Matlab/Simulink을 이용한 PMSM 벡터제어 시뮬레이션 및 해석

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Analysis and Simulation of Vector Control for PMSM using Matlab/Simulink

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Abstract - In this paper, the implementation of the Permanent Magnet Synchronous Machine (PMSM) model based on the Matlab/Simulink is described. Due to the analysis of the mathematical dq-modeling, a vector controlled PMSM drive simulation is approached. With the simulated system, unlike in black block models, all machine parameters are accessible for control and verification. Based on the Matlab/Simulink, the model of the PMSM with load torque is established, the simulation is studied and some conclusions are given.

1. INTRODUCTION

Permanent Magnet Synchronous Motors (PMSMs) are widely used in industrial applications, especially in servo drive applications, where the constant power operation is desired. Vector control has been adopted to achieve a high performance variable speed control of AC motors. Although there have been many studies of vector controlled AC motors, but they are shown in black block models with no details and the PMSM drives have not been sufficiently investigated [1][4].

In some papers, the S-functions, that are software source codes for Simulink blocks, are recommended to use [2][3]. But in fact, this way does not fully utilize the power and ease of Simulink. Another simulation uses the Simulink Power System block-set [5], but this block-set is also based on the S-functions and is not easy to work with some of the rest of the Simulink blocks.

In this paper, a simulation based on the analysis of the mathematical PMSM model is described. Using the dq-modeling analysis, the whole PMSM model can be separated into blocks, where each block solves the different model equations. Therefore, unlike the presented black block models, the machine parameters can be accessed for control and verification.

2. THE PMSM DRIVE MATHEMATICAL MODEL

The transformations of PMSM in the rotor reference frame are calculated as following [6]:

$$v_d = R_s i_d + \frac{d}{dt}\lambda_d - \omega_r \lambda_q \tag{1}$$

$$v_q = R_s i_q + \frac{d}{dt}\lambda_q + \omega_r \lambda_d \tag{2}$$

$$\lambda_d = L_s i_d + \lambda_f \tag{3}$$

$$\lambda_q = L_s i_q \tag{4}$$

Substituting (3), (4) into (1), (2) yields the motor drive model:

$$v_d = R_s i_d + L_s \frac{d}{dt} i_d - \omega_r L_s i_q \tag{5}$$

$$v_q = R_s i_q + L_s \frac{d}{dt} i_q + \omega_r L_s i_d + \omega_r \lambda_f \tag{6}$$

$$T_e = \frac{3}{2}\frac{p}{2}\lambda_f i_q = K_T i_q \tag{7}$$

Hence,

$$\frac{d}{dt} i_d = \frac{1}{L_s}(v_d - R_s i_d + \omega_r L_s i_q) \tag{8}$$

$$\frac{d}{dt} i_q = \frac{1}{L_s}(v_q - R_s i_q - \omega_r L_s i_d - \omega_r \lambda_f) \tag{9}$$

$$\frac{d}{dt}\omega_r = \frac{p}{2}\frac{T_e - T_L}{J} \tag{10}$$

$$\frac{d}{dt}\theta_r = \omega_r \tag{11}$$

where
v_d, v_q are stator dq-frame voltages.
i_d, i_q are stator dq-frame voltages.
λ_d, λ_q are stator dq-frame flux linkages.
λ_f is the magnet mutual flux linkage.
R_s is the stator resistance.
L_s is the stator inductance.
ω_r is the rotor angular velocity.
θ_r is the rotor angle.
p is the number of pole pair.
J is the moment of inertia.
K_T is the torque constant.
T_e, T_L are the electromagnetic and load torque

3. CONTROLLER DESIGN

3.1 Current controller

From (5-6), we can obtain the control law for the current loop control. The final command variables of dq-frame voltages can be used to derive the current controller. As shown in (5-6), there are couplings between channels such as the dependence on the rotor speed affecting the dq-frame currents. This may be canceled out by means of the state feed-back by adding the de-coupling terms in (12-13).

$$v_{d\_ff} = -\hat{\omega}_r L_s i_q^* \tag{12}$$

$$v_{q\_ff} = \hat{\omega}_r L_s i_d^* + \hat{\omega}_r \lambda_f \tag{13}$$

Figure 1 shows the closed current control loop in the q-axis. The current control loop in d-axis has the same structure with this.

