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Stability of the Rotor Flux Oriented Speed Sensorless Permanent Magnet Synchronous Motor Control (Conference Paper)

Wuri Harini, B., Subiantoro, A., Yusivar, F.
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Universitas Indonesia, Electrical Engineering Department, Kampus UI Depok West Java, 16424, Indonesia

Abstract

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This paper analyzes the effect of Park transformation on the stability of the Permanent Magnet Synchronous Motor Control (PMSM) sensorless control system. In the sensorless control method, the transformation from a-p to the d-q frame can cause problems, especially stability issues. System stability is analyzed in two ways. They are stability analysis with and without taking the frame transformation into account. The sensorless control system that will be analyzed uses MRAS as the observer and Proportional Integral (PI) as a current controller. When analyzing without taking the frame transformation into account, it is proved that the sensorless control system of PMSM is stable, but when analyzing with taking the frame transformation into account, the system can be unstable. The transformation can cause estimation errors. The error can cause the stability problems, too. It is proved that the system can be unstable when the estimated position value differs from the actual position. © 2018 IEEE.

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Stability of The Rotor Flux Oriented Speed Sensorless Permanent Magnet Synchronous Motor Control

Bernadeta Wuri Harini, Aries Subiantoro, Feri Yusivar
Electrical Engineering Department
Universitas Indonesia
Kampus UI Depok 16424, West Java, Indonesia
yusivar@yahoo.com

***Abstract*— This paper analyzes the effect of Park transformation on the stability of the Permanent Magnet Synchronous Motor Control (PMSM) sensorless control system. In the sensorless control method, the transformation from *α-β* to the *d-q* frame can cause problems, especially stability issues. System stability is analyzed in two ways. They are stability analysis with and without taking the frame transformation into account. The sensorless control system that will be analyzed uses MRAS as the observer and Proportional Integral (PI) as a current controller. When analyzing without taking the frame transformation into account, it is proved that the sensorless control system of PMSM is stable, but when analyzing with taking the frame transformation into account, the system can be unstable. The transformation can cause estimation errors. The error can cause the stability problems, too. It is proved that the system can be unstable when the estimated position value differs from the actual position.**

Keywords*— *PMSM; sensorless control; transformation; α-β frame; d-q frame

I. Introduction

One type of Alternating Current (AC) motor is Permanent Magnet Synchronous Motor (PMSM). Due to its high-performance reliability, the PMSM has been widely used in the industry for variable speed applications[1]. One of them is PMSM used as a driving force on electric vehicles.

To control motor speed, the motor requires a controller. In addition to conventional methods, currently, the sensorless control method is developed. The advantage of the sensorless control method is this method does not use speed sensor or position sensor. The stator current is measured using a current sensor to estimate the speed of the motor. The estimation is done by an observer. One type of observer is Model Reference Adaptive System (MRAS)[2].

One problem of sensorless control that is used in the electric vehicle is the electric vehicle actually move in the wrong direction, especially when a large load that has reverse torque direction is given to the motor. This phenomenon has been revealed by Harini, B.W. et al[3]. The paper explained when the motor rotation has been stabilized at 90 rpm, the motor rotation detained from outside by a brake so that the motor does not rotate. When the motor rotation detained, the estimated value of the speed is stable at 66 rpm, although actually, it does not rotate. It means that the estimate of the motor speed is wrong.

The wrong orientation can happen because of the transformation effect from stationary reference frame (α,β,0) into a rotating reference (d, q, 0) frame. In the sensorless control method, the three-phase mathematical model of PMSM will be changed into the two-phase mathematical model using Clarke and Parke transformations[4]. The Clarke transformation converts the balanced three-phase quantities into two-phase stationary reference frame (α,β,0). The Park transformation converts from stationary reference frame into a rotating reference (d, q, 0) frame. This transformation has no effect on the control system that uses the sensor because the position is directly measured. In the sensorless system, there can be estimation errors, especially at the time of transients. Previous research has shown that the control system in the *d-q* frame is stable[5]. In this paper, we will analyze the effect of the transformation from *α-β* to the *d-q* frame, especially stability issues. The analyzed system is a sensorless system in the *d-q* frame. System stability is analyzed in two ways. They are stability analysis with and without the frame transformation into account. When analyzing with taking the frame transformation into account, the PMSM is modeled in the *α-β* frame.

