Controller design

The purpose of this chapter is to design a suitable control system for the intended sensorless control schemes (which will be described in the next chapters). In chapter two, the Field Oriented Control approach was selected to be the type applied in this project. Afterward in chapter three, this approach was presented as the floorboard of this thesis. The steps used to turn the current and speed regulators are shown in this chapter, assuming a closed loop (sensored) operating condition.

4.1 Field Oriented Control of PMSM

The principle of the FOC approach is to get a decoupled (or independent) control of the produced torque and the flux level under steady state and dynamic conditions, (see chapter two for more details). This is achieved by controlling the two current components (in the dq reference frame) separately.

4.1.1 Current controller

The equations describing the machine stator voltage and flux linkage in the rotor dq reference frame are once more considered here, identically to equations (1) and (2) presented in chapter two.

$$
\begin{aligned}
V_{sd} &= R_s i_{sd} + \frac{d\lambda_{sd}}{dt} - \omega_m \lambda_{sq} \\
V_{sq} &= R_s i_{sq} + \frac{d\lambda_{sq}}{dt} + \omega_m \lambda_{sd}
\end{aligned} \tag{8}
$$

$$
\begin{aligned}
\lambda_{sd} &= L_s i_{sd} + \lambda_m \\
\lambda_{sq} &= L_s i_{sq}
\end{aligned} \tag{9}
$$

Where ω_m and λ_m are the synchronous angular rotational velocity and the permanent magnet flux respectively.
The key point in the current controller design is to obtain the machine transfer function first, and then choose suitable controller parameters based on this transfer function.
Equation (9) can be substituted in equation (8) and solved for the current components (using Laplace transform) as shown below:

$$i_{sd} = (V_{sd} + \omega_m L_s i_{sq})[\frac{1}{R_s + sL_s}]$$
$$i_{sq} = [V_{sq} - \omega_m (L_s i_{sd} + \lambda_m)][\frac{1}{R_s + sL_s}] \tag{10}$$

Equation (10) can be illustrated in a block diagram form as shown in the figure below

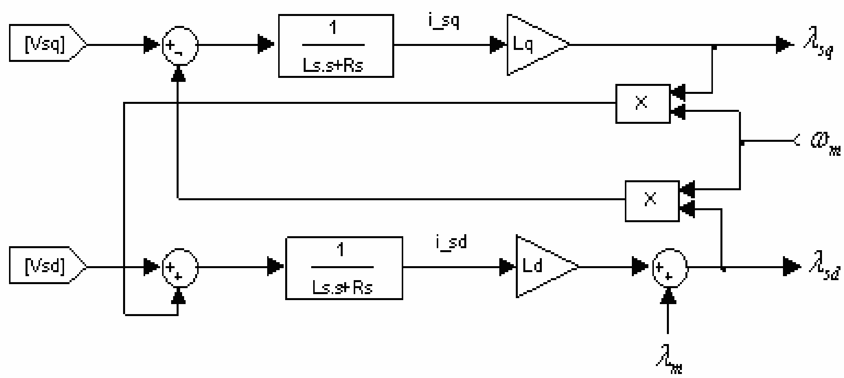


Figure 4.1: *current equations in the dq reference frame, including cross coupling terms.*

In steady state, i_{sd} and i_{sq} can be seen as DC values. Therefore Proportional-Integral (PI) regulators can be used to achieve zero error during steady state.
From figure 4.1, it can be seen that i_{sd} and i_{sq} are not independents (due to the cross coupling). To decouple these current components, i_{sd} will be set to zero (optimum torque production).

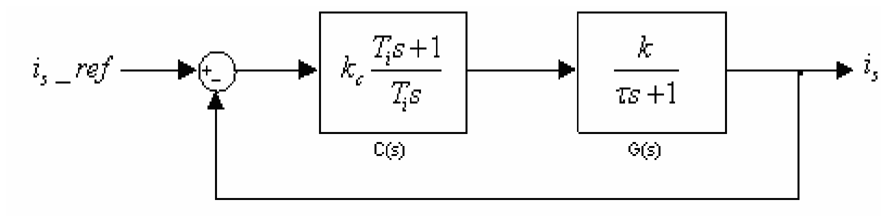
4.1.2 Current regulator parameters

The PI controller parameters applied in this project are tuned based on the pole and zero placement approach. Consider the equations below, representing the transfer function of the PM motor (assuming a linear machine model) and the transfer function of the current regulator respectively.

$$G(s) = \frac{k}{\tau s + 1}$$
$$C(s) = k_c \frac{T_i s + 1}{T_i s} \tag{11}$$

Where $k = \frac{1}{R_s}$, $\tau = \frac{L_s}{R_s}$ and k_c a positive gain. The model for designing the current controller is shown in figure 4.2.

