Design of High Performance Converter for PMSM Applied to Flywheel Energy Storage Array

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Abstract. A multi-objective visual design method of permanent magnet synchronous motor (PMSM) drive system which is applied to flywheel energy storage array is proposed. D-partition technique is applied to obtain the parameters stable region. Besides, frequency-domain specifications such as gain margin and phase margin, time-domain specifications such as overshoot and settling time are considered. Furthermore, a parameters design method is proposed and the optimized performance can be derived which meets the time- and frequency-domain specifications simultaneously. Simulation and experimental results verify the effectiveness and practicability.

Introduction

Flywheel energy storage array is an advanced energy storage technology, which has the advantages of high energy storage, high power, high efficiency, long life and no pollution. are applied practically [1]. As the core component of flywheel energy storage system, the performance of permanent magnet synchronous motor (PMSM) affects the performance of the whole flywheel energy storage system [2]. Normally proportional-integral (PI) controller is frequently used in adjustable speed-motor drives [3]. PI controller plays a key role in current control loop to regulate the magnetic flux linkage and electromagnetic torque of PMSM drives [4].

Numerous methods have been presented so far to design the controller considering the performance indexes, which can be classified into two categories: time-domain method [5]-[6] and frequency-domain method [7]-[8]. Time-domain method includes Routh-Hurwitz stability criterion [5] and root locus method [6]. Time-domain method is not suitable for the high-order systems, and normally employs the dominant pole and dipole for approximation. Frequency-domain method can get rid of this shortcoming, which mainly contains Nyquist diagrams [7] and Bode diagrams [8]. However, these methods mentioned above cannot achieve both time- and frequency-domain specifications simultaneously [9].

Neimark put forward the D-partition technique [10] to study the stability of systems with adjustable parameters. For a PI-type controller, the stable region is drawn in PI parameters coordinate frame by means of D-partition technique [11]-[12], the proportional and integral coefficient can be selected intuitively and conveniently. Moreover, D-partition technique can also be employed in high-order and nonlinear system [11]. Furthermore, performance indexes analyze can be carried out based on the stable region [12]. In fact, PMSM current control loop is implemented in digital signal process (DSP) chip, bringing in computation and pulse width modulation (PWM) delays [13]. These delays are inevitable, and will deteriorate the stability and dynamic property of close loop system. The nonlinear system containing delay link can be analyzed by using D-partition technique [11].

This paper presents a multi-objective visual method to design the current controller for PMSM drive system. This method aims at achieving time- and frequency-domain specifications simultaneously to improve the stability and dynamic property of PMSM drive system. D-partition technique is employed to obtain the PI parameters stable region, considering the computation and PWM delays. Based on this, the performance improvements over gain margin, phase margin, overshoot and settling time are within the scope of this paper. Furthermore, satisfactory region of
controller parameters can be obtained, which makes the choices and optimizations of controller parameters more convenient and explicit.

**Mathematical Model of PMSM Drive System**

Fig. 1 shows the current control loop schematic diagram of PMSM drive system. Three-phase stator current \(i_a, i_b\) and \(i_c\) are sampled. \(\theta_e\) is detected by mechanical sensor, which is required to implement coordinate transformation. PI controller is employed here to regulate the synchronous reference frame current \(i_d, i_q\) to track the reference value \(i^*_d, i^*_q\) with zero steady-state error.

![Current loop control schematic diagram of PMSM drive system.](image)

Figure 1. Current loop control schematic diagram of PMSM drive system.

Generally, mathematical model of PMSM can be established by means of state space equation. Take \(x=[i_d, i_q]^T\) as the state variable, \(u=[u_d, u_q]^T\) as input variable, where \(i_d, i_q\) and \(u_d, u_q\) are \(d-q\) axis current and voltage. Specifically, the state space equation of PMSM is expressed as

\[
\dot{x} = \begin{bmatrix}
-\frac{R}{L_d} & \frac{\omega_e L_q}{L_d} \\
-\frac{\omega_e L_d}{L_q} & -\frac{R}{L_q}
\end{bmatrix} x + \begin{bmatrix}
\frac{1}{L_d} & 0 \\
0 & \frac{1}{L_q}
\end{bmatrix} u + \begin{bmatrix}
0 \\
-\frac{\omega_e \psi_f}{L_q}
\end{bmatrix}
\]

(1)

where \(R, L_d, L_q, \psi_f\) are the resistance, \(d\)-axis inductance, \(q\)-axis inductance and permanent magnet flux linkage of PMSM, \(\omega_e\) is electric angular speed of rotor.

From (1), it can be seen that the coupling existed in the \(d-q\) axis. Normally, a feedforward decoupling component is added, i.e., \(\sim \omega_e L_d d_d\), thus the decoupled mathematical expression of \(q\)-axis can be described as

\[
G_{PM-q}(s) = \frac{i_q}{u_q} = \frac{1}{R + L_q s}
\]

(2)

Considering the delay of digital control system, the block diagram of the \(q\)-axis current loop control is shown in Fig. 2. Accordingly, the open loop transfer function of the \(q\)-axis is expressed as

\[
G_{ol}(s) = \frac{K_{PWM} (K_p s + K_i) e^{-\tau_i} (1 - e^{-\tau_i})}{T s^2 (L_q s + R)}
\]

(3)

where \(K_p\) is the proportional coefficient, and \(K_i\) is the integral coefficient of PI controller.
Controller Parameters System Region

From (3), the closed-loop equation of $q$-axis is derived as

$$D(s) = K_i K_{PWM} e^{-sT_e} \left(1-e^{-sT_e}\right)s^3 + K_p K_{PWM} e^{-sT_e} \left(1-e^{-sT_e}\right)s^2 + T_s R_s + T_s R_L q$$  \hspace{1cm} (4)

The boundary of $K(n, 0)$ consists of $D(0) = 0$, $D(\infty) = 0$ and $D(\pm j\omega) = 0$, $\omega > 0$, which is called D-partition boundary [11]. From $D(0) = 0$, it can be seen that $K_i = 0$. From $D(\infty) = 0$, it is observed that the result has no relationship with $K_p$, $K_i$.

