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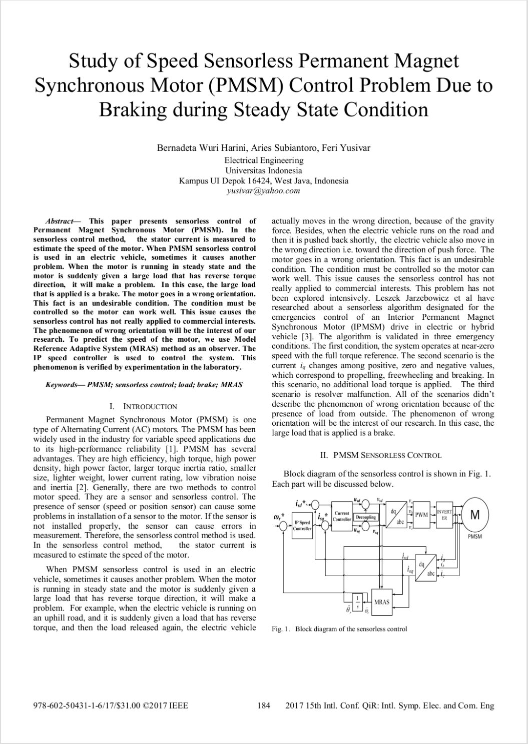

Study of Speed Sensorless Permanent Magnet Synchronous Motor (PMSM) Control Problem Due to Braking during Steady State Condition

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***Abstract*— This paper presents sensorless control of Permanent Magnet Synchronous Motor (PMSM). In the sensorless control method, the stator current is measured to estimate the speed of the motor. When PMSM sensorless control is used in an electric vehicle, sometimes it causes another problem. When the motor is running in steady state and the motor is suddenly given a large load that has reverse torque direction, it will make a problem. In this case, the large load that is applied is a brake. The motor goes in a wrong orientation. This fact is an undesirable condition. The condition must be controlled so the motor can work well. This issue causes the sensorless control has not really applied to commercial interests. The phenomenon of wrong orientation will be the interest of our research. To predict the speed of the motor, we use Model Reference Adaptive System (MRAS) method as an observer. The IP speed controller is used to control the system. This phenomenon is verified by experimentation in the laboratory.**

***Keywords*— PMSM; sensorless control; load; brake; MRAS**

I. INTRODUCTION

Permanent Magnet Synchronous Motor (PMSM) is one type of Alternating Current (AC) motors. The PMSM has been widely used in the industry for variable speed applications due to its high-performance reliability [1]. PMSM has several advantages. They are high efficiency, high torque, high power density, high power factor, larger torque inertia ratio, smaller size, lighter weight, lower current rating, low vibration noise and inertia [2]. Generally, there are two methods to control motor speed. They are a sensor and sensorless control. The presence of sensor (speed or position sensor) can cause some problems in installation of a sensor to the motor. If the sensor is not installed properly, the sensor can cause errors in measurement. Therefore, the sensorless control method is used. In the sensorless control method, the stator current is measured to estimate the speed of the motor.

When PMSM sensorless control is used in an electric vehicle, sometimes it causes another problem. When the motor is running in steady state and the motor is suddenly given a large load that has reverse torque direction, it will make a problem. For example, when the electric vehicle is running on an uphill road, and it is suddenly given a load that has reverse torque, and then the load released again, the electric vehicle actually moves in the wrong direction, because of the gravity force. Besides, when the electric vehicle runs on the road and then it is pushed back shortly, the electric vehicle also move in the wrong direction i.e. toward the direction of push force. The motor goes in a wrong orientation. This fact is an undesirable condition. The condition must be controlled so the motor can work well. This issue causes the sensorless control has not really applied to commercial interests. This problem has not been explored intensively. Leszek Jarzebowicz et al have researched about a sensorless algorithm designated for the emergencies control of an Interior Permanent Magnet Synchronous Motor (IPMSM) drive in electric or hybrid vehicle [3]. The algorithm is validated in three emergency conditions. The first condition, the system operates at near-zero speed with the full torque reference. The second scenario is the current i_q changes among positive, zero and negative values, which correspond to propelling, freewheeling and breaking. In this scenario, no additional load torque is applied. The third scenario is resolver malfunction. All of the scenarios didn't describe the phenomenon of wrong orientation because of the presence of load from outside. The phenomenon of wrong orientation will be the interest of our research. In this case, the large load that is applied is a brake.

