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Stability analysis of MRAS speed sensorless control of permanent magnet synchronous motor (Conference Paper)

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Abstract

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This paper presents stability analysis of Permanent Magnet Synchronous Motor (PMSM) sensorless control . In the sensorless control method, the stator current is measured to estimate the speed of the motor . To estimate the speed of the motor , we use Model Reference Adaptive System (MRAS) method as an observer. The Integral Proportional (IP) speed controller is used to control the system. The nonlinear system is linearized and expressed in state space form. To determine the stability of the system, it is necessary to find the eigenvalues of the matrix. The stability of the system is also analyzed using Bode stability criterion and Root Locus. © 2017 IEEE.

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Stability Analysis of MRAS Speed Sensorless Control of Permanent Magnet Synchronous Motor

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***Abstract*—This paper presents stability analysis of Permanent Magnet Synchronous Motor (PMSM) sensorless control. In the sensorless control method, the stator current is measured to estimate the speed of the motor. To estimate the speed of the motor, we use Model Reference Adaptive System (MRAS) method as an observer. The Integral Proportional (IP) speed controller is used to control the system. The nonlinear system is linearized and expressed in state space form. To determine the stability of the system, it is necessary to find the eigenvalues of the matrix. The stability of the system is also analyzed using Bode stability criterion and Root Locus.**

Keywords—PMSM; sensorless control; MRAS; state space, stability; eigenvalues; Bode; Root Locus

I. Introduction

In an effort to realize green technology, today, many electrically driven vehicles are developed. Compared to vehicles with power from petroleum, electric-powered vehicles have many advantages. Some of the advantages of electric cars are emission-free electric cars, resulting in no impact on the environment, energy saving, no noise pollution, and lower maintenance costs compared to conventional fuel cars [1].

One of the important parts in electrically driven vehicles is electric motors. Generally, electric motors consist of Direct Current (DC) and Alternating Current (AC) motors. The drawback of DC motor is that DC motor requires periodic maintenance, it cannot be used in corrosive environments and it cannot be used for high-speed [2]. This problem can be overcome by the application of an alternating current motor, which has a simple structure, high maintenance and economical, and is strong and resistant to heavy loads.

One type of AC motor is Permanent Magnet Synchronous Motor (PMSM). PMSM motor is a 3 phase synchronous motor with permanent magnet rotor surrounded by stator in the form of the coil. PMSM motor is widely used because it has high efficiency, torque, power, and power factor, and smaller size and lightweight. In addition, the PMSM has a lower current rate, as well as a lower noise and inertia of vibration [3]. If the DC motor torque can be adjusted by controlling the motor current, this is not the case with the AC motor. In AC motors, both the phase angle and the current modulator (which means the current vector) must be controlled [2]. Therefore vector control is required. By using vector control, the torque and flux that produce the current are decoupled so that it can be controlled separately.

In the conventional method, to control the motor speed required speed sensor mounted on the motor. The addition of the sensor will increase the cost and will cause problems when installing the sensor. Currently, some uncensored control methods are developed, both position sensors and speed sensors. This method is called sensorless control. To estimate the value of speed, an observer is used. There are several types of observers. One of them is Model Reference Adaptive System (MRAS).

The objective of this research is to analyze the stability of sensorless control on PMSM. The sensorless control system that will be analyzed uses MRAS as the observer, Proportional Integral (PI) as current controller and Integral Proportional (IP) as the speed controller. The nonlinear system is linearized and expressed in state space form. To determine the stability of the system, it is necessary to find the eigenvalues of the matrix. The stability of the system is also analyzed using Bode stability criterion and Root Locus. Hamada, D. et al [4] had analyzed the stability of sensorless PMSM with a Reduced Order Observer. Other researchers who analyzed sensorless control system of PMSM were 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 [5] and kim, H. et al with a paper of A High-Speed Sliding-Mode Observer for the Sensorless Speed Control of a PMSM [6].