Figure 4.2: *model for the current controller design.*



Based on the model of figure 4.2, the open loop and close loop transfer functions of the system can be derived. These transfer functions are presented in the equation below (respectively).

$$G_o = k_c k \frac{T_i s + 1}{T_i s(\tau s + 1)}$$
$$G_c = k_c k \frac{T_i s + 1}{T_i s(\tau s + 1) + k_c k(T_i s + 1)} \tag{12}$$

From equation (12), it can be seen that the open loop system has one zero and one pole. If it was possible to locate these points (zero and pole) so that $T_i = \tau$, then equation (12) will be simplified as shown in the following equation.

$$G_o = \frac{k_c k}{T_i s}$$
$$G_c = \frac{k_c k}{T_i s + k_c k} \tag{13}$$

Then the controller will be tuned only by adjusting the gain k_c. However, for real systems, the condition $T_i = \tau$ could be difficult to be fulfilled, since the machine time constant changes in response to any change of the machine parameters. Therefore, for a realistically well

performing PI regulator, the design procedure would require the zero to be placed in a very close neighborhood of the pole.
Table 4.1 shows the selected current controller parameters used in this project.

Table 4.1: *current regulator parameters.*

q-axis current	d-axis current
$T_i = 0.0041$	$T_i = 0.0041$
$k_c = 100$	$k_c = 100$

The plots depicted in figure 4.3 describe the behavior of the closed loop cascade connection of the designed current controller and the plan.

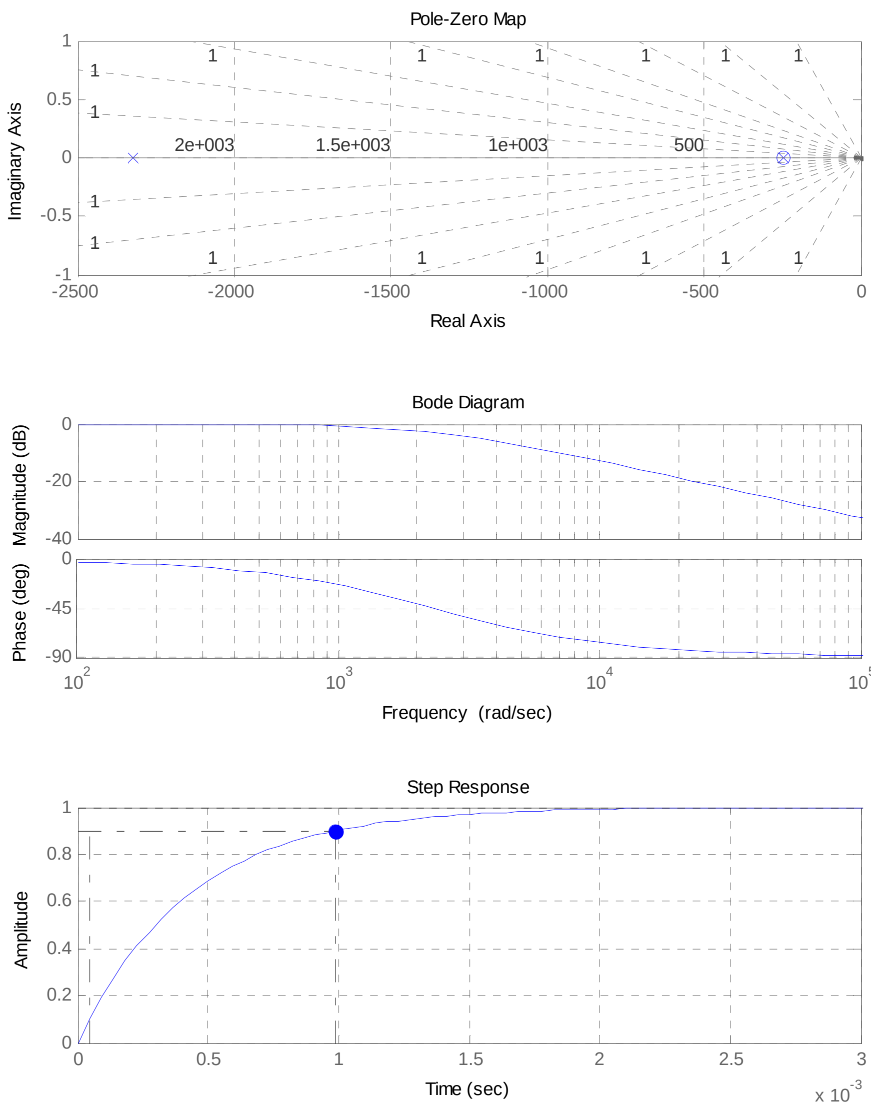


Figure 4.3: *current controller's behavior.*

The speed controller (which is not presented here), is designed based on the same approach as that of the current controllers. A discrete version of both controllers (for the implementation in DSPACE) is obtained using the MATLAB function c2d assuming as sampling times for the current and the speed controllers $T_{s\_i} = 25\mu s$ and $T_{s\_w} = 500\mu s$ respectively.

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