II. PMSM SENSORLESS CONTROL

Block diagram of the sensorless control is shown in Fig. 1. Each part will be discussed below.

Fig. 1. Block diagram of the sensorless control

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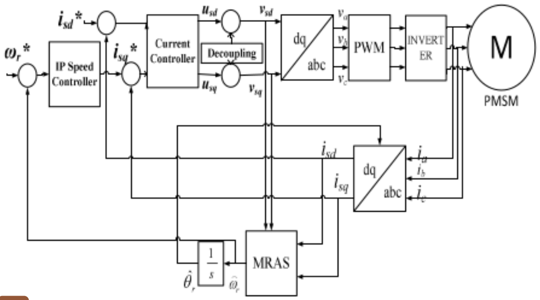

Fig. 1. Block diagram of the sensorless control

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A. PMSM Model

The three-phase mathematical model of PMSM will be changed into a two-phase mathematical model using Clarke and Park transformations [1]. The Clarke transformation converts the balanced three-phase quantities ($V_{sa, sb, sc}$) into two-phase stationary reference frame ($\alpha,\beta,0$) using (1):

$$\begin{bmatrix} v_{s\alpha} \\ v_{s\beta} \\ v_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} v_{sa} \\ v_{sb} \\ v_{sc} \end{bmatrix} \tag{1}$$

where $V_{s\alpha}$ and $V_{s\beta}$ are the stator voltage in α,β reference frame.

The Park transformation converts from stationary reference frame into a rotating reference (d, q, 0) frame using (2).

$$\begin{bmatrix} v_{sd} \\ v_{sq} \end{bmatrix} = \begin{bmatrix} \cos\theta_e & \sin\theta_e \\ -\sin\theta_e & \cos\theta_e \end{bmatrix} \begin{bmatrix} v_{s\alpha} \\ v_{s\beta} \end{bmatrix} \tag{2}$$

where θ_e is the electric angle of the motor, while V_{sd} and V_{sq} are the stator voltage in d-q reference frame.

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The PMSM mathematical model in d-q frame [4] is

$$\begin{bmatrix} v_{sd} \\ v_{sq} \end{bmatrix} = \begin{bmatrix} R_s + pL_s & -N\omega_r L_s \\ N\omega_r L_s & R_s + pL_s \end{bmatrix} \begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} + \begin{bmatrix} 0 \\ N\omega_r \psi_F \end{bmatrix} \tag{3}$$

where p is d/dt, i_{sd} is the stator current in d-axis, i_{sq} is the stator current in q-axis, 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 electric torque of PMSM is

$$t_e = \{\psi_F i_{sq} + (L_{sd} - L_{sq}) i_{sd} i_{sq}\} \tag{4}$$

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 [5] is

$$\frac{d\theta_e}{dt} = N\omega_r \tag{5}$$

where

$$\frac{d\omega_r}{dt} = \frac{t_e - t_L}{J} \tag{6}$$

where t_L is the load torque and J is the inertia of the motor.

B. Decoupling

On electric models of PMSM motors, there is a relationship between d and q-axis components (cross coupling) on the part which is not linear between ω and i. PI controller can only control linear equations. It is necessary to decouple them so the motor can be seen as a linear system by controllers. The block diagram of decoupling is shown in Fig.2.

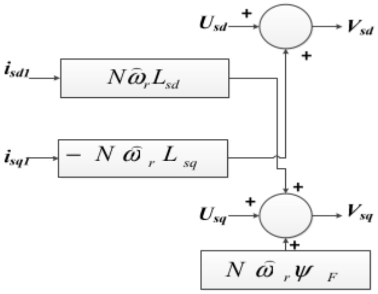


Fig. 2. Block diagram of decoupling

The decoupling equations [6] are

$$V_{sd} = U_{sd} - N\hat{\omega}_r L_{sq} i_{sq1} \tag{7}$$

$$V_{sq} = U_{sq} + N\hat{\omega}_r L_{sd} i_{sd1} + N\hat{\omega}_r \psi_F \tag{8}$$

where

$$\frac{d}{dt} i_{sd1} = \frac{1}{T_d} i_{sd}^* - \frac{1}{T_d} i_{sd1} \tag{9}$$

$$\frac{d}{dt} i_{sq1} = \frac{1}{T_d} i_{sq}^* - \frac{1}{T_d} i_{sq1} \tag{10}$$

