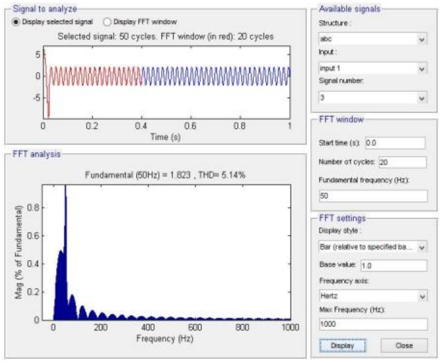

Figure 13. Iq with Noise signal

5. CONCLUSION

In this paper, an investigation is made for position and speed estimation of the IPMSM drive using EKF algorithm by estimating d and q-axes currents under electromagnetic noise effect. By considering the non-linearity of PMSM and existence of inverter in revolving condition, speed and rotor position estimation of IPMSM drive are obtained through an Extended Kalman Filter (EKF) algorithm using linearization of average values. From the results the estimated rotor position in comparison with the actual position indicates that the EKF algorithm is effective and can be used to replace the position encoder. But it is observed that from the simulation results as the d-axis and q-axis currents are affected by electromagnetic noise signals which may cause the machine parameters like inductance and flux linkages are sensitive to change. This may give approximate results to estimate the position and speed of the motor by using EKF method. This can be improved by considering the electromagnetic noise signal during the various speed ranges by selecting proper covariance matrix P and system matrices Q and R which plays an important role to give accurate estimation of rotor position and speed of the motor.

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