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High frequency signal injection method for sensorless permanent magnet synchronous motor drives

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ABSTRACT

The objective of this project is to design a high frequency signal injection method for sensorless control of permanent magnet synchronous motor (PMSM) drives. Generally, the PMSM drives control requires the appearance of speed and positon sensor to measure the motor speed hence to feedback the information for variable speed drives operation. The usage of the sensor will increase the size, cost, extra hardwire and feedback devices. Therefore, there is motivation to eliminate this type of sensor by injecting high frequency signal and utilizing the electrical parameter from the motor so that the speed and positon of rotor can be estimated. The proposed position and speed sensorless control method using high frequency signal injection together with all the power electronic circuit are modelled using Simulink. PMSM sensorless drive is simulated and the results are analyzed in terms of speed, torque and stator current response without load disturbance but under the specification of varying speed, forward to reverse operation, reverse to forward operation and step change in reference speed. The results show that the signal injection method performs well during start-up and low speed operation.

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1. INTRODUCTION

In permanent magnet synchronous motor (PMSM) drives, the rotor positions information is compulsory which is measured by speed sensor. An encoder installed on the shaft of the motor will extract this kind of data but it has disadvantages in the sense that it causes system cost, volume and weight to increase substantially. Additionally, the overall reliability of the drive decreased, specifically on rugged condition. For sensorless PMSM drives, the motor speed and rotor position are calculated using either fundamental excitation method or by using signal injection method. The fundamental excitation method is estimated by using the dynamic model of the motor in term of voltage or currents equations. The signal injection methods are implemented by using the detection of anisotropy caused by saliency of the rotor or by magnetic saturation [1-8]. Fundamental excitation methods consist of non-adaptive and adaptive methods. Non adaptive method is based on measured current and voltages. Other than that, this method employs the fundamental equations for PMSM. This is the simplest method and yet the results are easy to be computed. Also, the responses are very fast and almost no delay. While for adaptive methods, the sensorless technique employs different observers and adaptation mechanisms to estimate the speed and rotor position. The basic idea of this method is the error between measured values and actual value is corrected through adaption mechanism. Through this method, all the states in the PMSM drives system can be estimated including the states that are tough to be measured. In contrast, this method is not performing well at low speed, requires complex algorithm and calculation. Researches in this adaptive method for sensorless PMSM drives show that, it can be categorized into two major groups. One group is using model reference adaptive system (MRAS) and another group is using various type of observer as the adaptation mechanism. Example of observer-based estimator are sliding mode observer (SMO) and extended kalman filter (EKF), while example of Saliency and signal injection method is high frequency signal injection methods. The EKF is based on full-order stochastic observer for nonlinear dynamic system. The benefit of EKF is its capacity to directly estimate the motor speed which is fast speed response but the downside is that EKF needs heavy on-line 4×4 matrix computing which become a challenging issue for a fix-pointed processor system [9-12].

The electromotive force induced by rotor magnet in the phases of stator are called as “back EMF”, which contain data about the speed and position of the rotor axis. Its shape and value of alternating waveform represent the information of the speed and location of rotor magnet axis respectively [13]. For medium and high speed, Back-EMF is the most suitable method to detect the rotor location without encoder or resolver by utilizing the Back-EMF from the motor model. The constraint of the Back-EMF method is rotor position determination is related to the speed, the accuracy decrease at low and zero rotational speed, in other word, the motor equation element containing the rotor position data get too small to be detected [13-16]. Sliding mode is a non-linear model that utilize the switching law in governing the system. SMO for PMSM exploit the mismatch between the estimated and measurement value of stator current to acquire the Back-EMF that encompasses the rotor location and speed data. Nonetheless, the chattering phenomenon is the main drawback of SMO. The chattering causes system oscillation, performance to sluggish and unsteadiness to the system [17], even though SMO method is low sensitivity to actual model, it is more robust and have excellent performance [17-20]. MRAS performance is excellent in the region of medium to high speed to control the PMSM. The MRAS estimates the motor Back-EMF where the rotor position data can be retrieved. Traditional design is built on Lyapunov method and estimation law is intended in making sure the estimated state converge to the actual values. There are six parameters to be tuned and the connection between these parameters and the estimator performance is indirect, hence the estimator parameters need to be tuned manually [21-22].