**Figure 3.** Controller parameters stable region based on D-partition method.

The steps of the proposed multi-objective visual design method is presented as follows.

**Step 1)** Draw the controller parameters stable region. Thus controller parameters stable region can be obtained by D-partition technique, as shown in Fig. 3. It is seen from Fig. 3 that if $K_i$ is 0, the maximum value of $K_p$ is 9.58; if $K_p$ is 5.74, the maximum value of $K_i$ is 18360.

**Step 2)** Draw the multi-objective optimization domain. The requirements of these specifications are: the range of phase margin is 40°-60°; the range of gain margin is 5dB-10dB; overshoot and settling time are as small as possible. All the controller parameters that satisfy the requirements of phase margin and gain margin are contained in Fig. 4, which is called the desired margin domain. It is found that settling time and overshoot are contradictory and the trade off should be considered. A, B, and C are selected in the desired margin domain, which the overshoot is 30%, 20% and 10%, and settling time is 0.0032s, 0.0045s and 0.0069s, respectively.

**Table 1.** The performance specifications of PMSM drive system with the chosen PI parameters.

<table>
<thead>
<tr>
<th>Specifications</th>
<th>A (2.5,1950)</th>
<th>B (2.6,1350)</th>
<th>C (2.6,600)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gain margin (dB)</td>
<td>11</td>
<td>10.9</td>
<td>11</td>
</tr>
<tr>
<td>Phase margin (°)</td>
<td>47</td>
<td>52.5</td>
<td>59</td>
</tr>
<tr>
<td>Overshoot (%)</td>
<td>28</td>
<td>20</td>
<td>9.8</td>
</tr>
<tr>
<td>Settling time (ms)</td>
<td>3.2</td>
<td>4.5</td>
<td>6.9</td>
</tr>
</tbody>
</table>

**Step 3)** Select the optimal controller parameters. Normally, it is desired that $q$-axis current loop of PMSM has small settling time to track torque command fast, and not too large overshoot. Therefore, B is selected and performance indexes of system are: gain margin is 10.9dB, phase margin is 52.5°, overshoot is 20%, and the settling time is 0.0045s.
Simulation and Experimental Results

Fig. 5 is the simulation waveform of $q$-axis current step response, with A, B and C being selected respectively. Load step changes from light-load to full-load at 0.04s. The values of overshoot and settling time read from Fig. 4 are consistent with Table I, which proves out the effectiveness of the design method.

Fig. 6 shows the simulation waveform of three-phase current, with B being selected, i.e., $K_p=2.6$, $K_i=1350$. Load step changes from no-load to full-load at 0.04s. It is intuitively shown that three-phase current is sinusoidal, overshoot and settling time are small. The result proves that the system is of good stability and dynamic property, when the controller is design using the proposed method.
Figure 7 shows experimental waveforms of stability and dynamic property with the PI parameters A, B, C in Fig. 4, under the condition that load step changes from no-load to full-load. In Fig. 7(a), A is selected, i.e., $K_p=2.5$, $K_i=1950$; in Fig. 7(b), B is selected, i.e., $K_p=2.6$, $K_i=1350$; in Fig. 7(c), C is selected, i.e., $K_p=2.6$, $K_i=600$. When load step happens at $t_3$, $t_4$ and $t_5$ respectively, the $q$-axis current changes from 0A to 71A.

It is observed that in Fig. 7(a), the overshoot is 17.1%, the settling time is 2.1ms; in Fig. 7(b), the overshoot is 4.5%, the settling time is 4.8ms; in Fig. 7(c), there is no overshoot, the settling time is 7ms. The settling time of experimental results is close to the theoretical analysis value, however the overshoot of experimental results is smaller than theoretical analysis value. It is because the analog filter on the DSP board weakens the peak of the signal. Moreover, the results show that PMSM drive system is of good stability and dynamic property while using the designed current controller, and the proposed design method is effective and particle.

![Figure 7](image-url)

Figure 7. Experimental waveforms of stability and dynamic performance. (a) Load step happens at $t_4$, with $K_p$ equaling to 2.5, $K_i$ equaling to 1950. (b) Load step happens at $t_5$, with $K_p$ equaling to 2.6, $K_i$ equaling to 1350. (c) Load step happens at $t_6$, with $K_p$ equaling to 2.6, $K_i$ equaling to 600.

**Summary**

This paper presents a multi-objective design method of current controller for PMSM drive system, which is applied to flywheel energy storage array. D-partition technique is used to obtain the controller parameters stable region. Based on this, the current controller is designed achieving time- and frequency-domain specifications simultaneously.
It is concluded that controller parameters stable region obtained by the D-partition technique is the whole controller parameters satisfying system stability. The selection of controller parameters should not exceed this region. Besides, the designed current controller can satisfy the requirements and good performance can be achieved.

Acknowledgement

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References