II. PMSM Model

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

$$\begin{bmatrix} v_{sd} \\ v_{sq} \end{bmatrix} = \begin{bmatrix} R_s + pL_s & -N\omega_r L_s \\ N\omega_r L_s & R_s + pL_s \end{bmatrix} \begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} + \begin{bmatrix} 0 \\ N\omega_r \psi_F \end{bmatrix} \tag{1}$$

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 equation (1) can be stated as

$$\frac{d}{dt}i_{sd} = \frac{V_{sd} - R_s i_{sd} + N\omega_r L_{sq} i_{sq}}{L_{sd}} \quad (2)$$

$$\frac{d}{dt}i_{sq} = \frac{V_{sq} - i_{sd} N\omega_r L_{sd} - R_s i_{sq} - N\omega_r \psi_F}{L_{sq}} \quad (3)$$

The electric torque of PMSM is

$$T_e = \{\psi_F i_{sq} + (L_{sd} - L_{sq}) i_{sd} i_{sq}\} \quad (4)$$

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 [7] is

$$\frac{d\theta_e}{dt} = N\omega_r \quad (5)$$

where

$$\frac{d\omega_r}{dt} = \frac{T_e - T_L}{J} \quad (6)$$

where T_L is the load torque and J is the inertia of the motor. If equation (4) is substituted into equation (6), the equation (6) becomes

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

III. SENSORLESS CONTROL

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

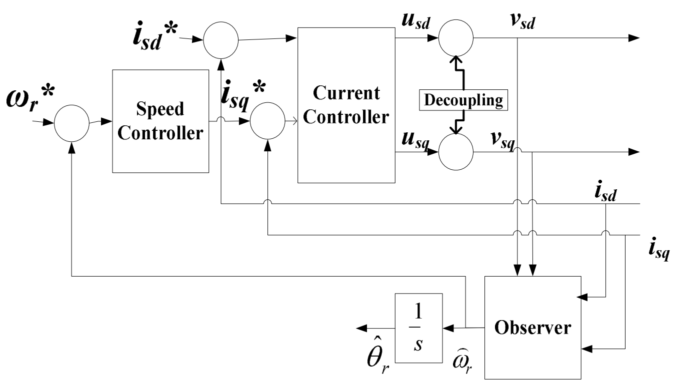

Fig. 1. Block diagram of the sensorless control.

A. Decoupling

Decoupling part is used to decouple cross-coupling between d and q-axis components (ω and i) which is not linear. This decoupling is necessary because the PI controller can only control linear equations. The decoupling equations [8] are

$$V_{sd} = U_{sd} - N\hat{\omega}_r L_{sq} i_{sq1} \quad (8)$$

$$V_{sq} = U_{sq} + N\hat{\omega}_r L_{sd} i_{sd1} + N\hat{\omega}_r \psi_F \quad (9)$$

where

$$\frac{d}{dt}i_{sd1} = \frac{1}{T_d} i_{sd}^* - \frac{1}{T_d} i_{sd1} \quad (10)$$

$$\frac{d}{dt}i_{sq1} = \frac{1}{T_d} i_{sq}^* - \frac{1}{T_d} i_{sq1} \quad (11)$$

$$\frac{d}{dt}X_{sd} = i_{sd}^* - i_{sd} \quad (12)$$

$$\frac{d}{dt}X_{sq} = i_{sq}^* - i_{sq} \quad (13)$$

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. The current controller equations [8] are

$$u_{sd} = \left(K_{pd} + K_{id}\int dt\right)\left(i_{sd}^* - i_{sd}\right) \quad (14)$$

$$u_{sq} = \left(K_{pq} + K_{iq}\int dt\right)\left(i_{sq}^* - i_{sq}\right) \quad (15)$$

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

$$K_{pd} = \frac{L_{sd}}{T_d} \qquad K_{id} = \frac{R_s}{T_d} \qquad K_{pq} = \frac{L_{sq}}{T_d} \qquad K_{iq} = \frac{R_s}{T_d} \quad (16)$$

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C. Speed Controller

The equation of IP speed controller [9] is

$$\begin{aligned} i_{sq}^{*} &= \int K_i\left(\omega_r^{*} - \hat{\omega}_r\right)dt - K_p\hat{\omega}_r \\ &= K_i X_{wr} - K_p\hat{\omega}_r \end{aligned} \tag{17}$$

where

$$\frac{d}{dt}X_{wr} = \left(\omega_r^{*} - \hat{\omega}_r\right) \tag{18}$$

where K_p and K_i are the speed controller gain.