So far, various classes of sensorless method are reviewed in this literature review. It presents the pros and cons for each method. It also discusses about the suitability of the methods. The main interest in this research is to have sensorless control at low speed and standstill, therefore this project proposes to use signal injection method to solve the problem of poor performance of PMSM drives to detect rotor position and speed at low and zero speed. Figure 1 shows the overall block diagram of high frequency signal injection where the detection of rotor position is accomplished via injection of additional signals (current/voltage) using fundamental excitation. This applied signals with the magnetic rotor saliency of the motor, resulting thus subsequent voltage and current to obtain rotor position data. The drawback of the current injection is the bandwidth estimation which controlled by the current controller. Meanwhile the bandwidth estimation is controlled by the observer bandwidth for the voltage injection method [23-25].

2. RESEARCH METHOD

2.1. Modelling of PMSM sensorless drives

Figure 1 explains high frequency voltage injection into the PMSM drives. The required component is speed controller, vector transformation, PWM generator, high frequency voltage injection in d-q axis, current estimator, and demodulation process and speed observer. The comparison between reference speed and estimated speed will produce speed error which is fed to speed controller and its output will be used for vector transformation which can transform d-q reference current to three-phase reference current. The three-phase reference current which are then compared with actual current measured from PMSM, will produce currents errors in the PWM generator which are then used to generate switching signal for the inverter. The rotor position (θ_{re}) is estimated using signal injection scheme. The rotor speed can then be estimated using integrator in speed observer [14].

2.2. External high frequency rotating voltage signal injection

The injected voltages at frequency ωi are given as:

$$\begin{bmatrix} V_{asi} \\ V_{bsi} \\ V_{csi} \end{bmatrix} = V_i \begin{bmatrix} sin\,\theta_i \\ sin\left(\theta_i - \frac{2\pi}{3}\right) \\ sin\left(\theta_i + \frac{2\pi}{3}\right) \end{bmatrix} \text{ where } \theta i = \omega_i t \quad (1)$$

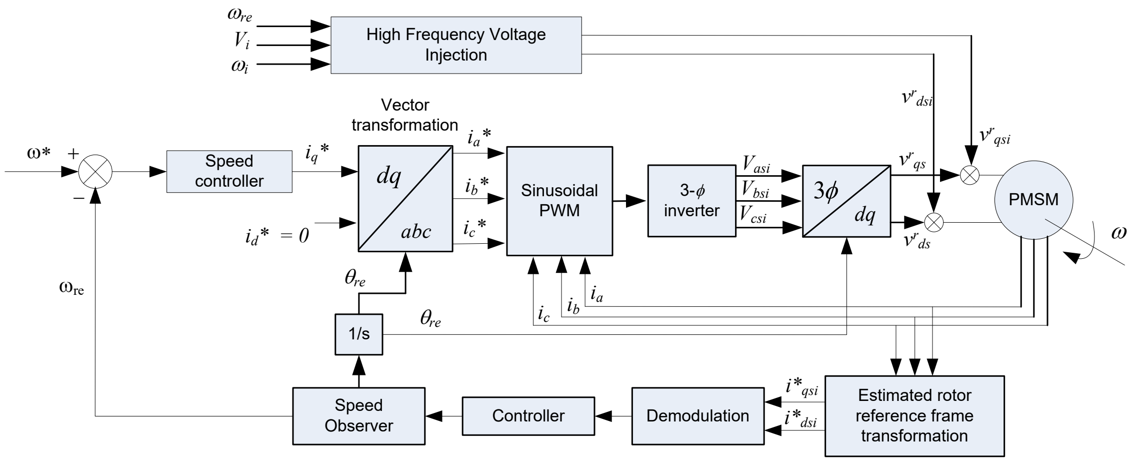


Figure 1. Sensorless PMSM drives using high frequency signal injection

Then the three phase injected voltage are transformed into d-q axes in the same reference frame and presented as follows:

$$V_{qs} = -\frac{2}{3}\left[V_{asi}\,sin\,\theta + V_{bsi}\,sin\left(\theta - \frac{2\pi}{3}\right) + V_{csi}\,sin\left(\theta - \frac{4\pi}{3}\right)\right]$$

$$V_{ds} = -\frac{2}{3}\left[V_{asi}\,cos\,\theta + V_{bsi}\,cos\left(\theta - \frac{2\pi}{3}\right) + V_{csi}\,cos\left(\theta - \frac{4\pi}{3}\right)\right] \qquad (2)$$

