DETERMINATION OF REGULATOR PARAMETERS FOR SMPM VECTOR CONTROL

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Abstract

Simple method for feedback parameters setting for vector speed controlled PMSM is described. Pole placement method is applied to a conventional structure with PI controllers and sliding mode control structure. Control performance of both methods is verified by simulations. As conclusion it was found that both methods satisfy control quality criteria including prescribed settling time and conditions for vector control.

1 Determination of PI controler parameters

Control system with PMSM in d_q rotational frame coupled to the rotor is describes by the Eq. (1), (2), (3) and shown in Fig. 1. Feedback parameters of individual axes for control of flux and torque of the speed controlled drive are computed from transfer functions of Fig. 2 and Fig. 3, which corresponds to d-axis and q-axis respectively.

$$\frac{di_d}{dt} = \frac{1}{L_d}\left(u_d - R_S i_d + p\omega_R \Psi_q\right) \qquad \frac{di_q}{dt} = \frac{1}{L_q}\left(u_q - R_S i_q - p\omega_R \Psi_d\right) \tag{1}$$

$$\Psi_d = L_d i_d + \Psi_{PM} \qquad \Psi_q = L_q i_q \tag{2}$$

$$\frac{d\omega_R}{dt} = \frac{1}{J_R}\left(M_{el} - M_{Ls}\right) \qquad M_{el} = \frac{3}{2}p\left(\Psi_d i_q - \Psi_q i_d\right) \tag{3}$$

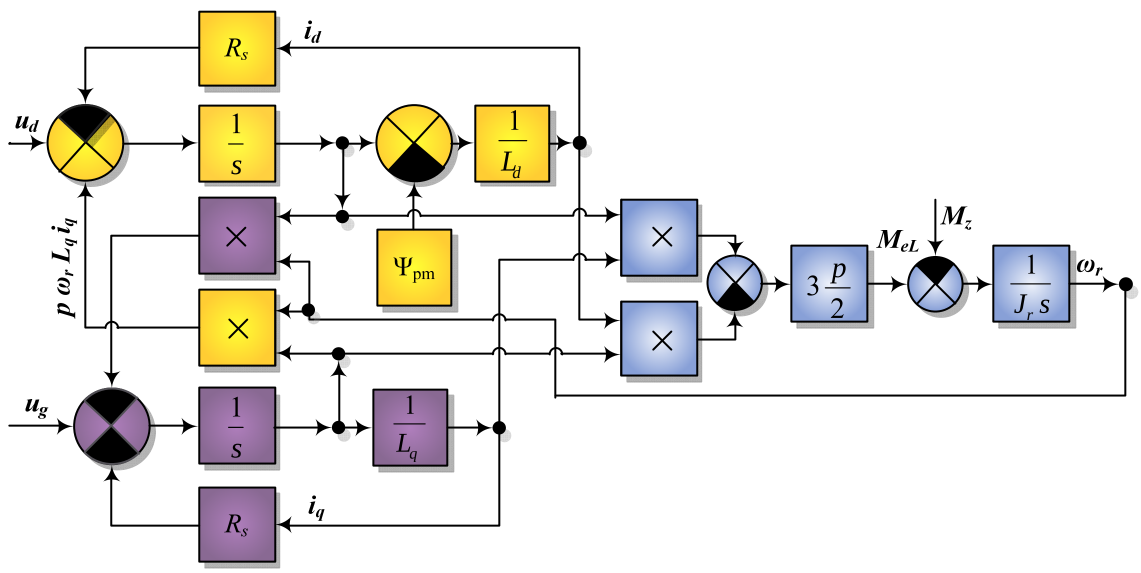

Figure 1 SMPM in d,q transformation

Mason's rule is exploited to determine transfer functions between flux current component, i_d and input voltage, u_d (*shown in Fig.2*) as well as transfer function between rotor speed ω_r and input voltage u_q (*shown in Fig.3*).

$$\frac{i_x(s)}{u_x(s)} = \frac{\frac{1}{L_x}\frac{1}{s}}{1+\frac{R_s}{L_x}\frac{1}{s}} = \frac{\frac{1}{L_x s}}{\frac{L_x s + Rs}{L_x s}} = \frac{1}{L_x s + Rs} = \frac{\frac{1}{Rs}}{1+\frac{L_x}{R_s}s} = \frac{K_a}{1+sT_{a-x}} \tag{4}$$

$$K_a = \frac{1}{R_s},\ T_{a-x} = \frac{L_x}{R_s} \tag{5}$$

Index x is introduced for substitution of common parts only and means d or q axis due to fact that transfer function of current controlled loops are exactly the same. The first order transfer function is exploited for replacement.