So far, no researcher has examined the effect of this transformation on PMSM sensorless system stability by using this method. Usually, if the model is used in the *d-q* frame, then the stability will be analyzed in the *d-q* frame, as done by J Linares-Flores et al[6]. The variables calculated by the observer are considered to be indistinguishable from the actual values, i.e., $\hat{\theta} \approx \theta$ and $\hat{\omega} \approx \omega$. If the model is used in the *α-β* frame, then the stability will be analyzed in the *α-β* frame, as done by H Lee et al[7].

Some researchers have analyzed the system of controls associated with this transformation. J. Sadoughi et al have compared the performance of induction motor in stationary and rotating reference frame [8]. The paper explained that the dynamic response of torque and the speed response in rotor reference frame is much better than the stator reference frame. L. Jarzebowicz has analyzed the error of calculating average *d-q* current components using regular sampling and Park transformation in FOC Drives [9]. The paper explained that the higher the speed of the motor, the greater the error. Gunawan, R. and Yusivar, F has researched to reduce the estimation error in a speed sensorless control of induction motor [10]. Other researchers has analyzed the stability of the sensorless control system that is applied at PMSM, such as Hamada, D. et al [11] that analyzed the stability of sensorless PMSM with a Reduced Order Observer, Rashed, M et al in a paper entitled Sensorless Indirect-Rotor-Field-Orientation Speed Control of a Permanent-Magnet Synchronous Motor With Stator-Resistance Estimation [12] and Kim, H. et al with a paper of A High-Speed Sliding-Mode Observer for the Sensorless Speed Control of a PMSM [13].

The sensorless control system that will be analyzed uses MRAS as the observer and Proportional Integral (PI) as a current controller. The system that will be analyzed is an open loop system, without a speed controller. The nonlinear model of the PMSM sensorless system in the *α-β* frame and the *d-q* frame is linearized and then expressed in state space form.

II. PMSM MODEL

The Park transformation converts from stationary reference frame into a rotating reference (*d, q*, 0) frame using (1).

$$\begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} = \begin{bmatrix} \cos\theta_r & \sin\theta_r \\ -\sin\theta_r & \cos\theta_r \end{bmatrix} \begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix} \quad (1)$$

The PMSM model is expressed in two models, ie models in the stationary reference frame (*α,β*,0) and a rotating reference (*d, q*, 0) frame. The PMSM mathematical model in the *α-β* frame is

$$\begin{bmatrix} v_{s\alpha} \\ v_{s\beta} \end{bmatrix} = \begin{bmatrix} R_s + pL_s & 0 \\ 0 & R_s + pL_s \end{bmatrix} \begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix} + N\omega_r\psi_F \begin{bmatrix} -\sin\theta_r \\ \cos\theta_r \end{bmatrix} \quad (2)$$

where $v_{s\alpha}$ is the stator voltage in α-axis, $v_{s\beta}$ is the stator current in β-axis, p is d/dt, R_s is the stator resistance, L_s is the stator inductance, N is the number of pole pairs, ω_r is the rotor speed, and ψ_F is the magnet flux linkage. The equation (2) can be stated as

$$\frac{d}{dt} i_{s\alpha} = \frac{1}{L_s}\left(v_{s\alpha} - R_s i_{s\alpha} + N\omega_r\psi_F \sin\theta_r\right) \quad (3)$$

$$\frac{d}{dt} i_{s\beta} = \frac{1}{L_s}\left(v_{s\beta} - R_s i_{s\beta} - N\omega_r\psi_F \cos\theta_r\right) \quad (4)$$

