Development of Wide Range High Efficiency for Electric Propulsion System

Kun-Lun Chuang, Yong-Kai Lin, Shin-Hung Chang and Bo-Tseng Sung

Mechanical and Systems Research Laboratories, Industrial Technology Research Institute,
195, Sec 4, Chung Hsing Rd., Chutung, Hsinchu, Taiwan, R. O. C.,
KLChuang@itri.org.tw

Abstract
This study focuses on development of a control strategy for a 50kW permanent magnet synchronous motor (PMSM). Through above-mentioned control strategy, the performance of PMSM can be enhanced for wide speed ranges high efficiency. In this paper, vector control is implemented based on feed-forward current control strategy. Therefore, the feature of the proposed control scheme is to improve performance of the proportional-integral (PI) current control, including overshoot, transient response time and parameters tuning time. Finally, the effectiveness of the proposed control strategy for 50kW PMSM is verified by experimental results.

Keywords: PMSM, vector control, feed-forward current control, proportional-integral current control.

1 Introduction
In recent years, home application industry continuously requires high efficiency power electrical machine because of increasing demand of energy and environmental issues. The more energy and environmental regulations have been enhanced, the more various efforts to suppress increasing product cost have been attempted. Due to the advantages of small size, light weight, fast response and high efficiency, permanent magnet synchronous motor (PMSM) is widely used in aviation and aerospace, military, industrial and agricultural areas [1].

On the other hand, vector control clearly requires instantaneous control of stator current. Vector control usually realized with digital PWM controller in rotating (d-q) reference frame of vector control is to control flux and torque of machine to drive the motor to accurately trace the reference command value irrespective of load, machine parameter and any external environmental changes. In vector control stator current is controlled instantaneously which reduces the torque ripples and improves overall performance of machine [2]. Vector control PMSM drives decouples torque, flux and it also makes the control quite easier. Consequently, vector control becomes the core control strategy of PMSM.

In general, conventional proportional-integral-differential (PID)-type controllers have been widely used in industry due to their simple control structure, ease of design, and inexpensive cost. However, the PID-type controller can not provide perfect control performance if the controlled plant is highly nonlinear and uncertain. The motivation of this study is to design a real-time control scheme that possesses the evolutionary capability of the feed-forward current control strategy [3].

2 Dynamic model of PMSM
Mathematical modeling of motor is required for simulation and analysis of drive system. PMSM equations are presented in d-q reference frame [4]. The stator flux-linkage equations are given by:

\[ V_{qs} = r_s i_{qs} + \frac{d\lambda_{qs}}{dt} + \omega L_{ds} \lambda_{ds} \]  (1)
\[ V_{ds} = r_s i_{ds} + \frac{d\lambda_{ds}}{dt} - \omega_c \lambda_{qs} \]  
\[ (2) \]

where \( \omega_c \) is the electrical angular velocity, \( r_s \) is the stator resistance for per-phase, \( i_{qs} \) and \( i_{ds} \) are the d-q axes stator currents, respectively, \( V_{qs} \) and \( V_{ds} \) are the d-q axes stator voltages, respectively, \( \lambda_{ds} \) and \( \lambda_{qs} \) are flux linkages, respectively.

The d and q axes Flux Linkages in rotor reference frame are given by
\[ \lambda_{qs} = L_{s} i_{qs} + L_{m} i_{qr} \]  
\[ (3) \]
\[ \lambda_{ds} = L_{s} i_{ds} + L_{m} i_{dr} \]  
\[ (4) \]

The PM excitation can be modeled as a constant current source \( I_{f} \). The rotor flux is along the d-axis, so the d-axis rotor current is \( i_{fr} \). The q-axis current in the motor is zero, because there is no flux along this axis in the rotor, by assumption
\[ \lambda_{qs} = L_{qs} i_{qs} + L_{m} i_{qr} \]  
\[ (5) \]
\[ \lambda_{ds} = L_{ds} i_{ds} + L_{m} i_{dr} + L_{m} i_{fr} \]  
\[ (6) \]

where \( L_{m} \) is mutual inductance between the stator winding and rotor magnets. Above voltage equations can be represented in matrix form as given below

\[
\begin{bmatrix} V_{qs} \\ V_{ds} \end{bmatrix} = \begin{bmatrix} r_s + sL_{qs} & \omega_s L_{ds} \\ -\omega_s L_{qs} & r_s + sL_{ds} \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \end{bmatrix} + \begin{bmatrix} \omega_c \lambda_{fr} \\ 0 \end{bmatrix}
\]
\[ (7) \]

This is the dynamic model of PMSM used in vector control. The developed torque motor is being given by
\[ T_e = \frac{3}{2} \frac{P}{2} \left( \lambda_{ds} i_{qs} - \lambda_{qs} i_{ds} \right) \]  
\[ (8) \]

Use (5) and (6) into (8) can be rewritten as
\[ T_e = \frac{3}{2} \frac{P}{2} \left[ \lambda_{fr} i_{qs} + \left( L_{ds} - L_{qs} \right) i_{dr} i_{qs} \right] \]  
\[ (9) \]