Transfer function of the loop for flux component of stator current including PI controller of Fig. 2 has form:

$$\frac{i_d(s)}{i_{ddem}(s)} = \frac{K_{Rid}\frac{1+sT_{Rid}}{T_{Rid}}\frac{K_a}{1+sT_{a-d}}}{1+K_{Rid}\frac{1+sT_{Rid}}{T_{Rid}}\frac{K_a}{1+sT_{a-d}}} = \frac{1}{\frac{T_{Rid}}{K_{Rid}K_a}s^2+1} \tag{6}$$

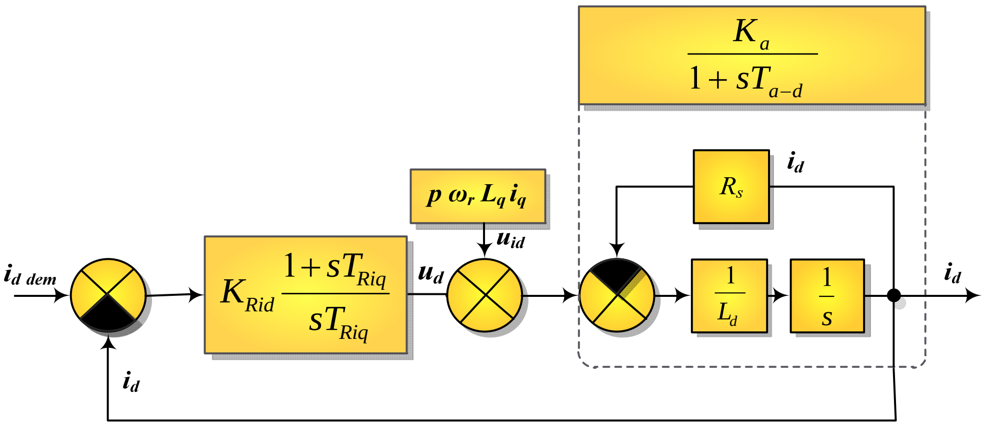

Figure 2 Block diagram of flux component of stator current i_d

The individual gains for this control loop are determined by Dodds formula Eq.(7) [1] . Denominator of transfer function Eg.(6) is compared with polynomial having prescribed behavior Eg.(7c), where n is order of the system and ω_0 is natural frequency corresponding to Dodd's formula Eg.(7a), to derive gain values. In settling time, T_u the controlled variable reaches 95 % of the demanded value [2].

$$T_u = 1{,}5(1+n)\frac{1}{\omega_0} \quad \text{or} \quad \frac{y(s)}{y_{dem}(s)} = \left[\frac{1}{\frac{T_{s0L}}{1{,}5\ (1+n)}s+1}\right]^n, \quad (s+\omega_0)^n \tag{7 a,b,c}$$

Parameters of PI controller for control of stator current flux component are defined as:

$$K_{Rid} = \frac{3L_d}{T_{ud}},\quad T_{Rid} = \frac{L_d}{R_s} \tag{8}$$

This way control parameters of d-axes are completed.

The same approach can be used to determine the regulator parameters in q axis for the order of the system n=3. Also in this case the denominator of transfer function is compared with polynomial having prescribed behavior, which results in control with define settling time.

For the design of PI controller of torque current component the complete current control loop is replaced with the ideal first order transfer function, which results in:

$$\frac{i_q(s)}{i_{qdem}(s)} = \frac{1}{T_c s+1}, \qquad where \qquad T_c = \frac{T_{uq}}{3} \tag{9}$$

Transfer function, which corresponds to Fig. 3 without precompensator, has following form:

$$\frac{\omega(s)}{\omega_{dem}(s)} = \frac{\left(K_{R\omega}\frac{K_{i\omega}}{s}\right)\left(\frac{1}{T_c s+1}\right)\left(\frac{K_m}{Js}\right)}{1+\left(K_{R\omega}\frac{K_{i\omega}}{s}\right)\left(\frac{1}{T_c s+1}\right)\left(\frac{K_m}{Js}\right)} \tag{10}$$