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

C. Current Controller

In an AC machine, both the phase angle and the modulus of the current has to be controlled, on other words, the current vector has to be controlled [4]. With vector control of AC machines, the torque and flux producing current components are independently controlled by controlling the stator current in d-q reference frame using Proportional Integrator. The current controller equations [6] are

$$u_{sd} = \left(K_{pd} + K_{id}\int dt\right)\left(i_{sd}^* - i_{sd}\right) \tag{11}$$

$$u_{sq} = \left(K_{pq} + K_{iq}\int dt\right)\left(i_{sq}^* - i_{sq}\right) \tag{12}$$

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

D. Speed Controller

The output current motors (i_{sq}^*) in (12) is controlled by the Integral Proportional (IP) speed controller. The equation of IP speed controller [7] is

$$i_{sq}^* = \int K_i\left(\omega_r^* - \omega_r\right)dt - K_p\omega_r \qquad (13)$$

where K_p and K_i are the speed controller gain.

E. Model Reference Adaptive System (MRAS)

MRAS is one of observer type that is commonly used to estimate the speed of the rotor. Block diagram of MRAS is shown in Fig. 3.

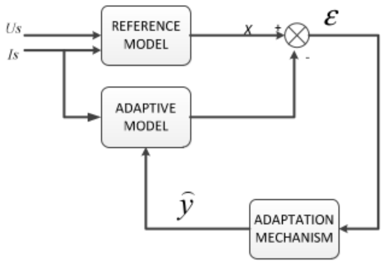


Fig. 3. Block diagram of MRAS [8]

MRAS will compare the output of reference models and adaptive models. The error between the two models is used in adaptive mechanism to estimate a variable ($\hat{y}$). The reference model uses the actual system, which means PMSM motors, while the adaptive model uses the output of the observer that is used to estimate the stator currents. Adaptive speed estimation mechanism uses (14) – (16) :

$$e_{wr} = i_{sd}\hat{i}_{sq} - i_{sq}\hat{i}_{sd} - \frac{\psi_F}{L_{sq}}\left(i_{sq} - \hat{i}_{sq}\right) \qquad (14)$$

$$X_{ewr} = \int_0^t e_{wr}\, dt \qquad (15)$$

$$\hat{\omega}_r = K_{wrp}\, e_{wr} + K_{wri}\, X_{ewr} \qquad (16)$$

where $\hat{i}_{sd}$ and $\hat{i}_{sq}$ are the current estimate in *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.

III. METHODS

This research uses PMSM that has parameters are shown in Table I. To predict the motor speed, we use Model Reference Adaptive System (MRAS) method as the observer. The IP controller is used to control the motor speed.

The method used in this research is shown in Fig. 4. Before controlling the motor, first, the PMSM is tested to obtain the motor parameters. Table I shows the PMSM parameters that are used in this research. The next step is building the algorithm of sensorless control using C-MEX Simulink as is shown in Fig. 1. Motor parameters obtained previously is then inserted into the algorithm. Before being used for an experiment in the laboratory, these algorithm is simulated using C-MEX Simulink. The constants of the observer, speed controller, and current controller are shown in Table II. The motor testing in the laboratory used Digital Control System Myway PE-Expert4. Fig. 5 shows the system installation. Furthermore, data retrieval is done on the real PMSM.