Meanwhile, the injected frequency of stator current can be written as:

$$\begin{bmatrix} i_{qsi} \\ i_{dsi} \end{bmatrix} = sin\,\theta_i \begin{bmatrix} I_1\,cos\,\theta_{re} - I_2\,cos(\,2(\theta_r - \theta_{re})) \\ -I_1\,sin\,\theta_{re} + I_2\,sin(\,2(\theta_r - \theta_{re})) \end{bmatrix} \qquad (3)$$

where,

$$I_1 = \frac{v_i}{\omega_i}\frac{\left(\frac{L_q + L_d}{2}\right)}{\left(\frac{L_q + L_d}{2}\right)^2 - \left(\frac{L_q - L_d}{2}\right)^2};$$

$$I_2 = \frac{v_i}{\omega_i}\frac{\left(\frac{L_q - L_d}{2}\right)}{\left(\frac{L_q + L_d}{2}\right)^2 - \left(\frac{L_q - L_d}{2}\right)^2}; \qquad (4)$$

The d-axis current is then transformed into estimated rotor reference frame which yield as shown in (5)

$$i^e_{dsi} = i_{qsi}\,sin(\,\theta_{re}) + i_{dsi}\,cos(\,\theta_{re}) \qquad (5)$$

As shown in (5) can be rewritten as:

$$i^e_{dsi} = i_2\,sin\,\theta_i\,[sin\{2(\theta_r - \theta_{re})\}] \qquad (6)$$

As shown in (6), it has the information about rotor position error. High frequency revolving voltage injection is formed by three-phase voltage vector using as shown in (1) with injection voltage (V_i) and high frequency, (f_i) which are then transformed into d-q axis using Park-Clarke transformation. The d-q axes voltage will undergo transformation into estimated position reference frame and the output will be added with d-q axes voltage in rotor-reference frame. This subsystem is shown in Figure 2 [14], for the abc to d-q axis conversion, the cosine and sine wave generator is used.

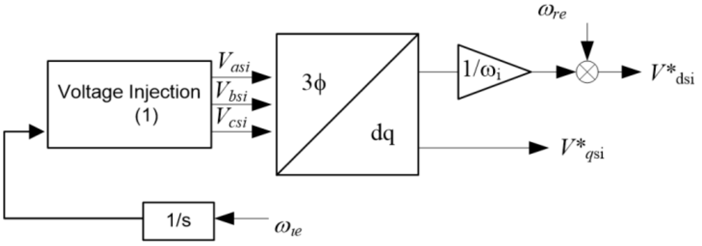


Figure 2. Voltage injection for PMSM block diagram

While Figure 3 depict Band-Pass filter that is used to separate the injected signal from the fundamental component. The Band-Pass filtered signal is then, demodulated and multiplied with sin (θ_i) to obtain the required rotor position. The output signal is further processed by a low-pass filter to eliminate the second harmonic components, so that the position error can be reduced before fed to the controller. Figure 4 explains that a tracking observer is necessary to extract the information of rotor position and motor speed from the position error. The rotor position can be calculated easily by using integrator given that the rotor estimated speed is determined correctly. The electromagnetic torque signal (7) is added at the output of PID controller for faster dynamic performance [14]. The electric torque and "B" is the damping coefficient is written as:

$$T_e = \frac{3}{2}\frac{P}{2}\left[\left(L_d - L_q\right)i^r_{ds} + \lambda_{af}\right]i^r_{qs} \tag{7}$$