Because motor is use interior permanent magnet (IPM). So \( L_{ds} = L_{qs} \), \( i_{qs} = i_{dr} = 0 \), \( L_{m} i_{fr} = \lambda_{fr} \). Therefore, according to (9) is expressed the follow equation [5].
\[ T_e = \frac{3}{2} \frac{P}{2} \left[ \lambda_{fr} i_{qs} + \left( L_{ds} - L_{qs} \right) i_{dr} i_{qs} \right] \]  
\[ (10) \]

The mechanical torque equation is
\[ T_e = J_m \frac{d\omega}{dt} + B_m \omega + T_L \]  
\[ (11) \]

where \( J_m \) is the moment of inertia of the motor, \( B_m \) is the viscous coefficient of the motor, \( T_L \) is the load torque, \( T_e \) is the motor torque, \( w_c \) is the mechanical rotor speed and equals to \( w_c = \frac{2}{P} \), where \( P \) is the number of the poles.

### 3 Control methodology

This research presents the performance development of wide range high efficiency for electric propulsion system. The control block diagram of the proposed control strategy is depicted in Fig. 1.

#### 3.1 Major Control Design

In this study, in order to achieve wide speed ranges high efficiency. First, there are two PI controllers which achieve current control of d-q axes. Secondly, feed-forward current control is introduced to compensate the performance of two PI current control outputs of d-q axes in overall operation range. Thirdly, the third harmonic injection is used to reduce computation complexity of a motor controller. Since simple computation of PWM signals, it can raise both rates of program execution and voltage utility. The detailed description of major control design is exhibited in the following subsections.

#### 3.1.1 PI controllers

The two PI controllers have high steady-state precision; easy algorithm, good stability and high reliability. Define current error of d-q axes, \( e_q^* = i_{qs}^* - i_{qs} \), and \( e_d^* = i_{ds}^* - i_{ds} \). Therefore, two PI current control outputs of d-q axes can be written as
\[ V_q = (K_p^p + \frac{K_i^p}{S}) e_q \]  
\[ (12) \]
\[ V_d = (K_p^d + \frac{K_i^d}{S}) e_d \]  
\[ (13) \]

where \( K_p^p \), \( K_i^p \), \( K_p^d \) and \( K_i^d \) are control gains, \( S \) is Laplace operator.
3.1.2 Feed-forward current control

The feed-forward current control equations of d-q axes via feedback current, motor speed, stator inductance, stator resistance and flux linking can be written as

\[
V_{qs\_ff} = r_i^* + \omega_L i_{ds} + \omega_L \lambda_f
\]  
(14)

\[
V_{ds\_ff} = r_i^* - \omega_L r_{qs}\cdot i_{qs}'
\]  
(15)

The cross couple control block diagram is depicted in Fig. 2. The cross couple control is introduced to compensate two PI current control error of d-q axes in overall operation range. It can be written as

\[
U_{qs\_cross} = K_{cross} \omega_L (i_{ds}^* - i_{ds})
\]  
(16)

\[
U_{ds\_cross} = K_{cross} \omega_L (i_{qs}^* - i_{qs})
\]  
(17)

where \(K_{cross}\) is cross couple gain.

Figure 2: Cross couple control block diagram

3.1.3 Harmonic injection

In order to reduce computation complexity and raised voltage utility. Therefore, the third harmonic injection is used in the major control system. It is designed in Fig. 3, and can be written as

\[
v_{\text{harmonic}} = -0.5(v_{\text{max}} + v_{\text{min}})
\]  
(18)

\[
v_{\text{max}} = \text{max} \{v_{as}^*, v_{hs}^*, v_{cs}^*\}
\]  
(19)

\[
v_{\text{min}} = \text{min} \{v_{as}^*, v_{hs}^*, v_{cs}^*\}
\]  
(20)

\[
v_{as}^* = v_{as}^* + v_{\text{harmonic}}
\]  
(21)

\[
v_{hs}^* = v_{hs}^* + v_{\text{harmonic}}
\]  
(22)

\[
v_{cs}^* = v_{cs}^* + v_{\text{harmonic}}
\]  
(23)

Figure 3: Harmonic injection control block diagram

4 Numerical simulation and experimental results

The detailed specifications of 50kW PMSM is shown in Table I.