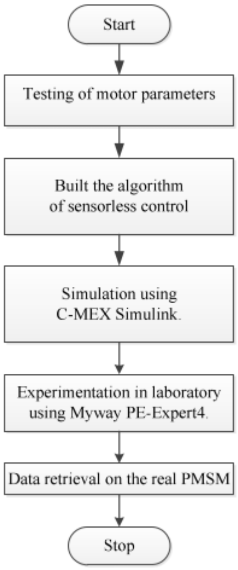


Fig. 4. Research method

TABLE I. PMSM PARAMETERS

Parameters	Quantities	Unit
Td	0.01	second
dt	0.0001	second
N	4	
R_s	0.14710296	Ω
L_{sd}	0.29420592	mH
L_{sq}	0.382467696	mH
Ke	0.055977	Vpeak/rad/s
psi (ψ_F)	0.0133994	Ke/N
J	0.01	kgm^2

The methods of data retrieval are:

- The speed of the motor is set to certain speed
- Motor runs until stable (steady-state condition)
- Reverse torque load (brake) is applied to the motor at steady-state. When the motor rotates in constant (steady-state), a brake is applied to the rotation of the motor. There are two scenarios. First, the motor rotation will stop, but the estimation process continues to run.

Second, the brake is applied to the motor at a moment and then the brake is released again so that the motor does not stop running.

- In these conditions, the values of i_{sd}, i_{sq}, $\hat{i}_{sd}$, $\hat{i}_{sq}$, $\hat{\omega}_r$, and t_e are taken every 1 ms.
- All of the data will be analyzed.

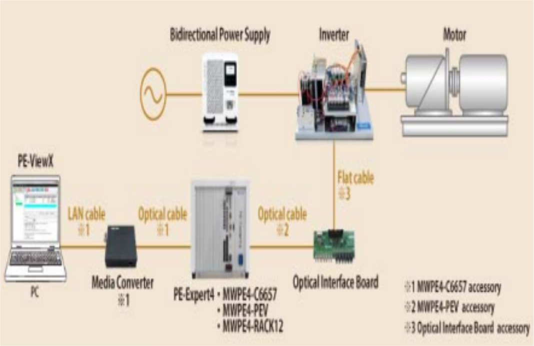


Fig. 5. System installation

TABLE II. THE CONSTANTS

Functions	Constants	Values
Current Controller	K_{pd}	29.42059198
	K_{id}	14.71029599
	K_{pq}	38.24676957
	K_{iq}	14.71029599
Speed Controller	K_p	0.2125
	K_i	0.9
Observer	K_{wrp}	0.01
	K_{wri}	0.1

IV. RESULTS AND DISCUSSION

The result of the experimentation is shown in Fig. 6 - Fig. 8 below. The variables that are shown in Fig. 6 and Fig. 7 are I_d (i_{sd}), I_{dest} ($\hat{i}_{sd}$), I_q (i_{sq}), I_{qest} ($\hat{i}_{sq}$), W_{rest} ($\hat{\omega}_r$), and T_e (t_e). The variables that are shown in Fig. 8 are I_d (i_{sd}), I_{dest} ($\hat{i}_{sd}$), I_q (i_{sq}), and I_{qest} ($\hat{i}_{sq}$). Both scenarios, the reference speed of the motor are set to 90 rpm.

As described in methods above, there are two scenarios that are used in the experiment. The first scenario is shown in Fig. 6. When the motor rotation has been stabilized (gray background color), the same as the set point (90 rpm), the motor rotation detained from outside by a brake so that the motor does not rotate (yellow background color). Despite the fact that the motor does not rotate, but the estimated value of the speed motor (W_{rest}) appears to be incorrect, as shown in Fig. 6a. When the motor rotation detained, the estimated value of the speed dropped to 51.88 rpm and then stabilized at 66 rpm. The estimated values indicate that the motor still rotates at a speed of 66 rpm, although actually, the motor stops running.

The conditions of detained motor rotation also affect the value of I_d and I_{dest} as is shown in Fig. 6b. The value of I_d slightly increased (overshoot) while the value of I_{dest} falls below 0. When the motor is operating at the steady-state condition, the value of I_q and I_{qest} are 0 (Fig. 6c). When motor rotation detained, the value of I_{qest} dropped to -12.8 A then rises to above 4 A. Value I_q stabilized at around 4.5 A. This indicates that the value of stability I_q and I_{qest} has changed from 0 A to more than 4 A.

