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Position Sensor Error Analysis for PMa-SynR Motor Drive system

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Abstract

Synchronous reluctance motors are among the most popular electric motors today, due to their relatively good features, but the important thing to consider about these motors is to calculate and estimate their rotor position, and failure to do so may cause damage in their control system. Therefore, many methods such as sensorless, hall-effect, GMR, encoder, etc. were used to compute and estimate the rotor position, each of which has its own advantages and disadvantages. Besides, in many articles, the effect of positional error and the effect of this error on the control system and the method of dealing with this chronic problem are not analytically stated, and only this phenomenon has been studied in operation. Whereas, in this paper, firstly, a variety of conventional methods available for estimating and calculation the rotor position of synchronous reluctance motors briefly is introduced, and then investigated the effect of the error on the control system and at the end, the results of simulation and mathematical analyzes the impact of this error on the control system is presented.

Keywords: Position Sensor; PMa-SynR; MTPA; Eigenvalue; Model Linearization.

1. INTRODUCTION

Using of electric motors is indisputable in many devices for powertrain. Among the many types of motors used, synchronous motors have attracted adequate attention for better performance in terms of torque, speed, and efficiency. Among the different types of synchronous machines today, the synchronous reluctance motors have become one of the most reputable electrical motors in various industries, including electric vehicles. [1]

Significant features of this type of machine are the lack of current in the rotor, robust rotor structure, and high power density, high similarity to induction machines, high stability and simple control [2-3]. Typically, these motors are controlled as closed loops because the benefits of using these machines can be used [4]. These types of motors are generally controlled by a variety of methods such as FOC, MPC and sliding mode [5]. In each of the motor control methods, the speed and position of the rotor must be measured or estimated using computational methods. [6]. In the family of synchronous motors, especially synchronous reluctance motors, the precision of the estimation or measurement of the rotor position plays an undeniable fundamental role in the control of motor speed and dynamical stability [7-8]. For this purpose, many computational methods have been proposed to estimate the position and speed of the rotor; for instance, sensorless, Hall-effect, GMR, resolver [7]. In the sensorless method, measurements are used by the position estimation method; this method is most often exploited due to sensor removal, cheaper price and easier implementation, but this method has acute problems, such as the creation of the motor torque fluctuation and the low accuracy of the control; which, makes it difficult to use this method at low speeds [9-11]. Speed measurement for rotor position estimation is commonly performed using 1- Hall Effect sensor 2-encoder 3-Tocogenerator [9, 12, and 13]. The Hall effect sensor operates based on the use of a number of magnetism components in the rotor and the use of sensors to detect the passage of each magnet material; the Hall effect sensor output signal is a function of the magnetic field density applied to the sensor, when the magnetic flux density around the sensor passes through a specific threshold, the sensor detects this and produces an output voltage called "Hall Voltage";

which, is referred to as Analog Hall effect sensor. Also, there is another type of this sensor that has a digital output that can be used to count the number of pulses [7, 9, and 14]. Normally, the use of Hall effect sensor in systems that require high measurement accuracy and variation in temperature conditions are not recommended and using of it could be dangerous because it can typically cause errors such as error in the sensor core, internal fault, sensor temperature changes, and so on; which in some cases increases the error of estimating motor position and disorders the operation of synchronous motors. [15]
Another evaluation method is the use of speed encoder, and the basis of this is that output pulse is proportional to the speed of the motor. The encoder structure consists of a slot disc whose number of slots is proportional to the encoder resolution; to detect the rotational direction of the motor, two outputs with a 90-degree phase difference are used together. [16] The motor speed is measured by counting the number of pulses produced by the encoder; which can be implemented in 3 ways. Firstly, counting based on pulses at a specified time (Model M), which has error at low-speed. Secondly, measure the time passed between sequential pulses (T model) which this method has low precision at high speeds. These two thorny problems led the researchers to use another way to alleviate these controversial issues then next method (M / T mode) could integrate the two methods together, but of course, this method has problems such as variable measurement time; that is why there is a trade-off between the resolution and the other system features. [16] The use of the speed Encoder for its simple implementation and lack of offset, fine precision, noise immunity and no need for repair and adjustment is more notable in industrial motors [2, 16].
Another method of speed measurement which is the most expensive than the previous two methods, is the use of a tachogenerator. The basis of this method is voltage-produced which is proportional to the speed value; also, this voltage can reach up to 100-volt. [12] Due to the voltage level, they are not directly connected to the microcontrollers, and the interfacing circuits must be used; usage of these circuits creates offsets, nonlinear behaviors and dead bands at the Taco output voltage; as a result, speed measurement in the synchronous reluctance motor is more difficult, and this is why Taco is rarely exerted today. [12]
The investigation of the error in the speed measurement by the sensor and the disturbance in the estimation of the rotor position in various references such as [17] and [18] and [19] have been investigated. In [20], the speed instability due to offset error and nonlinear factors in estimation of rotor position has been investigated, but the mathematical analysis has not been expressed to explain the reason of the instability, and only with experimental and simulation results, the instability of the system has been discussed.
In this paper, using the Analytical Analyze and the motor model in the space d-q, the position measurement error enters to the control calculations, and by analyzing the results obtained, the error in the motor position measurement, due to the error value causes changes in the control components and components at different frequencies than the original value; which, results led to disorder the control system; then, in the next section, a comprehensive analysis of how these changes are affected and their dependence on the amount of position error is done, and according to the simulation results shown, the presence of the position measurement error caused a change in the location of the roots of the motor state-space equations; if the position sensor error increases, this error can cause overall instability and disruption of the control system.
The remainder of this article can be categorized in the following sections: Control strategy of PMa-SynR Motor and linearization of PMASynRM dynamic equations along with the formulation, is presented in 2. In 3, Case studies and Problem definition is presented and the simulation results and the conclusion are discussed in the last two sections.