The PMSM mathematical model in the *d-q* frame [2] is

$$\begin{bmatrix} v_{sd} \\ v_{sq} \end{bmatrix} = \begin{bmatrix} R_s + pL_s & -N\omega_r L_s \\ N\omega_r L_s & R_s + pL_s \end{bmatrix} \begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} + \begin{bmatrix} 0 \\ N\omega_r\psi_F \end{bmatrix} \quad (5)$$

where v_{sd} is the stator voltage in *d*-axis, v_{sq} is the stator voltage in *q* axis, i_{sd} is the stator current in *d*-axis, i_{sq} is the stator current in *q*-axis. The equation (5) can be stated as

$$\frac{d}{dt} i_{sd} = \frac{V_{sd} - R_s i_{sd} + N\omega_r L_{sq} i_{sq}}{L_{sd}} \quad (6)$$

$$\frac{d}{dt} i_{sq} = \frac{V_{sq} - i_{sd} N\omega_r L_{sd} - R_s i_{sq} - N\omega_r\psi_F}{L_{sq}} \quad (7)$$

The electric torque of PMSM is

$$T_e = \left\{\psi_F i_{sq} + \left(L_{sd} - L_{sq}\right) i_{sd} i_{sq}\right\} \quad (8)$$

where L_{sd} is the stator inductance in *d*-axis and L_{sq} is the stator inductance in *q*-axis.

The mechanical model of PMSM [14] is

$$\frac{d\theta_r}{dt} = N\omega_r \quad (9)$$

where

$$\frac{d\omega_r}{dt} = \frac{T_e - T_L}{J} \quad (10)$$

where θ_r is the position of the rotor, ω_r is the speed, T_L is the load torque and J is the inertia of the motor.

III. SENSORLESS CONTROL

Block diagram of the closed loop sensorless control system is shown in [3]. Block diagram of the open loop sensorless control system is shown in Fig. 1.

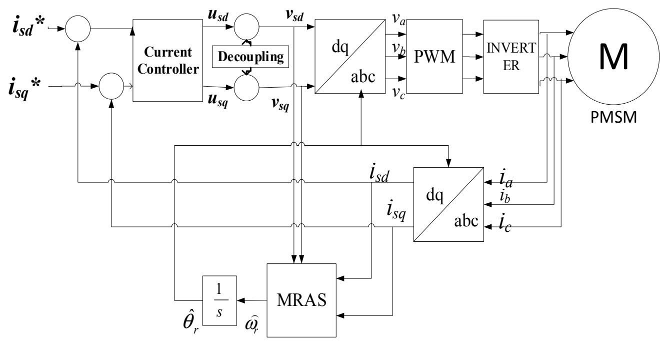


Fig. 1. Block diagram of the open loop sensorless control

Each part will be explained below.

A. Decoupling

Decoupling part is used to decouple cross-coupling between *d* and *q*-axis components (*ω* and i) which is not linear. This is necessary because the PI controller can only control the linear equations. The decoupling equations [15] are

$$V_{sd} = U_{sd} - N\hat{\omega}_r L_{sq} i_{sq1} \quad (11)$$

$$V_{sq} = U_{sq} + N\hat{\omega}_r L_{sd} i_{sd1} + N\hat{\omega}_r \psi_F \quad (12)$$

where

$$\frac{d}{dt} i_{sd1} = \frac{1}{T_d} i_{sd}^{*} - \frac{1}{T_d} i_{sd1} \tag{13}$$

$$\frac{d}{dt} i_{sq1} = \frac{1}{T_d} i_{sq}^{*} - \frac{1}{T_d} i_{sq1} \tag{14}$$

$$\frac{d}{dt} X_{sd} = i_{sd}^{*} - i_{sd} \tag{15}$$

$$\frac{d}{dt} X_{sq} = i_{sq}^{*} - i_{sq} \tag{16}$$

where i_{sd}^{*} is the set point of i_{sd} and i_{sq}^{*} is the set point of i_{sq}.