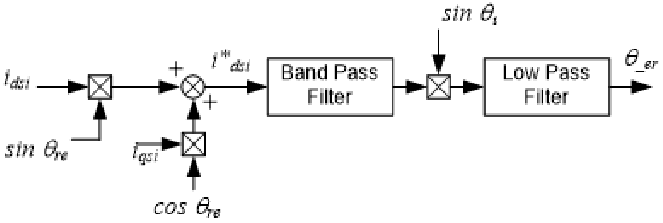


Figure 3. Demodulation

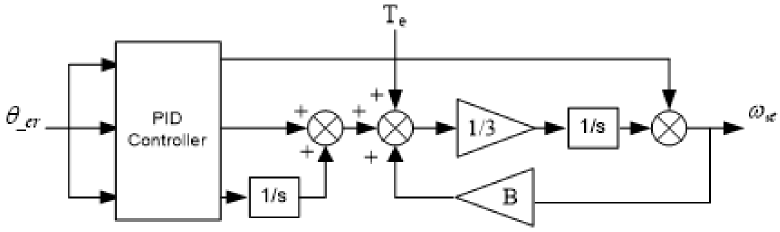


Figure 4. Rotor position and speed observer

3. RESULTS AND ANALYSIS

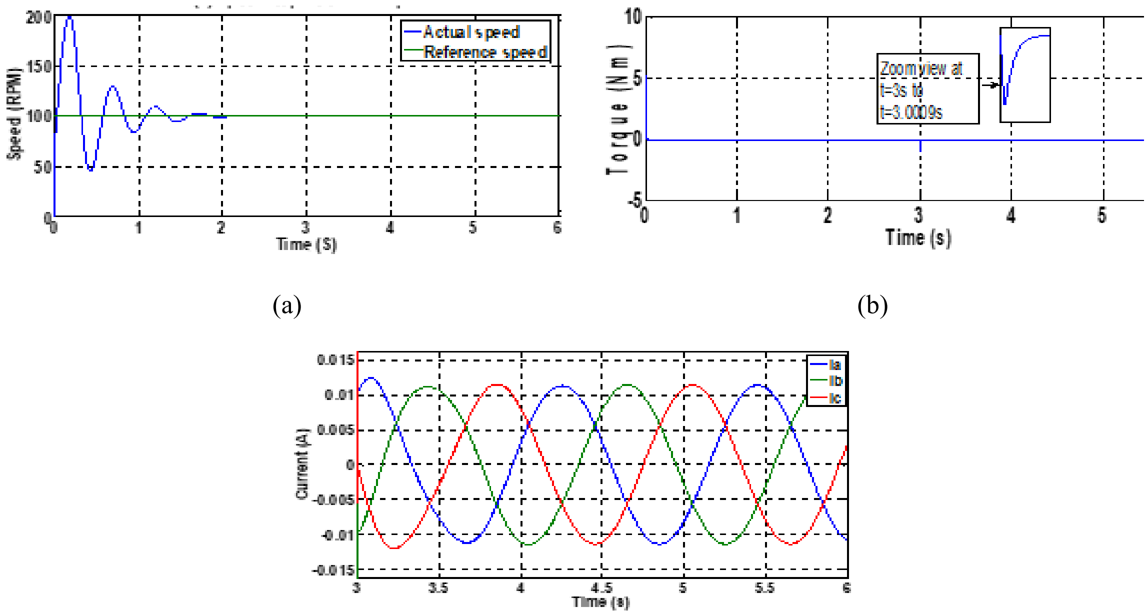
The parameter for PMSM which being used in simulation are as follows; sampling time is set to be $1e^{-6}$ seconds, the injected frequency, (f_i) is 2 KHz and amplitude (V_i) is 10 V. While the motor specification is tabulated in Table 1.

3.1. Operation from standstill without load

The reference speed is set at 0 rpm and 100 rpm. Figure 5 shows the speed, torque and stator current response at 100 rpm which is at low speed. The results prove that the system is able to operate from standstill and then match it reference speed at low speed. The speed response has a high overshoot due to difficulty of the observer to estimate the speed during initial condition which the current and voltage are zero.

Table 1 Motor specification

Section	Specification of motor	Details
	Preset model	05: 8 Nm 300 Vdc 2000 RPM–10Nm
	Stator phase resistance (ohm)	0.9585 Ω
	Inductances[Ld(H) Lq(H)]	[0.00525 ,0.00525]
	Flux linkage established by magnets (V.s)	0.1827
	Voltage Constant (V_peak L-L / krpm):	132.5525
	Torque Constant (N.m / A_peak):	1.0962
	Inertia, friction factor, pole pairs [J(kg.m^2) F(N.m.s) p( )]	[0.0006329, 0.0003035, 4]



(a) (b)

(c)

Figure 5. The response at 100 rpm for free acceleration; (a) speed, (b) torque, (c) I_{abc}