D. 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) :

$$e_{wr} = \frac{L_{sq}}{L_{sd}} i_{sd}\hat{i}_{sq} - \frac{L_{sd}}{L_{sq}} i_{sq}\hat{i}_{sd} - \frac{\psi_F}{L_{sq}}\left(i_{sq} - \hat{i}_{sq}\right) + \hat{i}_{sd}\hat{i}_{sq}\left(\frac{L_{sd}}{L_{sq}} - \frac{L_{sq}}{L_{sd}}\right) \tag{19}$$

$$X_{ewr} = \int_0^t e_{wr}\, dt \quad \text{ορ} \quad \frac{d}{dt}X_{ewr} = e_{wr} \tag{20}$$

$$\begin{aligned} \hat{\omega}_r &= K_{wrp} e_{wr} + K_{wri} X_{ewr} \\ &= K_{wrp}\frac{L_{sq}}{L_{sd}} i_{sd}\hat{i}_{sq} - K_{wrp}\frac{L_{sd}}{L_{sq}} i_{sq}\hat{i}_{sd} - K_{wrp}\frac{\psi_F}{L_{sq}} i_{sq} + K_{wrp}\frac{\psi_F}{L_{sq}}\hat{i}_{sq} + K_{wrp}\left(\frac{L_{sd}}{L_{sq}} - \frac{L_{sq}}{L_{sd}}\right)\hat{i}_{sd}\hat{i}_{sq} + K_{wri}X_{ewr} \end{aligned} \tag{21}$$

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

$$\frac{d}{dt}\hat{i}_{sd} = -\frac{R_s}{L_{sd}}\hat{i}_{sd} + \hat{\omega}_r\frac{L_{sq}}{L_{sd}}\hat{i}_{sq} + \frac{U_{sd}}{L_{sd}} \tag{22}$$

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

$$\frac{d\hat{\theta}}{dt} = N\hat{\omega}_r \tag{24}$$

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. Fig. 2 shows the sensorless control system of PMSM that is simulated using Simulink.

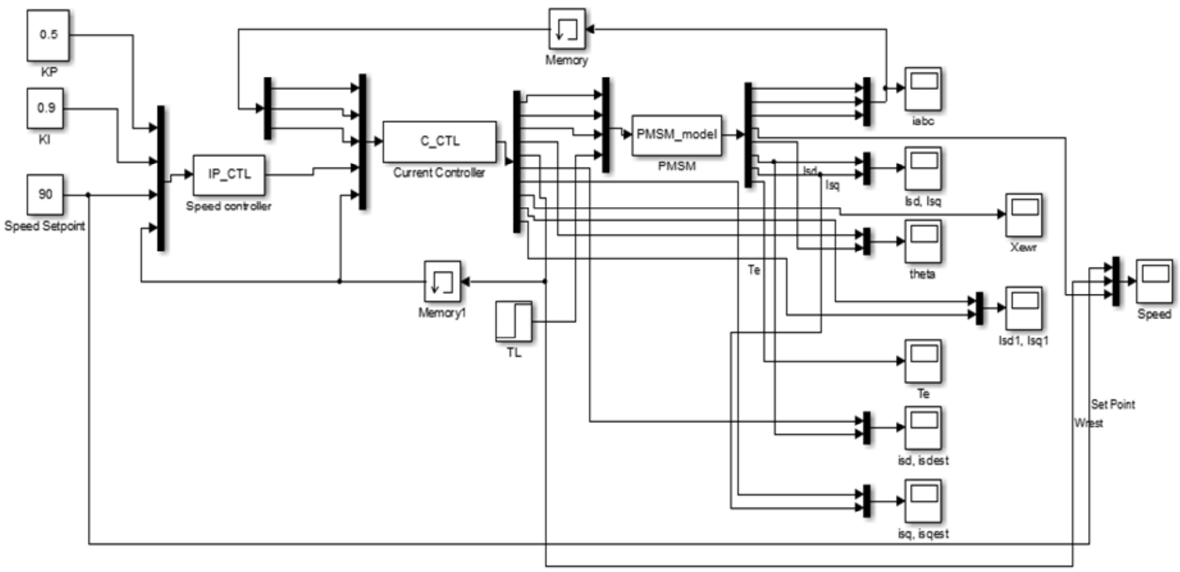

Fig. 2. The Simulink of PMSM sensorless control.

TABLE II. THE CONSTANTS

Functions	Constants	Values
Speed Controler	K_p	0.2125
	K_i	0.9
Observer	K_{wrp}	0.01
	K_{wri}	0.1

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 IP controller is used to control the motor speed.

The constants of the current controller are obtained from the formula in equation 13. The constants of the speed controller and observer that are shown in Table II are obtained by trial and error. The speed is set to 90 RPM. The simulation will provide steady-state values that are used as equilibrium values. They are i_{sd0}, i_{sq0}, i_{sd10}, i_{sq10}, $\hat{i}_{sd0}$, $\hat{i}_{sq0}$, X_{ewr0}, and ω_{r0}.