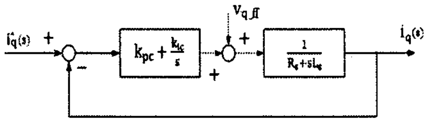


Fig.1. The closed-loop current control in q-axis

The closed-loop transfer function of the current control loop in Figure 1 is:

$$G_{cl}(s) = \frac{i_q(s)}{i_q^*(s)} = \frac{k_{pc}s + k_{ic}}{L_s s^2 + (R_s + k_{pc})s + k_{ic}} \tag{14}$$

Clearly, the PI zero of the controller may be used to cancel out the machine dynamics if k_{pc} and k_{ic} are chosen as L_s and R_s. From the definition of phase margin (PM), in order to tune the response of this closed-loop, the PI controller gains are additionally made proportional to the closed-loop bandwidth ω_c:

$$k_{ic} = \frac{\omega_c\sqrt{R_s^2+(\omega_c L_s)^2}}{\sqrt{1+K_c^2}} \tag{15}$$

$$k_{pc} = K_c\frac{k_{ic}}{\omega_c} \tag{16}$$

$$K_c = \frac{\omega_c k_{pc}}{k_{ic}} = \tan\left[PM - \frac{\pi}{2} + \tan^{-1}\left(\frac{\omega_c L_s}{R_s}\right)\right] \tag{17}$$

Figure 3(a) shows the frequency response of the current control loop.

3.2 Speed controller

The speed controller is designed with the consideration of the mechanical system. Especially, the load inertia constant is an important factor in the speed control. The operation of the motor will unstable with an improper value on it. In (10), the load toque, which contains the friction torque, corresponds to a system disturbance. The closed speed control loop is shown in Figure 2.

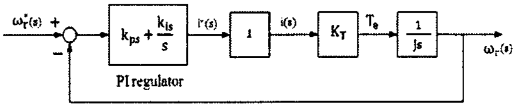


Fig.2. The closed-loop speed control

The closed-loop transfer function can be derived as:

$$G_{cl}(s) = \frac{\omega_r(s)}{\omega_r^*(s)} = \frac{(K_T k_{ps})s + K_T k_{is}}{Js^2 + (K_T k_{ps})s + K_T k_{is}} \tag{18}$$

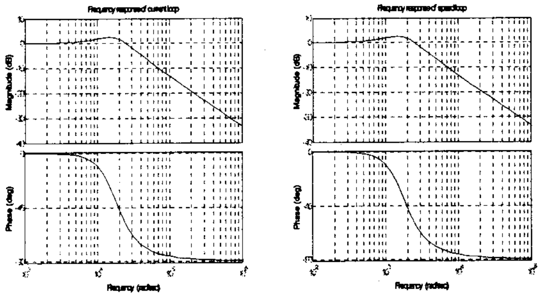
Similar to the current controller design, the PI controller gains may be determined as a function of the desired bandwidth ω_c:

$$k_{is} = \frac{\omega_c^2 J}{K_T\sqrt{1+K_s^2}} \tag{19}$$

$$k_{ps} = \frac{\omega_c K_s J}{K_T\sqrt{1+K_s^2}} \tag{20}$$

$$K_s = \frac{\omega_c k_{ps}}{k_{is}} = \tan(PM) \tag{21}$$

We can select the bandwidth ω_c to be order of magnitude smaller than that of the current loop, and reasonable value of phase margin. Figure 3(b) shows the frequency response of the speed control loop.



(a) current control loop (b) speed control loop

Fig.3. The frequency responses

3.3 Anti wind-up technique

The "wind-up" phenomenon occurs when the integrator keeps building up although the value of the output of the PI controller reaches the limited area. This causes the overshot-current, slows down the processing time and interrupts the motor operation. In the controller, the difference between the nominal controller output and that of the limiter is fed back through logical NOT as shown in Figure 4 [7]. It will be zero if there is no saturation.