B. Current Controller

The phase angle and the modulus of the current in an AC machine have to be controlled. It means that the current vector has to be controlled [2], so the torque and flux producing current components are independently controlled. This is done by controlling the stator current in the *d-q* reference frame using Proportional Integrator (PI). The current controller equations [15] are

$$u_{sd} = K_{pd}\left(i_{sd}^{*} - i_{sd}\right) + K_{id}\int\left(i_{sd}^{*} - i_{sd}\right)dt \tag{17}$$

$$u_{sq} = K_{pq}\left(i_{sq}^{*} - i_{sq}\right) + K_{iq}\int\left(i_{sq}^{*} - i_{sq}\right)dt \tag{18}$$

where K_{pd}, K_{id}, K_{pq}, and K_{iq} are the current controller gain in the *d-q* frame. The values of each gain are

$$K_{pd} = \frac{L_{sd}}{T_d} \qquad K_{id} = \frac{R_s}{T_d} \qquad K_{pq} = \frac{L_{sq}}{T_d} \qquad K_{iq} = \frac{R_s}{T_d} \tag{19}$$

C. Model Reference Adaptive System (MRAS)

The output of reference models and adaptive models in MRAS will be compared. The error between both models is used in adaptive mechanism to estimate a variable ($\hat{y}$). The reference model uses the actual system (PMSM motor). The adaptive model uses the output of the observer. The estimation mechanism for $L_{sd} \neq L_{sq}$ uses (16) – (21) :

$$e_{wr} = \frac{L_{sq}}{L_{sd}} i_{sd}\hat{i}_{sq} - \frac{L_{sd}}{L_{sq}} i_{sq}\hat{i}_{sd} - \frac{\psi_F}{L_{sq}}\left(i_{sq} - \hat{i}_{sq}\right) + \hat{i}_{sd}\hat{i}_{sq}\left(\frac{L_{sd}}{L_{sq}} - \frac{L_{sq}}{L_{sd}}\right) \tag{20}$$

$$X_{ewr} = \int_0^t e_{wr}\, dt \quad \text{or} \quad \frac{d}{dt} X_{ewr} = e_{wr} \tag{21}$$

$$\begin{aligned} \hat{\omega}_r &= K_{wrp} e_{wr} + K_{wri} X_{ewr} \\ &= K_{wrp}\frac{L_{sq}}{L_{sd}} i_{sd}\hat{i}_{sq} - K_{wrp}\frac{L_{sd}}{L_{sq}} i_{sq}\hat{i}_{sd} - K_{wrp}\frac{\psi_F}{L_{sq}} i_{sq} + K_{wrp}\frac{\psi_F}{L_{sq}}\hat{i}_{sq} + K_{wrp}\left(\frac{L_{sd}}{L_{sq}} - \frac{L_{sq}}{L_{sd}}\right)\hat{i}_{sd}\hat{i}_{sq} + K_{wri} X_{ewr} \end{aligned} \tag{22}$$

$$\frac{d}{dt}\hat{i}_{sd} = -\frac{R_s}{L_{sd}}\hat{i}_{sd} + \hat{\omega}_r \frac{L_{sq}}{L_{sd}}\hat{i}_{sq} + \frac{U_{sd}}{L_{sd}} \tag{23}$$

$$\frac{d}{dt}\hat{i}_{sq} = -\hat{\omega}_r \frac{L_{sd}}{L_{sq}}\hat{i}_{sd} - \frac{R_s}{L_{sq}}\hat{i}_{sq} + \frac{U_{sq}}{L_{sq}} \tag{24}$$

$$\frac{d\hat{\theta}}{dt} = N\hat{\omega}_r \tag{25}$$

where $\hat{i}_{sd}$ and $\hat{i}_{sq}$ are the current estimate in the *d-q* frame, $\hat{\omega}_r$ is the estimate of the rotor speed, K_{wrp} is a proportional gain of MRAS, and K_{wri} is an integrator gain of MRAS.

IV. METHODS

PMSM that we are used has parameters shown in Table I. The sensorless control system of PMSM is simulated using Matlab. System stability is analyzed in two ways. They are

a. stability analysis without taking the frame transformation into account. It means that we analyze the system in the *d-q* frame.
b. stability analysis with taking the frame transformation into account. In this method, the PMSM is modeled in the *α-β* frame. To determine the effect of differences between θ and $\hat{\theta}$ on system stability, the system is analyzed with the variation value of $\Delta\theta$ from -180^0 – 180^0. $\Delta\theta$ is the difference between θ and $\hat{\theta}$.