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 [10]

$$\frac{d\mathbf{x}(t)}{dt} = \mathbf{Ax}(t) + \mathbf{Bu}(t) \tag{25}$$

The output equation is

$$\mathbf{y}(t) = \mathbf{Cx}(t) + \mathbf{Du}(t) \tag{26}$$

The mathematical model that is shown in Fig. 2 can be seen in the Appendix. The model is then linearized to obtain the state equation below

$$\Delta\bar{\mathbf{x}} = \mathbf{A_L}\bar{\mathbf{x}} + \mathbf{B_L}\bar{\mathbf{u}} \tag{27}$$

$$\bar{\mathbf{y}} = \mathbf{C}\bar{\mathbf{x}} + \mathbf{D}\bar{\mathbf{u}} \tag{28}$$

The $\mathbf{A_L}$ is a linear matrix A and $\mathbf{B_L}$ is a linear matrix B. The state variables and control inputs are expressed as

$$\bar{\mathbf{x}} = [i_{sd} \quad i_{sq} \quad \hat{i}_{sd} \quad \hat{i}_{sq} \quad X_{ewr} \quad X_{sd} \quad X_{sq} \quad i_{sd1} \quad i_{sq1} \quad X_{wr} \quad \theta \quad \hat{\theta} \quad \omega_r]^T \tag{29}$$

$$\bar{\mathbf{u}} = [i_{sd} \quad \omega_r \quad T_L]^T \tag{30}$$

B. Equilibrium Values

To obtain the equilibrium values, the block diagram shown in Fig. 2 is simulated using Simulink. The responses of the simulation are shown in Fig. 3 – 7. The steady state values of the responses become the equilibrium values of the linear state space form. The equilibrium values are shown in Table III.

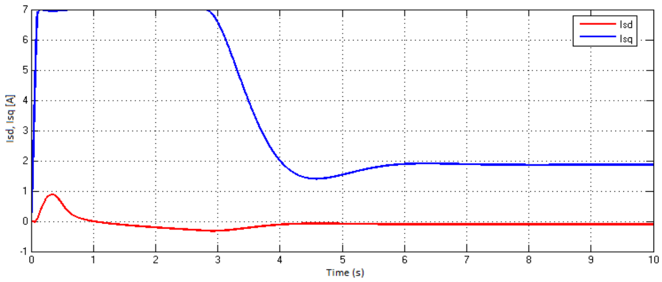

Fig. 3. The response of i_{sd} and i_{sq}.

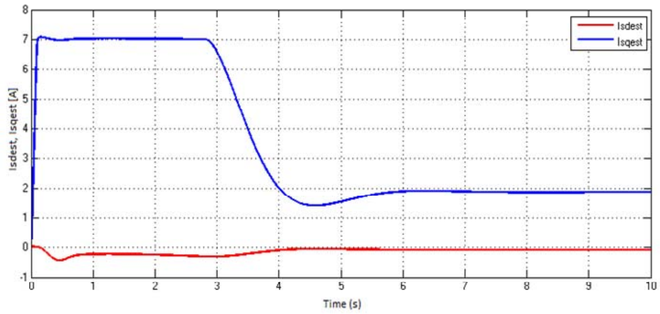

Fig. 4. The response of $\hat{i}_{sd}$ and $\hat{i}_{sq}$.

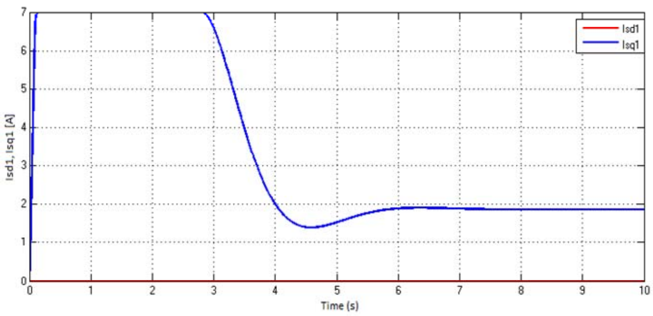

Fig. 5. The response of i_{sd1} and i_{sq1}.

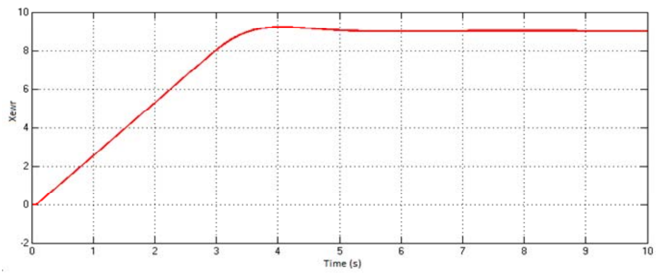

Fig. 6. The response of X_{ewr}.