Due to presence of the zero in numerator of transfer function Eq.(10) [6] the overshoots accompany speed control. These overshoots can be effectively suppressed by the first order precompensator having transfer function Eq.(11) inverse to the numerator's zero.

$$\frac{\omega_{dem}(s)}{\omega_{demcomp}(s)} = \frac{1}{T_{\omega comp}s+1}, \qquad where \qquad T_{\omega comp} = \frac{K_{R\omega}}{K_{I\omega}} \tag{11}$$

Transfer function of the speed closed loop is as:

$$\frac{\omega(s)}{\omega_{dem}(s)} = \frac{\left(K_{R\omega}\frac{K_{i\omega}}{s}\right)\left(\frac{1}{T_c s+1}\right)\left(\frac{K_m}{Js}\right)}{1+\left(K_{R\omega}\frac{K_{i\omega}}{s}\right)\left(\frac{1}{T_c s+1}\right)\left(\frac{K_m}{Js}\right)}\frac{1}{T_{\omega comp}s+1} = \frac{1}{\frac{T_pJ}{K_{i\omega}K_m}s^3+\frac{J}{K_{i\omega}K_m}s^2+\frac{K_{R\omega}}{K_{i\omega}}s+1}$$
$$= \frac{\frac{K_{i\omega}K_m}{T_pJ}}{s^3+\frac{1}{T_p}s^2+\frac{K_{R\omega}K_m}{T_pJ}s+\frac{K_{i\omega}K_m}{T_pJ}} = \frac{\frac{K_m}{T_{i\omega}T_pJ}}{s^3+\frac{1}{T_p}s^2+\frac{K_{R\omega}K_m}{T_pJ}s+\frac{K_m}{T_{i\omega}T_pJ}} \tag{12}$$

Again the denominator of transfer function Eq.(12) is compared with prescribed behavior polynomial, for n = 3[6]. Comparing the coefficients of the same order the required gains of controller are defined as shown in Eq.(14):

$$s^3+\frac{1}{T_p}s^2+\frac{K_{R\omega}K_m}{T_pJ}s+\frac{K_m}{T_{i\omega}T_pJ} \Leftrightarrow s^3+s^2\frac{18}{T_{u\omega}}+s\frac{108}{T_{u\omega}^2}+\frac{216}{T_{u\omega}^3} \tag{13}$$

$$K_{R\omega} = \frac{108JT_p}{K_mT_{u\omega}^2}, \quad T_{i\omega} = \frac{K_mT_{u\omega}^3}{216JT_p} \tag{14}$$

For correct function of speed control loop the following condition Eq.(15) should be satisfied:

$$\frac{1}{T_p} = \frac{18}{T_{u\omega}} \Rightarrow T_{uq} = \frac{T_{u\omega}}{6} \tag{15}$$

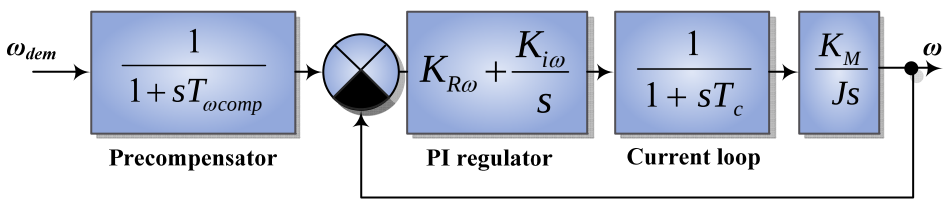

Figure 3 Block diagram of speed regulation

2 Results of simple PI controler loop

Fig. 4 shows time functions of the speed control together with corresponding current components in d anq axis. Subplot a) shows demanded and real speed. At the time t=0,1 s the motor was loaded with nominal torque. From this subplot is also clear that the speed settling time is very closed to prescribed value $T_{s\omega}$=0,02 s.