TABLE I. PMSM PARAMETERS

Parameters	**Quantities**	**Unit**	**Description**
Td	0.01	second	Time constant of current controller
dt	0.0001	second	Sampling time of controller
N	4		Number of pole pairs
R_s	0.14710296	Ω	Stator resistance
L_{sd}	0.29420592	mH	Stator inductance in *d*-axis
L_{sq}	0.382467696	mH	Stator inductance in *q*-axis
Ke	0.055977	Vpeak/rad/s	Electrical constant
psi (ψ_F)	0.0133994	Ke/N	Magnet flux linkage
J	0.01	kgm^2	Motor inertia

The sensorless control system uses

a. Model Reference Adaptive System (MRAS) method as the observer to estimate the motor speed.
b. The PI controller is used for the current control
c. The constants of the current controller are obtained from the formula in equation 19. The constants of the observer are obtained by trial and error. They are K_{wrp}= 0.01 and K_{wri} = 10. The initial value of i_{sq}^{*} is 7 A and then the final value is 1.86A. The simulation will provide steady-state values that are used as equilibrium values. The equilibrium values are $i_{sd0}, i_{sq0}, i_{sd10}, i_{sq10}, \hat{i}_{sd0}, \hat{i}_{sq0}$, $X_{ewr0}, \omega_{r0}, \theta_0, \hat{\theta}_0, i_{sd0}^{*}, i_{sq0}^{*}, i_{s\alpha0}, i_{s\beta0}, X_{sd0}$ and X_{sq0}.

V. RESULTS AND DISCUSSION

A. System Model and State Space Form

For a linear time-invariant system, the dynamic equations are written as state equations below [16]

$$\frac{d\mathbf{x}(t)}{dt} = \mathbf{Ax}(t) + \mathbf{Bu}(t) \tag{26}$$

The output equation is

$$\mathbf{y}(t) = \mathbf{Cx}(t) + \mathbf{Du}(t) \tag{27}$$

The model is then linearized to obtain the state equation below

$$\Delta\overline{\mathbf{x}} = \mathbf{A_L}\overline{\mathbf{x}} + \mathbf{B_L}\overline{\mathbf{u}} \tag{28}$$

$$\overline{\mathbf{y}} = \mathbf{C}\overline{\mathbf{x}} + \mathbf{D}\overline{\mathbf{u}} \tag{29}$$

The $\mathbf{A_L}$ is a linear matrix A and $\mathbf{B_L}$ is a linear matrix B. The state variables and control inputs of the system in the *α-β* frame are expressed as

$$\overline{\mathbf{x}} = \begin{bmatrix} i_{s\alpha} & i_{s\beta} & \theta_r & \omega_r & i_{sd1} & i_{sq1} & X_{sd} & X_{sq} & X_{ewr} & \hat{\theta}_r & \hat{i}_{sd} & \hat{i}_{sq} \end{bmatrix}^T \tag{30}$$

$$\overline{\mathbf{u}} = \begin{bmatrix} i^*_{sd} & i^*_{sq} & T_L \end{bmatrix}^T \tag{31}$$

$$\overline{\mathbf{y}} = \begin{bmatrix} i_{s\alpha} & i_{s\beta} & \theta_r & \omega_r & i_{sd1} & i_{sq1} & X_{sd} & X_{sq} & X_{ewr} & \hat{\theta}_r & \hat{i}_{sd} & \hat{i}_{sq} & i_{sd} & i_{sq} \end{bmatrix}^T \tag{32}$$

The state variables and control inputs of the system in the *d-q* frame are expressed as

$$\overline{\mathbf{x}} = \begin{bmatrix} i_{sd} & i_{sq} & \hat{i}_{sd} & \hat{i}_{sq} & X_{ewr} & X_{sd} & X_{sq} & i_{sd1} & i_{sq1} & \theta & \hat{\theta} & \omega_r \end{bmatrix}^T \tag{33}$$

$$\overline{\mathbf{u}} = \begin{bmatrix} i^*_{sd} & \omega_r & T_L \end{bmatrix}^T \tag{34}$$

$$\overline{\mathbf{y}} = \begin{bmatrix} i_{sd} & i_{sq} & \hat{i}_{sd} & \hat{i}_{sq} & X_{ewr} & X_{sd} & X_{sq} & i_{sd1} & i_{sq1} & \theta & \hat{\theta} & \omega_r \end{bmatrix}^T \tag{35}$$