2. Control strategy of PMa-SynR Motor

The four-pole rotor of a permanent magnet synchronous motor with d-q axes is shown in Fig. 1 [21].

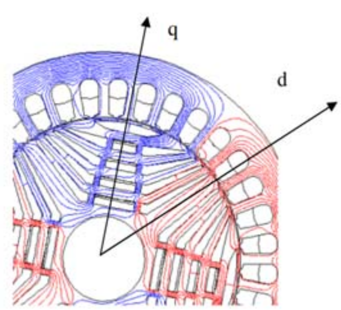

Fig. 1 Four pole rotor of PMa-SynRM

In order to obtain the system model, the dynamic equations of the system should be written. The following equations are the dynamic equations in a PMa-SynR [22]:

$$\frac{di_{ds}}{dt} = \frac{1}{L_d}[V_{ds} - r_s i_{ds} + \omega_r L_{qs} i_{qs} - \omega_r \lambda] \quad (1)$$

$$\frac{di_{qs}}{dt} = \frac{1}{L_q}[V_{qs} - r_s i_{qs} + \omega_r L_{ds} i_{ds}] \quad (2)$$

$$T_e - T_L = J\frac{d\omega_r}{dt} \quad (3)$$

$$T_e = \frac{3}{2}\frac{p}{2}\left[\left(L_{ds} - L_{qs}\right)i_{ds}i_{qs} + \lambda i_{ds}\right] \quad (4)$$

$$T_L = \beta\omega_r \quad (5)$$

In the above equations, i_{ds} and i_{qs} are stator d and q axes currents; V_{ds} and V_{qs} are stator d and q axes voltages. Also, L_{ds} and L_{qs} are stator d and q axes inductance. Eventually, J, r_s, ω_r, p, λ and β represent rotor inertia, stator single-phase resistance, rotor speed, the number of motor poles, the magnet flux added to the rotor and the air friction coefficient of flywheel disk, respectively.

The structure of a maximum torque per ampere (MTPA) control system of a PMa-SynRM is presented in Fig. 2. It is clear from the figure that the motor control system is a cascade type, with the inner loop controller for controlling the current, and the outer loop controller for controlling the speed. In the cascaded structure, the controller parameters should be designed in such a way that the inner loop is significantly faster than outer loop so that the control system is not disturbed and can weaken the external disturbances [23].

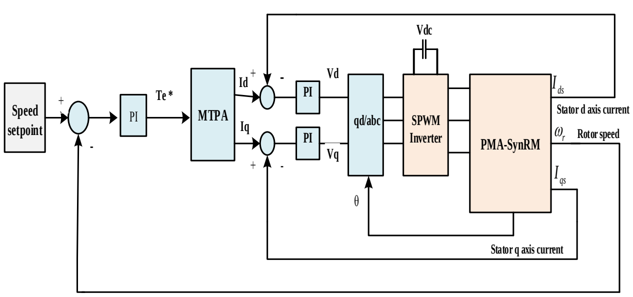

Fig. 2 Control scheme of PMa-SynRM.

