Chair of High-Power Converter Systems
Technical University of Munich Prof. Marcelo Lobo Heldwein

Arcisstr. 21 Email: hlu@ed.tum.de Tel.: +49 (0)89 289 28358
80333 Munich Web: www.epe.ed.tum.de/hlu Fax: +49 (0)89 289 28336

PRACTICAL COURSE

Simulation and Optimization of Mechatronic Drive Systems for MSPE

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Haoheng Li / 03797669
Haojun Cao /

Experiment 2
Control of the DC Drive

2.3 Armature Current Control

1.) * Integrator windup occurs when the controller output saturates, causing the integrator keeps accumulating error, which will cause overshoot and instability; it occurs when controller with a integrator such as PI and PID controllers; to prevent it, we can use anti-windup schemes, such as clamping the integrator output, back-calculation, conditional integration, etc.

2.) * From the differential equations:

$$\begin{cases} U_A = R_A I_A + L_A \frac{dI_A}{dt} + C_M \Psi_{EN} \Omega_M \\ \Theta_M \frac{d\Omega_M}{dt} = C_M \Psi_{EN} I_A \end{cases} \tag{2.1}$$

The transfer function of the DC machine from armature voltage U_A to angular speed Ω_M is:

$$F_{DCM}(s) = \frac{\Omega_M(s)}{U_A(s)} = \frac{V_{DCM}}{1 + sT_M + s^2 T_A T_M} \tag{2.2}$$

where $V_{DCM} = \frac{1}{C_M \Psi_{EN}}$, $T_A = \frac{L_A}{R_A}$ and $T_M = \frac{\Theta_M R_A}{(C_M \Psi_{EN})^2}$.
With the numerical values given in the tabel, we have:

$$F_{DCM}(s) = \frac{1.042}{1 + 0.031s + 0.000527s^2} \tag{2.3}$$

The poles of the system are:

$$s_{1,2} = -29.41 \pm j32.1 \tag{2.4}$$

For modulus optimum and symmetrical optimum, $\frac{T_1}{T_\sigma} \geq 4$ and the transfer function above doesn't meet this condition. To make the design by MO and SO, we can introduce a fast inner loop, such as current loop.

3.) * Introducing EMF E_A acts as a disturbance to the armature current loop. To compensate it, we can use a feedforward control by adding a voltage equal to E_A to the armature voltage reference. The value of compensation voltage should be equal to

$$E_{com} = \frac{C_M \Psi_{EN} \Omega_M}{V_{PE}} \tag{2.5}$$

2.3.1 Controller Design

4.) * Becasuse the armature current loop is inner loop, it should be designed to be much faster than the speed loop.

5.) * The transfer function between the armature voltage U_A and the armature current I_A

is:

$$F_{AI}(s) = \frac{I_A(s)}{U_A(s)} = \frac{1/R_A}{1 + sT_A} \tag{2.6}$$

The transfer function of power electronics parts is:

$$F_{PE}(s) = \frac{U_A(s)}{U_A^*(s)} = \frac{V_{PE}}{1 + sT_{PE}} \tag{2.7}$$

The transfer function of the current sensor is:

$$F_{IS}(s) = \frac{\hat{I}_A(s)}{I_A(s)} = \frac{1}{1 + sT_{F,I_A}} \tag{2.8}$$

Therefore, the transfer function of the current control loop is:

$$F_{I_A}(s) = F_{AI}(s)F_{PE}(s)F_{IS}(s) = \frac{\frac{V_{PE}}{R_A}}{(1 + sT_A)(1 + sT_{PE})(1 + sT_{F,I_A})} \tag{2.9}$$

The system above is a third-order system. Becasuse $T_{F,I_A} + T_{PE} \ll T_A$, we can approximate it to a second-order system by neglecting the smallest time constant:

$$F_{\hat{I}_A}(s) \approx \frac{\frac{V_{PE}}{R_A}}{(1 + sT_A)(1 + sT_{sum,I_A})} \tag{2.10}$$

where $T_{sum,I_A} = T_{F,I_A} + T_{PE}$.