B. Equilibrium Values

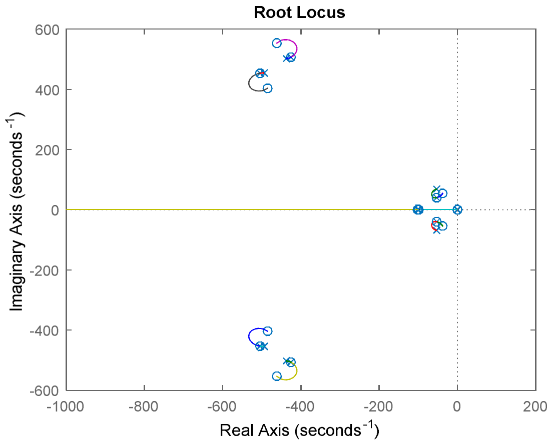
To obtain the equilibrium values, the block diagram of the closed loop sensorless control system is simulated using Simulink. The steady state values of the responses become the equilibrium values of the linear state space form. The equilibrium values are shown in Table II. The value of $i_{s\alpha 0}$ and $i_{s\beta 0}$ are calculated as equation (1). The values of θ and $\hat{\theta}$ are the same.

TABLE II. EQUILIBRIUM VALUES

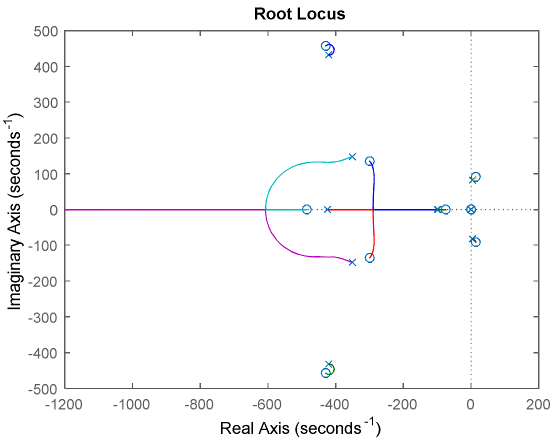
Parameters	Quantities	unit
$i_{sd0} = i_{sd10} = \hat{i}_{sd0} = i^*_{sd0} = i_{s\alpha 0}$	0	A
$i_{sq0} = i_{sq10} = \hat{i}_{sq0} = i^*_{sq0} = i_{s\beta 0}$	1.865	A
X_{ewr0}	10	
ω_{r0}	100	rad/s
X_{sd0}	-0.001	
X_{sq0}	0.0177	

C. Stability Analysis

The root locus diagram (Fig. 9) is drawn to evaluate the stability of the system. Fig. 9a shows the root locus of the system that is analyzed without taking the frame transformation into account. The system is modeled in the *d-q* frame. It can be seen that the system is stable because all poles are negative. Fig. 9b shows the root locus of the system that is analyzed by taking the frame transformation into account. The system is modeled in the *α-β* frame with the value of θ and $\hat{\theta}$ is the same, i.e. 0 degrees. It appears that although root locus in the *d-q* frame is stable, the root locus in the *α-β* frame is changing. It can be seen that the system has some positive poles at position 0 degrees. It means that the system is unstable. So there is a stability problem in changing the model from the *α-β* frame into the *d-q* frame.



a. *d-q* frame



b. *α-β* frame with $\theta = 0^0$

Fig. 9. The root locus of the system

As stated in the method, the system is analyzed with the variation value of $\Delta\theta$ from -180^0 – 180^0 (Fig. 10). The value of $\Delta\theta$=-180^0 is drawn in light blue, and the value of $\Delta\theta$=0^0 is drawn in yellow. Although the system has 12 poles, Fig. 10 just shows pole position changes of the ten poles at $\theta = 0^0$. The other two poles have no position changing so the poles aren't drawn here.