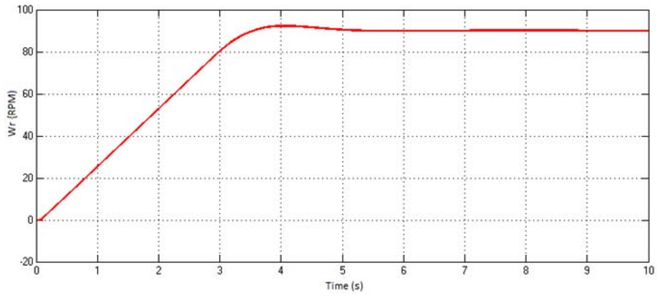

Fig. 7. The response of ω_r .

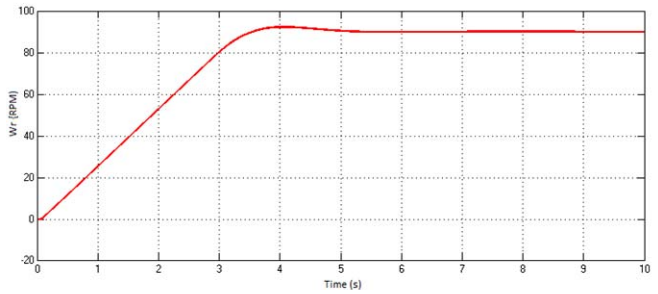

Fig. 8. Response of ω_r .

C. Stability Analysis

1) Stability Analysis using Eigenvalues Method: The equilibrium values are then substituted into A matrix. To analyze the system stability, it is necessary to find the eigenvalues of the A matrix using Matlab. The eigenvalues are

eig(A) = 1.0e+02 *

0.0000 + 0.0000i

0.0000 + 0.0000i

-4.8178 + 4.2333i

-4.8178 - 4.2333i

TABLE IV. EQUILIBRIUM VALUES

Parameters	**Quantities**	**Unit**
i_{sd0}	-0.101	A
i_{sq0}	1.864	A
i_{sd10}	0	A
i_{sq10}	1.8673	A
$\hat{i}_{sd0}$	-0.0975	A
$\hat{i}_{sq0}$	1.86	A
X_{ewr0}	9	
ω_{r0}	90	RPM

-4.2144 + 0.4055i

-4.2144 - 0.4055i

-0.5371 + 0.7969i

-0.5371 - 0.7969i

-0.9128 + 0.0000i

-0.7568 + 0.0000i

-0.0134 + 0.0174i

-0.0134 - 0.0174i

-1.0000 + 0.0000i

From the eigenvalues above, it appears that all poles are negative. This means that all poles are located to the left of the imaginary axis. Thus, the system is stable. This is reinforced by the speed response shown in Fig. 8. The speed of PMSM is stable at 90 RPM with settling time ± 3.3 seconds.

2) Stability Analysis using Bode Stability Criterion: As is described in the Bode stability criterion, the system is stable if the system has positive Gain Margin (GM) and Phase Margin (PM) [10]. The Bode plot of the system is shown in Fig.9. The system has Gain Margin (GM) = 35.4 dB and Phase Margin (PM) = 59.3 dB. Therefore, the system is stable.

3) Stability Analysis using Root Locus: Fig. 10 shows the Root Locus of ω_r vs ω_r^*. It appears that the system will be stable if the system is given a gain below 58.9.

VI. CONCLUSION

From the above calculations and simulations, it can be seen that the sensorless control system of PMSM above is stable. This can be known from the system's speed response, negative eigenvalue, and Bode stability analysis that has positive GM and PM. Root Locus plot shows that the system will be stable if the system is given a gain below 58.9.