Therefore the approximated transfer function of the current control loop is:

$$F_{\hat{I}_A}(s) = \frac{V_{S,I_A}}{(1 + sT_{1,I_A})(1 + sT_{\sigma,I_A})} \tag{2.11}$$

where $V_{S,I_A} = \frac{V_{PE}}{R_A} = 10$, $F_{equi,I_A}(s) = \frac{I_A(s)}{I_A^*(s)} \approx \frac{1}{1+sT_{equi,I_A}}$, $T_{1,I_A} = T_A$ and $T_{\sigma,I_A} = T_{sum,I_A} = 3ms$.

6.) * From the optimization table, we can design the PI controller by modulus optimum criterion:

$$F_{C,I_A}(s) = V_{\mathrm{r},I_A} \frac{1 + sT_{\mathrm{n},I_A}}{sT_{\mathrm{n},I_A}} \tag{2.12}$$

where $T_{\mathrm{n},I_A} = T_{\sigma,I_A} = T_A = 17ms$, and $V_{\mathrm{r},I_A} = \frac{T_{1,I_A}}{2V_{S,I_A}T_{\sigma,I_A}} = 0.283A^{-1}$.

2.4 Speed Control in the Armature Control Range

2.4.1 Controller Design

11.) * The closed-loop transfer function of the curren control loop is:

$$F_{equi,I_A}(s) = \frac{\hat{I}_A(s)}{I_A^*(s)F_{IS}(s)} = \frac{F_{C,I_A}(s)F_{PE}(s)F_{AI}(s)}{1 + F_{C,I_A}(s)F_{PE}(s)F_{AI}(s)F_{IS}(s)} = \frac{1 + sT_{f,I_A}}{1 + sT_{\sigma,I_A} + s^2 2T_{\sigma,I_A}^2} \tag{2.13}$$

12.) * If we apply a polynomial division by the numerator, we can get:

$$F_{equi,I_A}(s) = \frac{I_A(s)}{I_A^*(s)} \approx \frac{1}{1 + sT_{equi,I_A}} \tag{2.14}$$

where $T_{equi,I_A} = 2T_{\sigma,I_A} - T_{f,I_A} = 4ms$.

13.) * From the differential equations, we can derive the transfer function from the armature current reference I_A^* to the filtered angular speed $\hat{\Omega}_M$:

$$F_{\hat{\Omega}_M}(s) = \frac{\hat{\Omega}_M(s)}{I_A^*(s)} = F_{\hat{\Omega}_M,I_A}(s) \cdot \frac{1}{\Theta_M s} \cdot C_M \Psi_{EN} \cdot F_{equi,I_A}(s) \tag{2.15}$$

Simplify it to the standard form, we have:

$$F_{\hat{\Omega}_M}(s) = \frac{\hat{\Omega}_M(s)}{I_A^*(s)} = \frac{V_{S,\Omega_M}}{sT_{1,\Omega_M}(1 + sT_{\sigma,\Omega_M})} \tag{2.16}$$

where $V_{S,\Omega_M} = \frac{R_A}{C_M \Psi_{EN}} = 22.92$, $T_{1,\Omega_M} = T_M = \frac{R_A \Theta_M}{C_M^2 \Psi_{EN}^2} = 31ms$ and $T_{\sigma,\Omega_M} = T_{equi,I_A} + T_{F,\Omega_M} = 6ms$.

14.) * The above system is a IT_1 system. From the optimization table, we can design the PI controller by symmetrical optimum criterion:

$$F_{C,\Omega_M}(s) = V_{\mathrm{r},\Omega_M} \frac{1 + sT_{\mathrm{n},\Omega_M}}{sT_{\mathrm{n},\Omega_M}} \tag{2.17}$$

where $T_{\mathrm{n},\Omega_M} = 4T_{\sigma,\Omega_M} = 24ms$, and $V_{\mathrm{r},\Omega_M} = \frac{T_{1,\Omega_M}}{2V_{S,\Omega_M} T_{\sigma,\Omega_M}} = 0.113$.