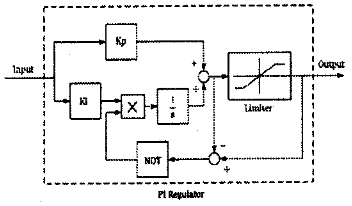


Fig.4. PI controller with anti wind-up

4. MATLAB/SIMULINK IMPLEMENTATION

Based on the analysis of the mathematical model of the PMSM and the vector control scheme, a vector controlled PMSM drive can be constructed, as illustrated in Figure 5. The following subsections will give some brief explanations of some parts.

4.1 The PI controllers

The PI controller are used in the current and speed loop control. The PI gains K_p and K_i are calculated in (15-16) for current loop and (19-20) for speed loop, respectively.

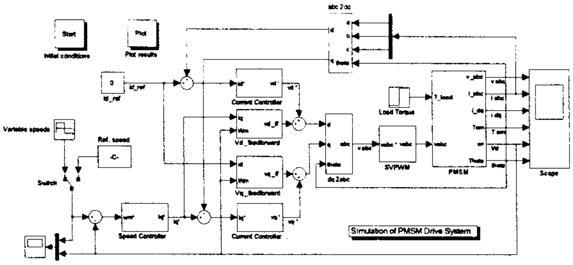


Fig.5. Simulink model of vector controlled PMSM drive

4.2 The decoupling blocks

The machine equations are coupling between them because the terms from d-axis appear in the equations of q-axis and in the opposite direction. These terms make the regulation process be more complicate. To handle this problem, the decoupling terms in (12-13) are added and their magnitudes are equal in module with coupling terms with opposite signs.

4.2 The PMSM block

The constructed PMSM model is based on the mathematical dq-model of the motor as in equations (5-11). These equations could be implemented using the "state-space" block in Matlab/Simulink, but for accessing to each point of the model, the discrete blocks are preferred.

5. THE SIMULATION RESULTS

By applying 220V three phases AC voltages at 60Hz with an inertia load, the PMSM model has been tested. The motor parameters which are used in the simulation are shown in Table 1. Figure 6 shows the simulation results of the implementation of the vector control scheme with PMSM model at a speed of 1500rpm. In this simulation, the PMSM drive system is verified in both forward and reverse direction.

Table I. Parameters of PMSM

Number of poles	8
Rated speed	1500 (RPM)
Rated voltage	220 (V)
Rated current	10.9 (A)
Stator resistance	0.224 (Ω)
Stator inductance	3.015 (mH)
Moment of inertia	10.9x10^{-4} (kgm^2)
Flux linkage	0.2859 (Wb-T)

6. CONCLUSION

In this paper, a PMSM model based on the analysis of the mathematical dq-model of the motor is constructed. And a vector controlled PMSM drive model is simulated by using the Matlab/Simulink, a popular and well-accepted program in the general industries; so that the ease of implementing control method with this model is demonstrated.

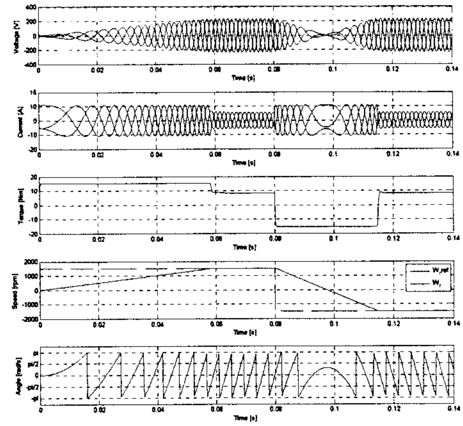


Fig.6. Phase voltages, currents, torque, speed and rotor position at 1500rpm

The control and the implementation of the motor drive system have been verified, and the simulation results have shown that the speed of the motor is well-controlled and the excitation current is in good response.

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