3.2. Step speed change in reference speed without load

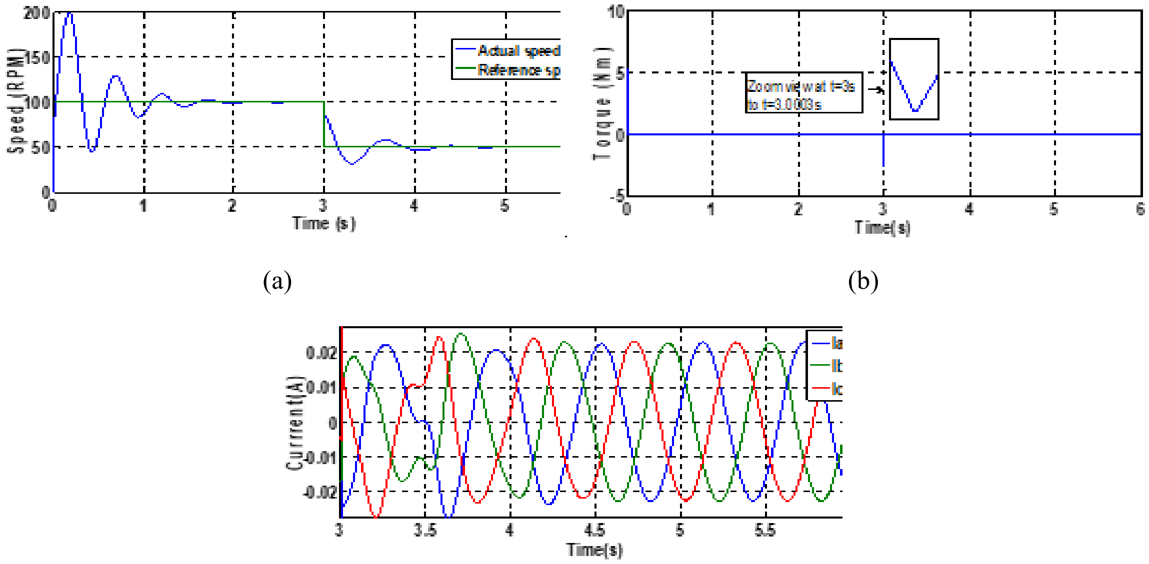
Figure 6 show the responses of speed, electromagnetic torque and stator current response without load. Initially, the reference speed is set at 100 rpm and then at the time = 3 second, the speed change to 50 rpm. At 3s, the speed is change from 100 rpm to 50 rpm, it can be deduced that the actual speed follows that of reference speed with low undershoot. The electromagnetic torque decrease to -0.9942 Nm when the speed is change but almost reach zero torque after some time. The stator current increases at 3s when the speed is change, it then decreases and stabilized quickly, the frequency of the current is 0.833 Hz.

3.3. Forward to reverse operation without load

Figure 7 show the responses of speed, electromagnetic torque and stator current response without load. Initially, the reference speed is set at 100 rpm and then at the time= 3 second, the speed is reverse to negative 100 rpm. Figure 7 depict when the speed reverse at 3 s, the speed response oscillates more compared to the speed when the motor is started with reference speed of 100 rpm, eventually the actual speed is able to track the reference speed very well, while the developed torque which drop to the lowest value of -2.71 Nm when the speed is reverse and then approaches zero as time goes by as there is no load applied to the motor. The stator current response which goes up when reference speed is reverse and then decrease immediately to around 0.02 A, the frequency of the current is 1.675 Hz.

3.4. Reverse to forward operation without load

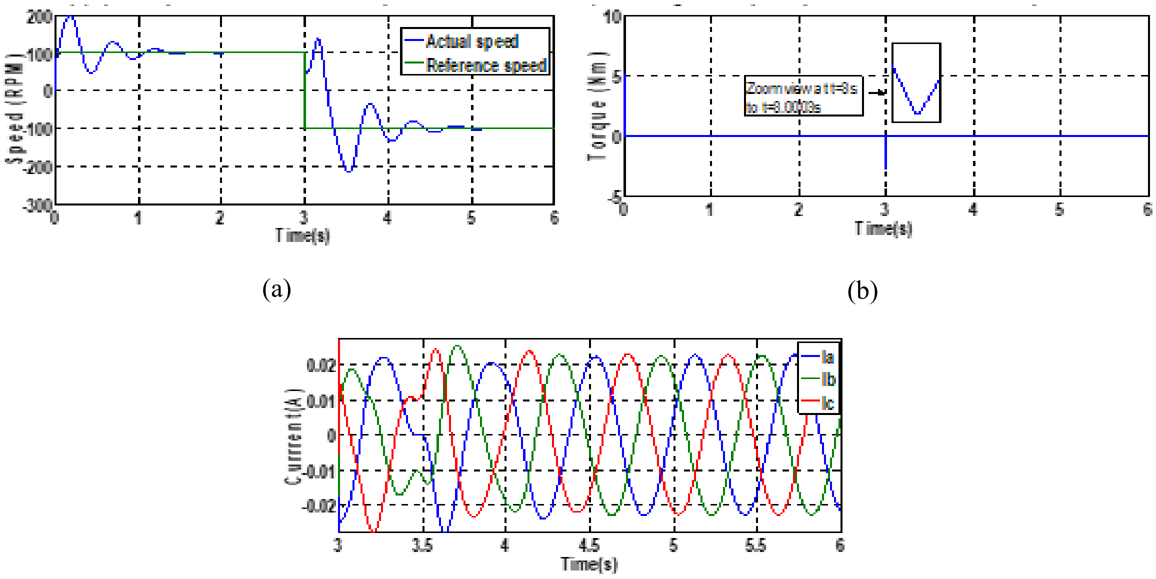
Figure 8 show the responses of speed, electromagnetic torque and stator current response without load. Initially, the reference speed is set at negative 100 rpm and then at the time=3 second, the speed is reverse to positive 100 rpm. Figure 8 describe the speed response which has a high overshoot when the speed change from negative 100 rpm to positive 100 rpm and after a while, the actual speed almost match the reference speed with only slight steady state error. while, the developed torque which increase to 2.71 Nm when the speed operation change from reverse to forward and as the case before, it went down to almost zero in value. Lastly the stator current response which have almost the same characteristic as the forward to reverse case with same frequency of 1.675 Hz.