<table>
<thead>
<tr>
<th>Item</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stator Outside Diameter</td>
<td>205 mm</td>
</tr>
<tr>
<td>Stator Inside Diameter</td>
<td>170 mm</td>
</tr>
<tr>
<td>Stator Inside Diameter</td>
<td>190 mm</td>
</tr>
<tr>
<td>Stack Length</td>
<td>80 mm</td>
</tr>
<tr>
<td>Min. air gap length</td>
<td>1 mm</td>
</tr>
<tr>
<td>Tooth width</td>
<td>8 mm</td>
</tr>
<tr>
<td>Stator Yoke width</td>
<td>15 mm</td>
</tr>
<tr>
<td>Max. Power</td>
<td>90 kW</td>
</tr>
<tr>
<td>Max. Torque</td>
<td>110 Nm</td>
</tr>
<tr>
<td>Max. Speed</td>
<td>1000 rpm</td>
</tr>
<tr>
<td>Sensor Type</td>
<td>Resolver and Hall Sensor</td>
</tr>
<tr>
<td>Slot Number</td>
<td>12 slots</td>
</tr>
<tr>
<td>Pole Number</td>
<td>6 poles</td>
</tr>
<tr>
<td>Nominal DC bus voltage</td>
<td>300 V</td>
</tr>
<tr>
<td>Maximum DC bus voltage</td>
<td>316 V</td>
</tr>
<tr>
<td>Maximum DC bus voltage</td>
<td>192 V</td>
</tr>
<tr>
<td>Supply Peak AC Current</td>
<td>350 A</td>
</tr>
</tbody>
</table>

Table I: The detailed specifications of 50kW PMSM

4.1 Numerical simulation

In this paper all numerical simulations are carried out using Matlab/Simulink software. Figure 4 shows the simulated results of d-q axes current control for the PI control strategy. As can be seen from subfigures (a)-(b) of Figs. 4, favorable tracking responses can be obtained. But occurrence of the overshoot and transient response are serious.

Figure 4: Control current of d-q axes for the PI control strategy
Figure 5 shows the simulated results of d-q axes current control for proposed control strategy. As can be seen from subfigures (a)-(b) of Figs. 5, favorable tracking responses can be obtained. From the simulated results in subfigures (a)-(b) of Figs. 5, the performance of the proposed control strategy can be achieved small occurrence of the overshoot and transient response. According to current of q axis in Fig. 4 (a) and Fig. 5 (a), the overshoot has 21 (A) improvements, and transient response has 0.006 (sec) improvements, in numerical simulations; than the PI control strategy. According to current of d axis in Fig. 4 (b) and Fig. 5 (b), the overshoot has 20 (A) improvements, and transient response has 0.006 (sec) improvements, in numerical simulations; than the PI control strategy. Consequently, the proposed control strategy is more suitable for electric propulsion system than the PI control strategy.

4.2. Experimental results

In order to realize the value of the proposed control strategy in practical applications, a digital signal processor (DSP) F2808-based control platform is used for electric propulsion system. The electric propulsion system includes motor and controller. In the study, Fig. 6 shows the 50kW PMSM and Fig. 7 shows the motor controller. The picture of the experimental set-up for electric propulsion system is depicted in Fig. 8.

This paper presents experimental results by a dynamometer. The experimental results include torque-speed curve as shown in Fig. 9, efficiency map as shown in Fig. 10, power and efficiency curves as shown in Fig. 11. Complete experiments guarantee the stability and the reliability of the electric propulsion system. From Fig. 9, the experimental result of torque-speed curve confirms that the maximum output torque of power module is 210 N.m. It is very obvious that good flux-weakening capability leads to wide speed range. We can got fine system performance in 3000~5000 rpm range as shown in Fig. 10.
Acknowledgments

The authors would like to acknowledge the financial support of Ministry of Economic Affairs (MOEA) of Taiwan, ROC, through grant number C353CC3100.

References


Authors

Kun-Lun Chuang was born in Hsinchu, Taiwan, R. O. C., in 1983. He received the B.S. degree in electrical engineering from Ming Hsin University of Science and Technology, Hsinchu, Taiwan, in 2006 and the M.S. degree in electrical engineering from Yuan Ze University, Taoyuan, Taiwan, in 2008. He is an engineer in Industrial Technology Research Institute, Hsinchu, Taiwan. His research interests include control theory applications and motor servo drives.

Dr. Yong-Kai Lin received the B.S., M.S., and Ph.D. degrees in electrical engineering from the National Taipei University of Technology, Taipei, Taiwan. He is currently an engineer in Mechanical and Systems Research Laboratories, Industrial Technology Research Institute, Hsinchu, Taiwan. His research interests include the field of fieldprogrammable gate array design and inverter control.
Dr. Shin-Hung Chang was born in Chung-Li, Taiwan, R. O. C., in 1979. He received the B. S. degree in electrical engineering from National Taiwan University of Science and Technology, Taipei, Taiwan, and the Ph. D. degree in electrical engineering from Yuan Ze University, Taoyuan, Taiwan, in 2002 and 2008, respectively. Since 2008, he has been a researcher and a project leader of EV key components in Industrial Technology Research Institute, Hsinchu, Taiwan. His research interests are intelligent, adaptive, and robust control theories and applications.

Mr. Bo-Tseng Sung was born in Taoyuan, Taiwan, R. O. C., in 1986. He received the B. S. degree in electronic engineering from Ta Hwa Institute of Technology, Hsinchu, Taiwan. He is an assistant engineer in Industrial Technology Research Institute, Hsinchu, Taiwan. His research interests are hardware design of motor controller, control and system integration.