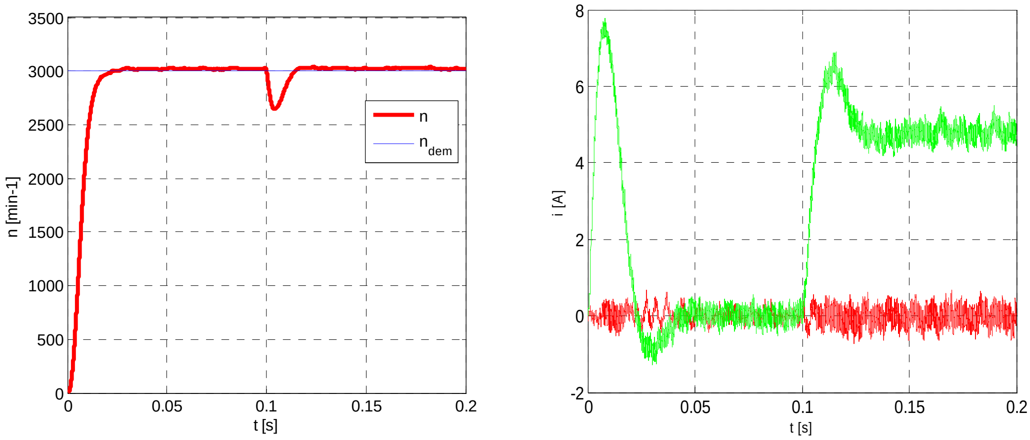

Figure 4: 'Rotor speed and correspending current components for PI speed control

3 Sliding Mode Control Feedback Gains Determination

This control technique supports the state feedback control. Main difference if compared with presented PI control structure is in robustness of this control system and in simplicity of feedback parameters design.

Sliding Mode Control is robust control technic in which control variable, u switches between two limits, $\pm u_{max}$ shown in Fig. 5 These limits are defined by voltage of DC bus. Switching function is defined as Eq. (16) where vector **y** is given as shows Eq. (17) [3]. Rewriten linear differential equation for switching boundary has form Eq. (18) and is decisive for control system behaviour. Control variable switches between its to limits as define Eq. (19) [4]. For zero initial conditions the closed loop transfer function has form as Eq. (20).

$$u = -u_{\max} sign\left[S\left(y, y_{dem}\right)\right] \tag{15}$$

$$S\left(y, y_{dem}\right) = y - y_{dem} + \sum_{i=1}^{r-1} w_i \ y^i \tag{16}$$

$$\mathbf{y} = \left[\mathrm{y}\,\dot{\mathrm{y}}\,\ddot{\mathrm{y}}\ldots\mathrm{y}^{(\mathrm{r}-1)}\right]^{\mathrm{T}} \tag{17}$$

$$y_{dem}(s) = y(s)\left[1 + \sum_{i=1}^{r-1} w_i s^{(i)}\right] \tag{18}$$

$$S\left(y, y_{dem}\right) = 0 \tag{19}$$

$$\frac{y(s)}{y_{dem}(s)} = \frac{1}{1 + w_1 s + w_2 s^2 + \ldots. + w_n s^n} \tag{20}$$

The switching boundary coefficients can be determined independently exploiting pole placement method. The design of control parameters corresponds to previous PI control description.

From SMC theory it is clear that to design correct switching surface the n-1 derivatives of controlled variable must be included as feedback. To eliminate the highest derivative it is possible to re-arrange the control system block diagram.

To adjust the gains for individual derivatives the pole placement method is applied again. For control of flux current component if smoothing integrator is exploited the order of the system shown in Fig. 5 is r=2 therefore only one derivative is required for feedback [5].

$$i_{ddem}(s) = i_d(s)\left(1 + sT_{si}/3\right) \tag{21}$$

If rearrangement of the block diagram is used then it results in control system shown in Fig. 6 and this way the flux current component derivative was eliminated [7].

$$u_d = K_{sm}\left[\left(\int i_{ddem} - i_d\right)dt - \frac{T_{si}}{3} i_d\right] \tag{22}$$