(a) (b)

(c)

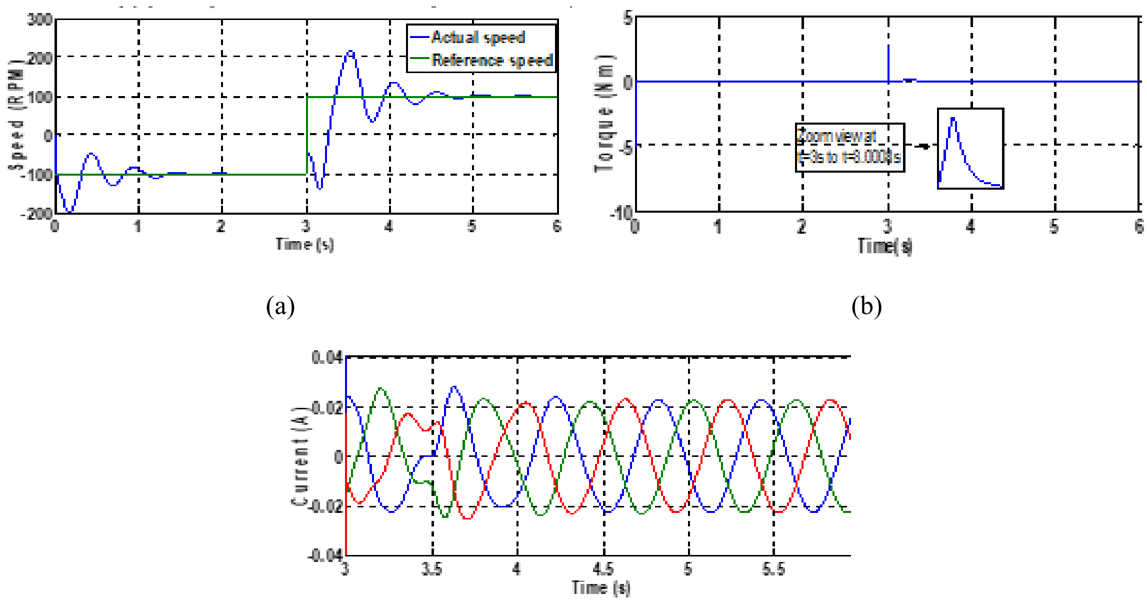
Figure 6. The response of step speed change in reference; (a) speed, (b) torque, (c) I_{abc}



(a) (b)

(c)

Figure 7. The response for forward to reverse operation; (a) speed, (b) torque and (c) I_{abc}



(a) (b)

(c)

Figure 8. The response for reverse to forward operation; (a) speed, (b) torque, (c) I_{abc}

4. CONCLUSION

On other hand, PMSM sensorless drives using high frequency signal injection is modelled using speed and position estimator equations. And only stator current is used as feedback in the drive system not the speed or position of the rotor. The sensorless drive system is analyzed based on several cases such as free acceleration, step change in reference speed, forward to reverse operation and reverse to forward operation. The transient responses from this cases were quite good and acceptable or in other word, there is close connection between theory and simulation, most important of all, the high frequency injection can be used to detect rotor position and speed at zero and low speed.

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