2.1. Linearization of PMASynRM dynamic equations

As it is obvious in the dynamics model of the motor, there is nonlinearity in the state space equations because of the coupled term such as $\omega_r L_q i_{qs}$ and $\left(L_d - L_q\right)i_d i_q$. Therefore, in order to design a linear controller, a linear model of the motor should be extracted. In this paper, the linearize equations are extracted using Taylor expansion. To this goal, at first needs to define the system operating point. As the motor is under the inertia load, the operating point is selected based on the motor nominal value. The Taylor expansion around the x_0 point is as follows:

$$f(x) = f(x_0) + \left.\frac{df(x)}{dx}\right|_{x=x_0}(x - x_0) + \frac{1}{2}\left.\frac{df^2(x)}{dx^2}\right|_{x=x_0}(x - x_0)^2 + \cdots \quad (6)$$

The higher order terms can be neglect from Taylor expansion in order to obtain the linearized equations. At first, all system parameters are assumed to change around the operating point, so:

$$i_{ds} = \Delta i_{ds} + i_{ds0} \quad (7)$$

$$i_{qs} = \Delta i_{qs} + i_{qs0} \quad (8)$$

$$\omega_e = \Delta\omega_e + \omega_{e0} \quad (9)$$

Using the above variables, the nonlinear terms of the motor dynamic equations are:

$$\omega_e L_q i_{qs} = L_q\left[\omega_{e0} i_{qs0} + i_{qs0}(\Delta\omega_e - \omega_{e0}) + \omega_{e0}(\Delta i_{qs} - i_{qs0})\right] \quad (10)$$

$$\omega_e L_d i_{ds} = L_d[\omega_{e0} i_{ds0} + i_{ds0}(\Delta\omega_e - \omega_{e0}) + \omega_{e0}(\Delta\Delta i_{ds} - i_{ds0})] \quad (11)$$

$$(L_d - L_q)i_{ds}i_{qs} = (L_d - L_q)\left[i_{ds0}i_{qs0} + i_{ds0}\left(\Delta i_{qs} - i_{qs0}\right) + i_{qs0}(\Delta i_{ds} - i_{ds0})\right] \quad (12)$$

The above equations are simplified around the operating point as follow:

$$\omega_e L_q i_{qs} = L_q\left[-\omega_{e0} i_{qs0} + i_{qs0}\Delta\omega_e + \omega_{e0}\Delta i_{qs}\right] \quad (13)$$

$$\omega_e L_d i_{ds} = L_d[-\omega_{e0} i_{ds0} + i_{ds0}\Delta\omega_e + \omega_{e0}\Delta i_{ds}] \quad (14)$$

$$(L_d - L_q)i_{ds}i_{qs} = (L_d - L_q)\left[-i_{ds0}i_{qs0} + i_{ds0}\Delta i_{qs} + i_{qs0}\Delta i_{ds}\right] \quad (15)$$

By definition state vector as $= [i_{ds}, i_{qs}, \omega]$, input vector $u = [v_{ds}, v_{qs}, T_{dis}]$ and output vector $y = [i_{ds}, i_{qs}, \omega]$,The linear state space model is then written as follows:

$$\begin{pmatrix} \widetilde{\Delta i_{ds}} \\ \widetilde{\Delta i_{qs}} \\ \widetilde{\Delta\omega} \end{pmatrix} = \begin{pmatrix} \frac{-r_s}{L_d} & \omega_{r0}\frac{L_q}{L_d} & i_{qs0}\frac{L_q}{L_d} - \frac{\lambda_{pm}}{L_d} \\ -\omega_{r0}\frac{L_d}{L_q} & \frac{-r_s}{L_q} & -i_{ds0}\frac{L_d}{L_q} \\ \frac{3[i_{qs0}(L_d - L_q) + \lambda_{pm}]}{j} & \frac{3[i_{ds0}(L_d - L_q)]}{j} & \frac{\beta}{j} \end{pmatrix} \begin{pmatrix} \Delta i_{ds} \\ \Delta i_{ds} \\ \Delta\omega \end{pmatrix} + \begin{pmatrix} \frac{1}{L_d} & 0 & 0 \\ 0 & \frac{1}{L_q} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} v_{ds} \\ v_{qs} \\ T_{dis} \end{pmatrix} + \begin{pmatrix} \frac{-L_q}{L_d}\omega_{r0}i_{qs0} \\ \frac{-L_d}{L_q}\omega_{r0}i_{ds0} \\ -\frac{3[(L_d - L_q)i_{ds0}i_{qs0}]}{j} \end{pmatrix} \quad (16)$$