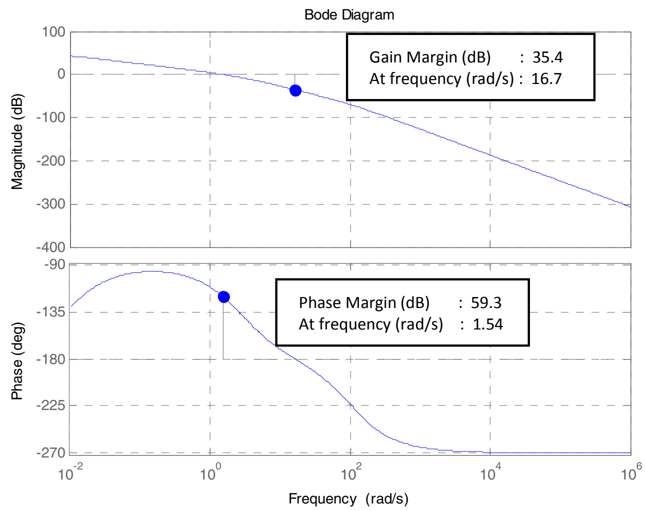

Fig. 9. Bode diagram of ω_r vs ω_r^* .

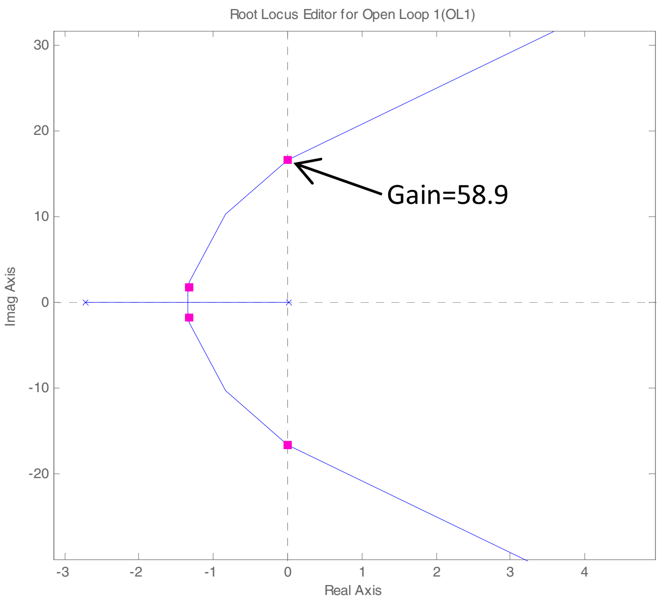

Fig. 10. Root Locus of ω_r vs ω_r^*.

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APPENDIX

$$\frac{d}{dt}i_{sd}=\frac{1}{L_{sd}}\begin{pmatrix} K_{pd}i_{sd}^{*}-\left(K_{pd}+R_s\right)i_{sd}+K_{id}X_{sd}-NK_{wrp}\dfrac{\left(L_{sq}\right)^2}{L_{sd}}i_{sq1}i_{sd}\hat{i}_{sq} \\ +NK_{wrp}L_{sd}i_{sq1}i_{sq}\hat{i}_{sd}+NK_{wrp}\psi_F i_{sq1}i_{sq}- \\ NK_{wrp}\psi_F i_{sq1}\hat{i}_{sq}-NK_{wrp}\left(L_{sd}-\dfrac{\left(L_{sq}\right)^2}{L_{sd}}\right)i_{sq1}\hat{i}_{sd}\hat{i}_{sq} \\ -NK_{wri}L_{sq}i_{sq1}X_{ewr}+NL_{sq}i_{sq}\omega_r \end{pmatrix} \quad \text{(A1)}$$

$$\frac{d}{dt}i_{sq}=\frac{1}{L_{sq}}\begin{pmatrix} \left(K_{pq}K_pK_{wrp}\dfrac{\psi_F}{L_{sq}}-K_{pq}-NK_{wrp}\dfrac{\left(\psi_F\right)^2}{L_{sq}}-R_s\right)i_{sq}+ \\ \left(NK_{wrp}\dfrac{\left(\psi_F\right)^2}{L_{sq}}-K_{pq}K_pK_{wrp}\dfrac{\psi_F}{L_{sq}}\right)\hat{i}_{sq}+ \\ \left(NL_{sd}K_{wri}i_{sd1}+N\psi_F K_{wri}-K_{pq}K_pK_{wri}\right)X_{ewr}+K_{iq}X_{sq}+ \\ K_{pq}K_iX_{wr}-K_{pq}K_pK_{wrp}\dfrac{L_{sq}}{L_{sd}}i_{sd}\hat{i}_{sq}+K_{pq}K_pK_{wrp}\dfrac{L_{sd}}{L_{sq}}i_{sq}\hat{i}_{sd} \\ -K_{pq}K_pK_{wrp}\left(\dfrac{L_{sd}}{L_{sq}}-\dfrac{L_{sq}}{L_{sd}}\right)\hat{i}_{sd}\hat{i}_{sq}+NL_{sd}K_{wrp}i_{sd1}i_{sd}\hat{i}_{sq} \\ -NL_{sd}K_{wrp}i_{sd1}i_{sq}\hat{i}_{sd}-NL_{sd}K_{wrp}\dfrac{\psi_F}{L_{sq}}i_{sd1}i_{sq}+NL_{sd}K_{wrp}\dfrac{\psi_F}{L_{sq}}i_{sd1}\hat{i}_{sq}+ \\ N\psi_F K_{wrp}i_{sd}\hat{i}_{sq}-N\psi_F K_{wrp}i_{sq}\hat{i}_{sd}-i_{sd}N\omega_r L_{sd}-N\omega_r\psi_F \end{pmatrix} \quad \text{(A2)}$$