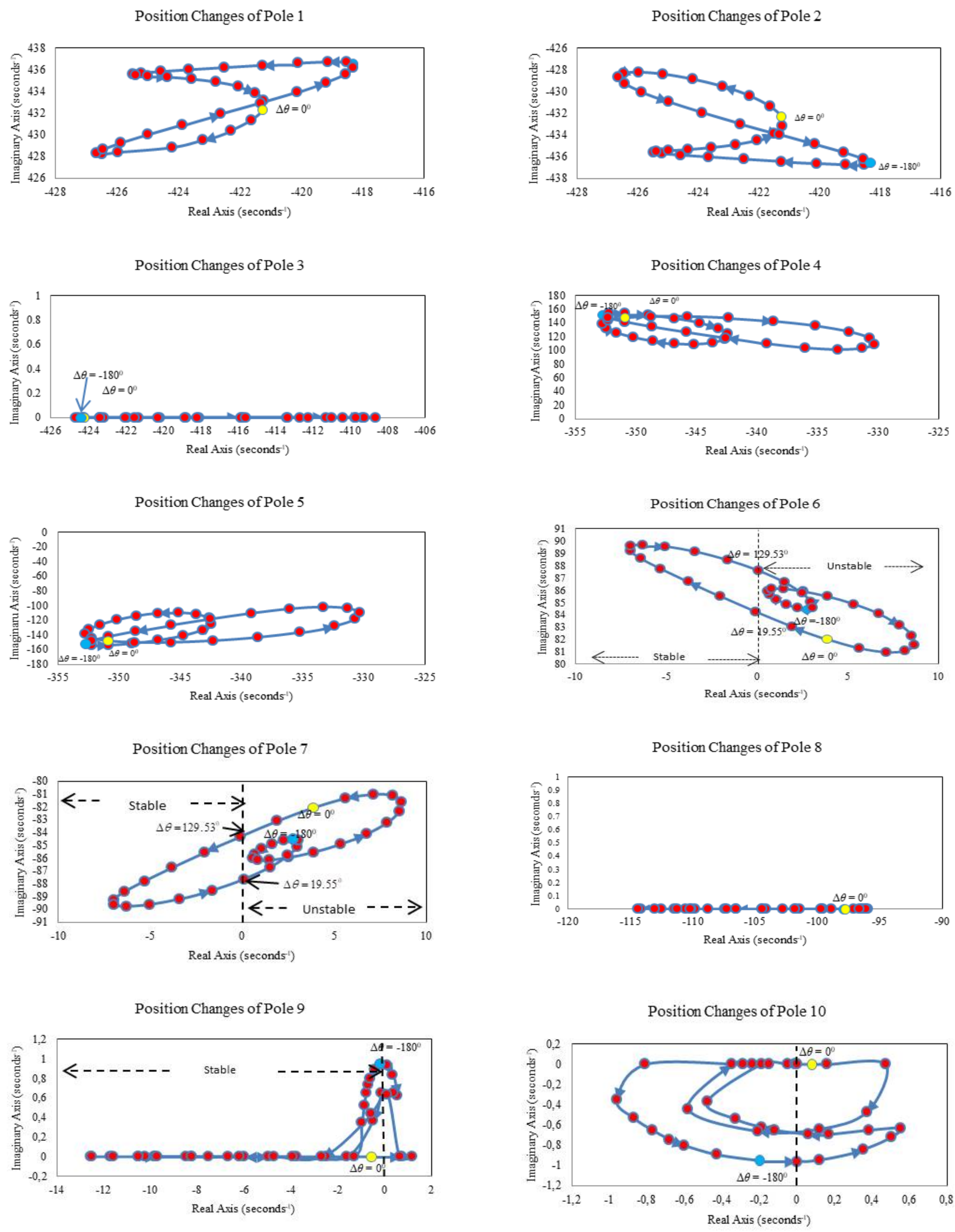


Fig. 10. The pole position changes of the system in the *α-β* frame with $\theta \neq \hat{\theta}$