2.2. Maximum Torque Per Ampere (MTPA) Control

In order to achieve the maximum torque per current ratio in the motor control system, it is necessary to calculate the optimal current angle to calculate the reference current for the d and q axes. The optimal angle of the phase current (β) is calculated from the following equation, which is known as the MTPA algorithm [24]:

$$\beta = \sin^{-1}\left(\frac{-\lambda + \sqrt{\lambda^2 + 8(L_d - L_q)^2 I_s^{\,2}}}{4(L_d - L_q)I_s}\right) \quad (17)$$

Where I_s is Calculated from the following equation:

$$I_s = \sqrt{I_d^{\,2} + I_q^{\,2}} \quad (18)$$

Thus, with considering β , reference currents of d and q axes can be calculated as follows:

$$I_d^{\,*} = I_s \cos(\beta) \quad (19)$$

$$I_q^{\,*} = I_s \sin(\beta) \quad (20)$$

The equations of the PMa-SynRM ((1) to (4)) are cross-coupled and are recognized as nonlinear terms. According to (1), the term $+\omega_r L_{qs} i_{qs}$ is a dependent term, and it is necessary to add it's compensate term to decouple the d-axis from q-axis. Also, according to (2), the term $\omega_r L_{ds} i_{ds}$ is a dependent term that in the same way with adding it's compensate term to the control system can decouple the q-axis from d-axis. By doing so, the control system is linearized and can utilize it to design a linear controller.

2.3. Rotor positions measurement with error

In the synchronous motor, the rotor position measurement or estimations accuracy is a vital case in motor stability and dynamic performance. Existence of error in rotor position affects directly the park transform and therefore disrupt the control system. For studies of error effect in the motor control system, the park transformer is rewritten after add error in rotor position. The mathematical equation describes as flows:

The park transformation matrix is defined as:

$$T = \begin{pmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ \sin(\theta) & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \\ 0 & 0 & 0 \end{pmatrix} \quad (21)$$

If an error as much as $\Delta\theta$ occur in the rotor angle, then the estimated angle can be written as:

$\hat{\theta} = \theta + \Delta\theta$

So the park transformation matrix is rewritten as below:

$$\phi = \theta - \frac{2\pi}{3}, \quad \psi = \theta + \frac{2\pi}{3} \quad (22)$$

$$\hat{T} = \begin{pmatrix} \cos(\theta)\cos(\Delta\theta) - \sin(\theta)\sin(\Delta\theta) & \cos(\phi)\cos(\Delta\theta) - \sin(\phi)\sin(\Delta\theta) & \cos(\psi)\cos(\Delta\theta) - \sin(\psi)\sin(\Delta\theta) \\ \sin(\theta)\cos(\Delta\theta) + \cos(\theta)\sin(\Delta\theta) & \sin(\phi)\cos(\Delta\theta) + \cos(\phi)\sin(\Delta\theta) & \sin(\psi)\cos(\Delta\theta) + \cos(\psi)\sin(\Delta\theta) \\ 0 & 0 & 0 \end{pmatrix}$$

With using Tylor expansion in small signal conditions (low error) be use the flowing approximation:

$$\sin(\Delta\theta) = \Delta\theta \qquad \cos(\Delta\theta) = 1 \tag{23}$$

The matrix $\hat{T}$ can be rewritten as:

$$\hat{T} = T_1 + T_2 \tag{24}$$

Where T_2 is the part of $\hat{T}$ which includes the offsets as bellow:

$$T_2 = \begin{pmatrix} -\sin(\theta)\Delta\theta & -\sin(\phi)\Delta\theta & -\sin(\psi)\Delta\theta \\ \cos(\theta)\Delta\theta & \cos(\phi)\Delta\theta & \cos(\psi)\Delta\theta \\ 0 & 0 & 0 \end{pmatrix} \tag{25}$$

If i_d, i_q are the current in d and q axes, then the current caused by the offset can be written as:

$$\begin{pmatrix} i_{q_m} \\ i_{d_m} \end{pmatrix} = T_2 \begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} = \begin{pmatrix} -i_{q_m}\Delta\theta \\ i_{d_m}\Delta\theta \end{pmatrix} \tag{26}$$