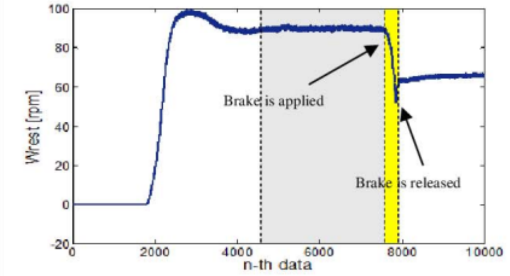
As the condition of the current and the estimated speed are changing, a large motor rotation disturbance from outside also affect the value of the electrical torque (T_e), as is shown in Fig. 6d. The value of T_e at the steady-state condition is 0 then increased to about 0.3 Nm.

The second scenario is shown in Fig. 7. When the motor rotation has been stabilized at 90 rpm speed rotation (gray background color), the brake is applied to the motor at a moment (yellow background color). Then, the brake is released again so that the motor does not stop running (white background color). Although there are some oscillations, the motor speed returns to its set point value (Fig. 7a). Likewise with the value of I_{dest}, I_{qest} and T_e, although oscillation occurs, the values of these variables return to their original values (Fig. 7b,7c,7d).

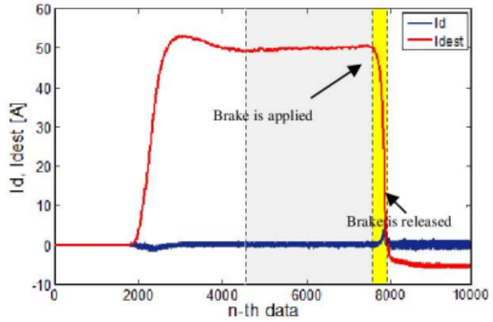
To clarify the trajectory of i_d and i_q, it is necessary to draw the locii of i_d versus i_q. With this locii, it will be known whether or not there is a difference between normal and abnormal conditions. Fig. 8 shows the response of I_d vs I_q and I_{dest} vs I_{qest} in the normal and abnormal condition. The normal condition is related to second scenario (Fig. 7), while the abnormal condition is related to first scenario (Fig. 6). Both figures are taken from the response when the brake is applied until the end.

Under normal condition (Fig. 8a), the endpoint will return to the starting point position, whereas in the abnormal condition (Fig. 8b) the endpoint does not return to the starting point position. This happens mainly on the locii of i_{dest} versus i_{qest}, whereas the initial and final positions for the locii of i_d versus i_q are almost identical. Fig. 8b shows that the operating point of the estimation value has changed from the point of initial work. The figure shows that there are more than one equilibrium points. In the future, these conditions should be prevented. Sensorless motor control is not allowed to work in the area of the abnormal equilibrium point. This issue is a huge problem for controlling the motor with the sensorless control method. If the estimate of the motor is wrong, it will cause the motor does not operate at the desired value. Of course, this condition will affect the performance of PMSM motors that are controlled by the sensorless control method.

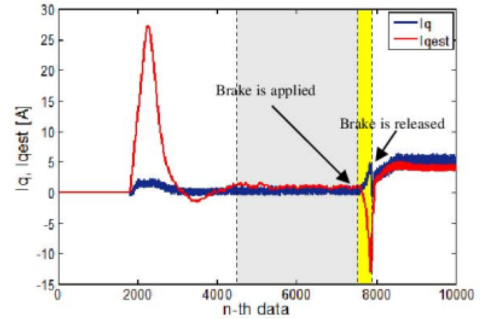
From the explanation above, the disturbance from a large reverse load torque at steady state is a really disturbing condition motor performance. The disturbance not only affects the value of current and speed, even it produces two equilibrium points. This condition can occur on the motor in general where if the motor is given a large torque so that the motor rotation stopped, the motor rotation can not return to the original speed. Therefore, this condition must be controlled so that the motor can operate normally.