Fig. 10 shows the system has four poles that the position of poles can be negative or positive depending on the value of $\Delta\theta$. They are pole 6, 7, 9 and 10. It means that the problem also occurs when the estimated position value ($\hat{\theta}$) differs from the actual position (θ). It can be seen in the pictures, the difference in value can cause changes in system stability. Poles 6, 7 and 10 with $\Delta\theta = 0$ are located at the right of the imaginary axis. Pole 9 with $\Delta\theta = 0$ is located at the left of the imaginary axis, but with the change of the $\Delta\theta$, the location of the pole can be to the right of the imaginary axis. This means the system is unstable.

Fig. 11 shows the stability boundaries. The system is stable for $41.81^0 < \Delta\theta < 129.53^0$. Fig. 12 shows the responses of i_{sd} and i_{sq} at $\Delta\theta = 50^0$ (stable) and $\Delta\theta = 10^0$ (unstable). The current responses the two reference inputs, i.e. i_{sd}^* and i_{sq}^*.

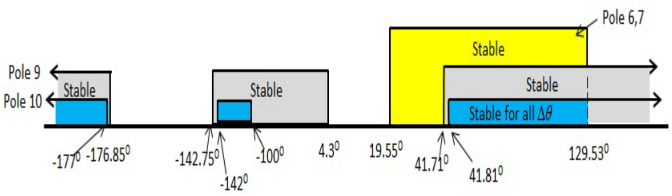
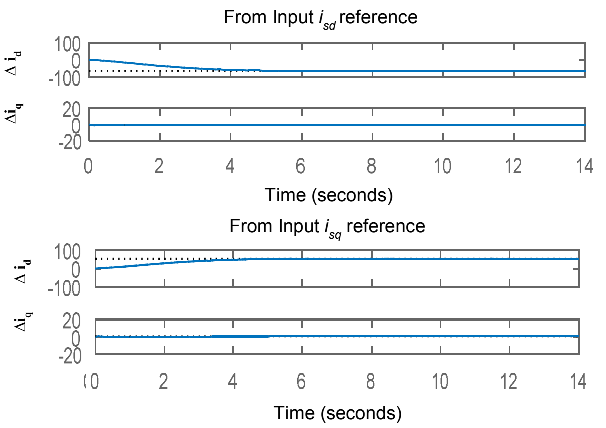
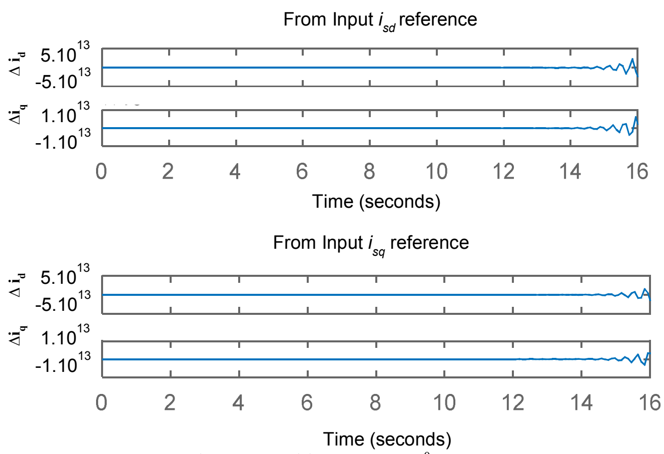


Fig. 11. System stability boundaries



a. Stable at $\Delta\theta = 50^0$



b. Unstable at $\Delta\theta = 10^0$

Fig. 12. The current responses of the system

VI. Conclusion

When analyzing without taking the frame transformation into account, it is proved that the sensorless control system of PMSM is stable, but when analyzing with taking the frame transformation into account, the system can be unstable. The estimation error because of the transformation can also cause the stability problems. It is proved that the system can be unstable when the estimated position value differs from the actual position. It means that the speed sensorless in rotor flux oriented using MRAS as an observer is unstable. This issue is very important to be solved.

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