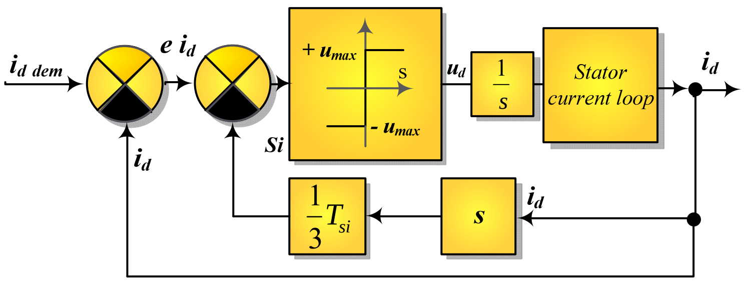

Figure 5: SMC control of i_d with current derivate feedback

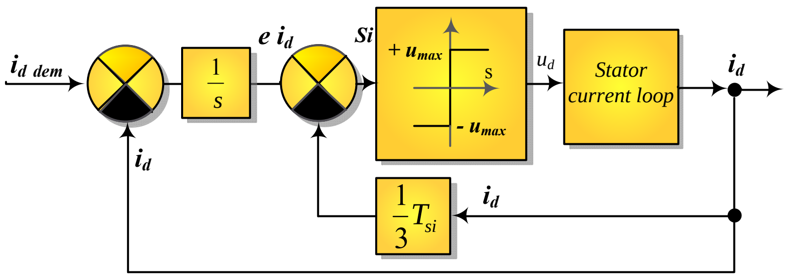

Figure 6: SMC modified block diagram of i_d after replacing

Elimination of the highest derivative is great advantage of SMC system rearrangement. This is approach which differs from ordinary SMC. There is also possibility to combine PI control in flux component control loop with SMC of speed control loop. Such approach can bring also fast response of flux control loop and robust behavior of speed control loop.

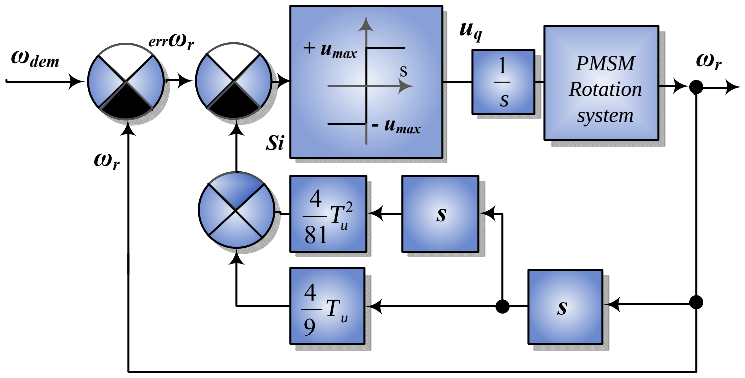

Figure 7: Currents, and rotor position

Block diagram for the design of stator current torque component loop is shown in Fig. 7. To adjust feedback gains the method of pole placement was exploited again.

4 Results

Simulation results for SMC of the speed of PMSM are shown in Fig. 9. For SMC the settling time was chosen 10-time higer if compared to the design of PI controller. Motor was loaded with nominal torque at the time t=0.5 s. From subplot a) it is also clear that the speed settling time $T_{s\omega}$=0,2 s is very closed to prescribed one.

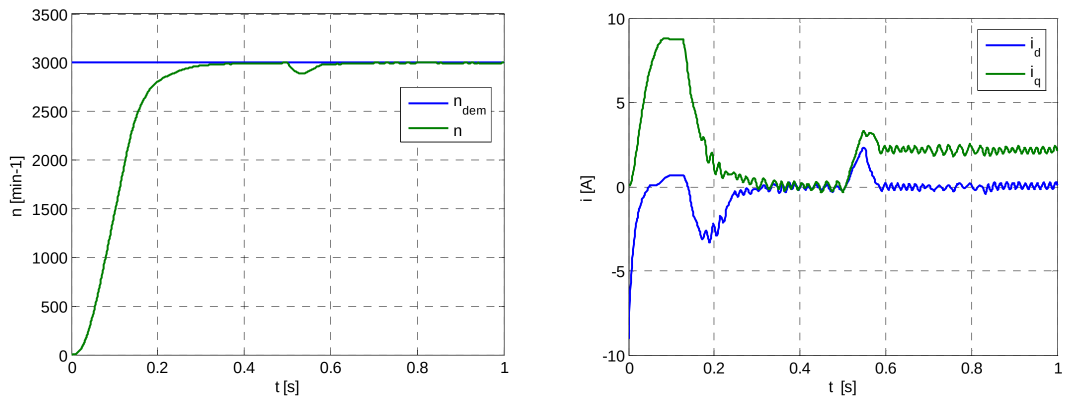

Figure 8: Rotor speed and correspending current components for SMC speed control

Conclusion

Comparison of simulation results of both presented methods shows good agreement with the prediction used for contyrol system design.

In practice the most widely used is method, which exploits PID controllers but as it was shown the other methods provide equally good or even better control results. It depends on the requirements of the control system user. Generally better control performace can be achived with faster stator current flux component control loop. It was also verified that robustness to parameters changes and external disturbances is higher for SMC if compared with ordinary PI control.

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