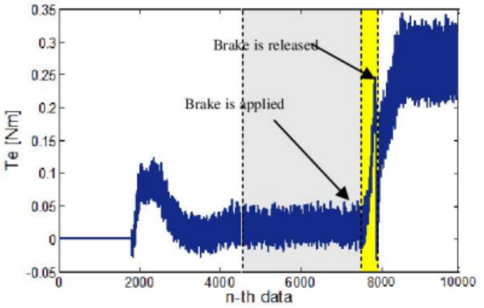
a. Response of ω_{rest}



b. Response of I_d, I_{dest}

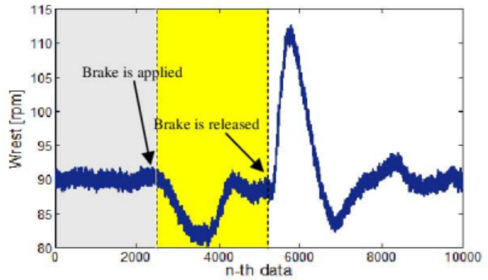


c. Response of I_q, I_{qest}

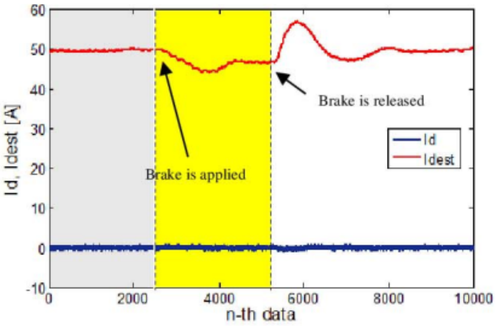


d. Response of T_e

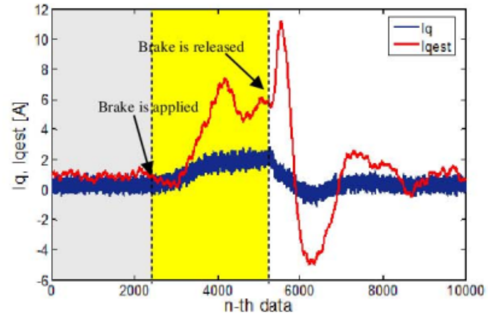
Fig. 6. Response of PMSM with Set Point (SP) = 90 RPM in abnormal condition



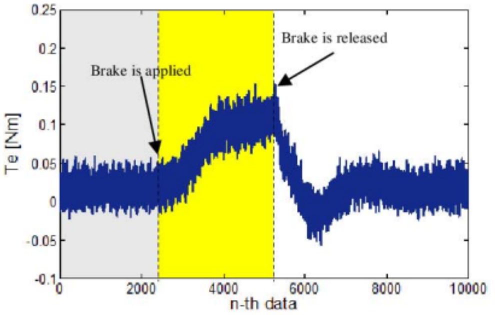
a. Response of ω_{rest}



b. Response of I_d, I_{dest}

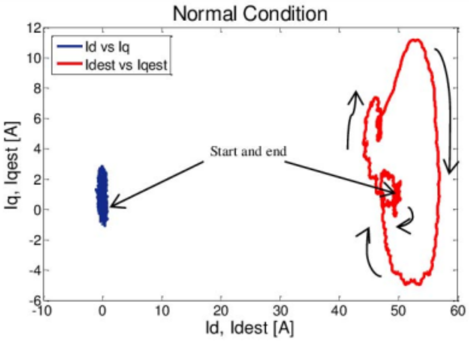


c. Response of I_q, I_{qest}

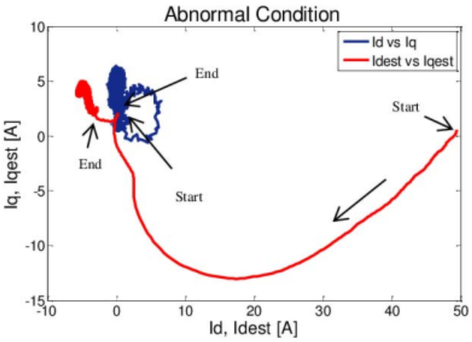


d. Response of T_e

Fig. 7. Response of PMSM with Set Point (SP) = 90 RPM in normal condition



a. Response of I_d vs I_q and I_{dest} vs I_{qest} in normal condition



b. Response of I_d vs I_q and I_{dest} vs I_{qest} in abnormal condition

Fig. 8. Locii of I_d I_q

V. CONCLUSION

Load torque reverse disturbance at steady state changes the operating point of the motor so greatly disturb the performance of the motor. Therefore, in future studies, this disturbance will be controlled so that the motor can operate normally and the performance of PMSM sensorless control increases. Sensorless motor control is not allowed to work in the area of the abnormal equilibrium point.

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