According to the (24) the above equation can be written as:

$$\begin{pmatrix} i_q \\ i_d \end{pmatrix} = \begin{pmatrix} i_{q_m} - i_{q_m}\Delta\theta \\ i_{d_m} + i_{d_m}\Delta\theta \end{pmatrix} \tag{27}$$

By linearizing the dynamical model of the motor in dq axes, the state space of the motor is []:

$$\frac{d}{dt}\begin{pmatrix} \dot{i}_d \\ i_q \\ \omega \end{pmatrix} = \begin{pmatrix} \dfrac{-r_s}{L_d(1+\Delta\theta)} & \dfrac{\omega_{r0}L_q}{L_d(1+\Delta\theta)} & i_q\dfrac{L_q}{L_d} - \dfrac{\lambda p_m}{L_d} \\ \dfrac{-\omega_{r0}L_d}{L_q(1-\Delta\theta)} & \dfrac{-r_s}{L_d(1-\Delta\theta)} & i_{ds0}\dfrac{L_d}{L_q} \\ 3\dfrac{i_q(L_d-L_q)+\lambda p_m}{j} & 3\dfrac{i_{ds}(L_d-L_q)}{j} & \dfrac{\beta}{j} \end{pmatrix} \begin{pmatrix} \dot{i}_d \\ i_q \\ \dot{\omega} \end{pmatrix} \tag{28}$$

According to the above equation, the eigenvalues of the transient matrix can be calculated in exchange for change of the $\Delta\theta$. Also the value of $\Delta\theta$ in order to unstable one of the motor transfer function poles can be calculated. According to the dynamical model of the motor, the stability of this motor depends on ω_{r0} in addition to $\Delta\theta$. As it will be shown in the future, the motor at low speeds is unstable while it is stable at high speeds.

3. Case studies and Problem definition

Assuming that the integration error of encoder is neglected by implementation of the offset in the dynamical model of the motor and using the linearized dynamical model, it is founded that the presence of this offset cause changes in the eigenvalues of the transient matrix. This is the main reason of instability in the motors. The eigenvalues of the transient matrix with no approximation of rotor position in 1000rpm and 500rpm is calculated as:

in v=1000rpm: eigenvalues before offset occurrence:

-116±128j , -10

in v=1000rpm: eigenvalues after offset occurrence:

-30±102j , -200

According to the above eigenvalues, if the offset is added to the dynamics, the eigenvalues will be changed. In this case, the mechanical poles dominate the electrical poles and the consequent is disorder in the motor speed. Because the controller parameters are obtained so that current control loop be faster than the speed control loop. While the poles and eigenvalues of the motor model will be changed if an offset added to the system measurement and as result the drive system performance tend to instability.

4. Simulation results

In order to show the effect of error as an offset on the performance of speed controller for a motor, a series of simulations has been carried out, the results of which are presented in this section. The case study of this section is a PMa-SynRM motor which is defined in dynamical model section. In this stupide the motor torque is consider as torque constant load Firstly a step command with initial value and amplitude as much as 500 rpm is applied to the motor as input for the control loop with no offset in the dynamical model and the response is shown in Fig. 3.

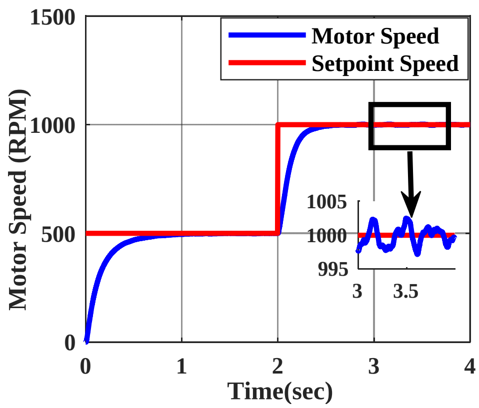

Fig. 3 speed response in the absence of error in the dynamical model of motor.

According to the Fig. 3, the response of the motor is acceptable and has settling time as much as 0.4 sec. The overshoot of transient response is close to zero and as it is shown in this figure, the speed of motor is stable. But if an offset as an error occur in the dynamical model of motor, the speed response will be unstable in low range of speed. In order to show this phenomena, an offset which is defined in the dynamical model section, is added to the model of motor and a command as much as 1000rpm is applied to the control loop. Fig. 4. Shows the response of motor in this case.