$$\begin{aligned} \frac{d}{dt}\hat{i}_{sd}={}&-\frac{R_s}{L_{sd}}\hat{i}_{sd}+K_{wrp}\left(\frac{L_{sq}}{L_{sd}}\right)^2 i_{sd}\left(\hat{i}_{sq}\right)^2-K_{wrp}\hat{i}_{sq}i_{sq}\hat{i}_{sd}-K_{wrp}\frac{\psi_F}{L_{sd}}\hat{i}_{sq}i_{sq}+K_{wrp}\frac{\psi_F}{L_{sd}}\left(\hat{i}_{sq}\right)^2+ \quad \text{(A3)} \\ &K_{wrp}\left(1-\left(\frac{L_{sq}}{L_{sd}}\right)^2\right)\hat{i}_{sd}\left(\hat{i}_{sq}\right)^2+K_{wri}\frac{L_{sq}}{L_{sd}}\hat{i}_{sq}X_{ewr}+\frac{K_{pd}}{L_{sd}}i_{sd}^{*}-\frac{K_{pd}}{L_{sd}}i_{sd}+\frac{K_{id}}{L_{sd}}X_{sd} \end{aligned}$$

$$\begin{aligned} \frac{d}{dt}\hat{i}_{sq}={}&-K_{wrp}\hat{i}_{sd}i_{sd}\hat{i}_{sq}+K_{wrp}\left(\frac{L_{sd}}{L_{sq}}\right)^2 i_{sq}\left(\hat{i}_{sd}\right)^2+K_{wrp}\psi_F\frac{L_{sd}}{\left(L_{sq}\right)^2}\hat{i}_{sd}i_{sq} \quad \text{(A4)} \\ &-K_{wrp}\psi_F\frac{L_{sd}}{\left(L_{sq}\right)^2}\hat{i}_{sd}\hat{i}_{sq}-K_{wrp}\left(\left(\frac{L_{sd}}{L_{sq}}\right)^2-1\right)\left(\hat{i}_{sd}\right)^2\hat{i}_{sq} \\ &-K_{wri}\frac{L_{sd}}{L_{sq}}\hat{i}_{sd}X_{ewr}-\frac{R_s}{L_{sq}}\hat{i}_{sq}+\frac{K_{pq}}{L_{sq}}K_iX_{wr} \\ &-\frac{K_{pq}}{L_{sq}}K_pK_{wrp}\frac{L_{sq}}{L_{sd}}i_{sd}\hat{i}_{sq}+\frac{K_{pq}}{L_{sq}}K_pK_{wrp}\frac{L_{sd}}{L_{sq}}i_{sq}\hat{i}_{sd}+\frac{K_{pq}}{L_{sq}}K_pK_{wrp}\frac{\psi_F}{L_{sq}}i_{sq} \\ &-\frac{K_{pq}}{L_{sq}}K_pK_{wrp}\frac{\psi_F}{L_{sq}}\hat{i}_{sq}-\frac{K_{pq}}{L_{sq}}K_pK_{wrp}\left(\frac{L_{sd}}{L_{sq}}-\frac{L_{sq}}{L_{sd}}\right)\hat{i}_{sd}\hat{i}_{sq} \\ &-\frac{K_{pq}}{L_{sq}}K_pK_{wri}X_{ewr}-\frac{K_{pq}}{L_{sq}}i_{sq}+\frac{K_{iq}}{L_{sq}}X_{sq} \end{aligned}$$