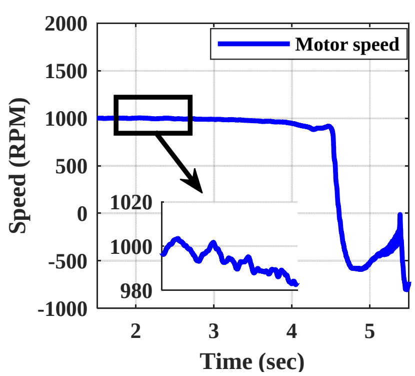

Fig. 4 speed response in the presence of error in the dynamical model of motor.

As in Fig. 4, the occurrence of error as an offset make the speed control loop unstable. According to this figure, an offset is occurred in t=2sec and cause to reduction of the motor speed. After 2.5 sec the speed of motor is completely unstable and cannot track the input reference. This is because of the offset in the dynamical model of motor which changes the poles and the eigenvalues of transient matrix of the model. Fig. 5 shows the root locus diagram of the dynamical model of the motor before and after the offset occurrence.

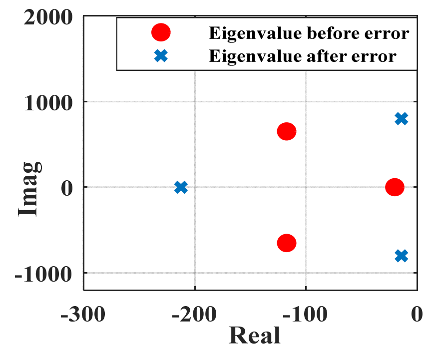

Fig. 5 Root locus diagram of the dynamical model of the motor before and after the offset occurrence.

According to the Fig. 5 the error cause to change in the poles and the eigenvalues of transient matrix of the model. This means the mechanical poles dominate the electrical poles and the consequent is disorder in the motor speed. So the motor speed in the presence of this error will be unstable. Fig. 6 shows the motor current after the occurrence of the offset in the model. According to this figure. In t= 2 sec the current in the dq axes has a fluctuation and then the error in the model cause the instability in this current. In other words the error cause to undesirable in the speed range and then changes in the motor current. Moreover the other figure confirm this phenomena and shows the instability of current after t=2 sec. in Fig.7 is shown the rotor position in error condition and compare with stable condition. The simulation result in Fig.7 is indicate that due to rotor position measurement equation is depend to motor integration of speed directly, instability problem occur step by step in motor speed.

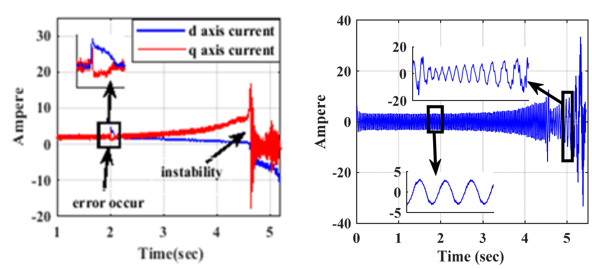

Fig. 6 Current of the motor in the presence of error in the dynamical model of motor.

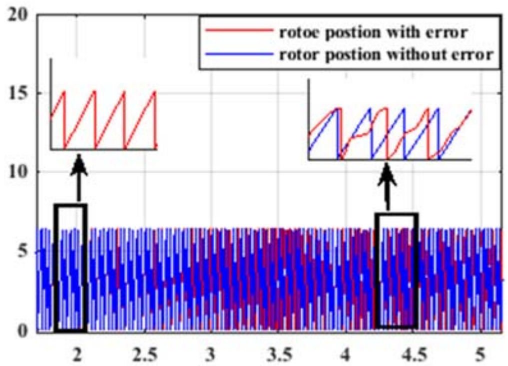

Fig.7 Rotor position

5. Conclusion

In this paper the PMa-SynR motor is investigated and traditional control method (vector control) is implemented. For using all of motor ability in torque generation, the method of MTPA is implemented in speed control system. For having analytical investigation, motor linearized state space model is calculated and is used from this model in controller design. In this motor, rotor position measurement is necessary in drive system. In this paper for investigation of error effect in rotor position, some error value is added to motor speed and its result in system stability is checked. Simulation result are shown the system performance is depended to value of error directly. For analysis of this problem, the linearized state space model of motor was used and the error in rotor position was added in state space model. Inspection of the geometrical position of the system poles and the simulation results over time show that a small offset in the speed measurement can cause the control system to become unstable.

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