$$\frac{d}{dt}X_{ewr} = \frac{L_{sq}}{L_{sd}} i_{sd}\hat{i}_{sq} - \frac{L_{sd}}{L_{sq}} i_{sq}\hat{i}_{sd} - \frac{\psi_F}{L_{sq}} i_{sq} + \frac{\psi_F}{L_{sq}}\hat{i}_{sq} + \left(\frac{L_{sd}}{L_{sq}} - \frac{L_{sq}}{L_{sd}}\right)\hat{i}_{sd}\hat{i}_{sq} \quad \text{(A5)}$$

$$\frac{d}{dt}X_{sd} = i_{sd}^{*} - i_{sd} \quad \text{(A6)}$$

$$\frac{d}{dt}X_{sq} = \begin{pmatrix} K_i X_{wr} - K_p K_{wrp}\frac{L_{sq}}{L_{sd}} i_{sd}\hat{i}_{sq} + K_p K_{wrp}\frac{L_{sd}}{L_{sq}} i_{sq}\hat{i}_{sd} + \\ K_p K_{wrp}\frac{\psi_F}{L_{sq}} i_{sq} - K_p K_{wrp}\frac{\psi_F}{L_{sq}}\hat{i}_{sq} \\ - K_p K_{wrp}\left(\frac{L_{sd}}{L_{sq}} - \frac{L_{sq}}{L_{sd}}\right)\hat{i}_{sd}\hat{i}_{sq} - K_p K_{wri} X_{ewr} \end{pmatrix} - i_{sq} \quad \text{(A7)}$$

$$\frac{d}{dt}i_{sd1} = \frac{1}{T_d} i_{sd}^{*} - \frac{1}{T_d} i_{sd1} \quad \text{(A8)}$$

$$\begin{aligned} \frac{d}{dt}i_{sq1} = {} & \frac{1}{T_d}K_i X_{wr} - \frac{1}{T_d}K_p K_{wrp}\frac{L_{sq}}{L_{sd}} i_{sd}\hat{i}_{sq} + \frac{1}{T_d}K_p K_{wrp}\frac{L_{sd}}{L_{sq}} i_{sq}\hat{i}_{sd} + \\ & \frac{1}{T_d}K_p K_{wrp}\frac{\psi_F}{L_{sq}} i_{sq} - \frac{1}{T_d}K_p K_{wrp}\frac{\psi_F}{L_{sq}}\hat{i}_{sq} \\ & - \frac{1}{T_d}K_p K_{wrp}\left(\frac{L_{sd}}{L_{sq}} - \frac{L_{sq}}{L_{sd}}\right)\hat{i}_{sd}\hat{i}_{sq} - \frac{1}{T_d}K_p K_{wri} X_{ewr} - \frac{1}{T_d} i_{sq1} \end{aligned} \quad \text{(A9)}$$

$$\begin{aligned} \frac{d}{dt}X_{wr} = {} & \omega_r^{*} - K_{wrp}\frac{L_{sq}}{L_{sd}} i_{sd}\hat{i}_{sq} + K_{wrp}\frac{L_{sd}}{L_{sq}} i_{sq}\hat{i}_{sd} + K_{wrp}\frac{\psi_F}{L_{sq}} i_{sq} \\ & - K_{wrp}\frac{\psi_F}{L_{sq}}\hat{i}_{sq} - K_{wrp}\left(\frac{L_{sd}}{L_{sq}} - \frac{L_{sq}}{L_{sd}}\right)\hat{i}_{sd}\hat{i}_{sq} - K_{wri} X_{ewr} \end{aligned} \quad \text{(A10)}$$

$$\frac{d\theta}{dt} = N\omega_r \quad \text{(A11)}$$

$$\frac{d\omega_r}{dt} = \frac{N\psi_F}{J} i_{sq} + \frac{N\left(L_{sd} - L_{sq}\right)}{J} i_{sd} i_{sq} - \frac{T_L}{J} \quad \text{(A12)}$$

$$\begin{aligned} \frac{d\hat{\theta}}{dt} = {} & NK_{wrp}\frac{L_{sq}}{L_{sd}} i_{sd}\hat{i}_{sq} - NK_{wrp}\frac{L_{sd}}{L_{sq}} i_{sq}\hat{i}_{sd} - NK_{wrp}\frac{\psi_F}{L_{sq}} i_{sq} + \\ & NK_{wrp}\frac{\psi_F}{L_{sq}}\hat{i}_{sq} + NK_{wrp}\left(\frac{L_{sd}}{L_{sq}} - \frac{L_{sq}}{L_{sd}}\right)\hat{i}_{sd}\hat{i}_{sq} + NK_{wri} X_{ewr} \end{aligned} \quad \text{(A13)}$$

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