Hardware Implementation of the Current Control Using the Internal Model Method in the Electric Power Steering Application

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Abstract—The object of this paper is to propose a development method for the implementation of the Electric Power Steering (EPS) system with the permanent magnet synchronous machine (PMSM). For achieving the desired assist power with good steering feel, the internal model control (IMC) method is applied to the current control loop of the PMSM. The IMC philosophy is used to generate parameters for conventional PI controllers. It can take the advantage mentioned to reduce the trial-and-error procedures and to shorten the development time for the EPS control system. In order to verify the control algorithm, this paper introduces the co-simulation technique to validate the proposed controller for high accurate description of vehicle dynamics and models of the steering behavior. Finally, the EPS control system is implemented by an embedded microprocessor. The results showed that the current control has good tracking performance, and both of simulations and experiments had the same steering responses.

Keywords—electric power steering; permanent magnet synchronous machine; internal model control.

I. INTRODUCTION

The EPS system has a compact structure compared with conventional one, and it is an on-demand system that operates only when the steering wheel is turned. Besides, the EPS has more flexibility by the advantage of electronic control of the motor. It is easy to adjust the steering system characteristic just by modifying the program of the EPS controller. This is also the reason why there are many features developed for the EPS system.

The magnitude, the direction, and the timing of torque output control of the assist motor are especially important. Hence, in order to develop the control logic for the EPS system, it needs to build the steering system model previously. Chen and Chen [1] applied Newton’s Law to build the dynamic model of every parts of the EPS system. Parmar and Hung [2] utilized the Lagrange’s Equations to construct the dynamic equations of the EPS system. Liao and Du [3] tried to combine the Matlab/Simulink and Adams to simulate the behavior of the vehicle and used the co-simulation technique to understand the effect of the EPS system on the vehicle motion. Choi et al. [4] associated SimPowerSystems with Matlab/Simulink to describe the effect of power electronics on the EPS system.

Furthermore, the assist power is provided by an electric motor and affects the steering feel directly. Kurishige et al. [5] and Pang et al. [6] introduced motor control methods for avoiding the fluctuation, from the rotation of the motor, to influence the steering wheel and preventing the driver from unfavorable steering feel.

The major purpose of this paper is to introduce a development method for the implementation of the EPS control system from simulation to experiment. According to the objective, this paper utilizes the co-simulation technique to predict the response between the EPS system and the vehicle before implementation. The IMC method has been adopted in the EPS control logic for the better current-tracking performance. This paper also employs the auto code-generation tool to implement the control algorithm on the embedded system, and carries out the EPS system on the test car.

II. MODELING

In this section, a mathematical model of the EPS system is considered, which is proper for controller design [7]. The schematic diagram of the EPS system is shown in Fig. 1. It is a typical column-type EPS system that consists of a torque sensor, an electric motor, a reduction gear, a column and a rack–pinion mechanism. In order to model the steering system behavior for the control logic design, it can obtain the equations of motion of the EPS system according to the Newton’s Law. The equations are shown below,

\[
T_h - K_t (\theta_{sw} - \theta_{sc}) - B_{sw} \dot{\theta}_{sw} = J_{sw} \ddot{\theta}_{sw}
\]

(1)

\[
T_{mn} + T_f - B_{sc} \dot{\theta}_{sc} + K_r (\theta_{sc} - \theta_{rs}) - k_r (\theta_{sc} - \frac{x_r}{r}) = J_{sc} \ddot{\theta}_{sc}
\]

(2)

\[
\frac{k_r}{r} (\theta_{sc} - \frac{x_r}{r}) - F_r - b_r \dot{x}_r = m_r \ddot{x}_r
\]

(3)

where \(T_h\) is the instructional torque on the steering wheel from the driver; \(K_t\) is the stiffness of the torsion bar; \(J_{sw}\) and \(B_{sw}\) are the inertia and the damping constant of the steering wheel; \(\theta_{sw}\) and \(\theta_{sc}\) are the steering wheel angle and the steering column angle respectively. \(T_{mn}\) and \(T_f\) are the electromagnetic drive and the friction torque on the steering column; \(J_{sc}\) and \(B_{sc}\) are the
inertia and damping constant of the steering column. \( k_r \) is the stiffness between the rack and pinion; \( x_r \) is the displacement of the rack; \( r \) is the stroke ratio. The angle of the pinion is equal to the column angle. \( F_r \) is the alignment force on the rack from the road wheel; \( m_r \) and \( b_r \) are the mass and the damping constant of the rack.

For better assistance performance, a 3-phase PMSM is adopted as the assist motor. In order to model the dynamics of PMSM, it can be described in the well-know d-q frame through the rotation reference frame transformation \[8][9]. The motor dynamic equation is stated as follows.

\[
T_m = n T_{ml} \quad (4)
\]

\[
T_m = i_q P \quad (5)
\]

\[
\begin{bmatrix}
V_d \\
V_q \\
\end{bmatrix} =
\begin{bmatrix}
R_d & \frac{d}{dt}L_d & -\omega_L L_q \\
\omega_L L_d & R_q & \frac{d}{dt}L_q \\
\end{bmatrix}
\begin{bmatrix}
I_d \\
I_q \\
\end{bmatrix}
+ \begin{bmatrix}
0 \\
\omega_L \phi_m \\
\end{bmatrix} \tag{6}
\]

\[
T_m - T_{ml} - B_r \theta_m = J_m \ddot{\theta}_m \quad (7)
\]

\[
\theta_e = \frac{P}{2 \theta_m} \quad (8)
\]

Equation (6) and (7) are the electrical and the mechanical equation of the PMSM. \( T_m \) and \( T_{ml} \) are the electromagnetic drive and the counter balance torque on the motor shaft, respectively; \( n \) is the gear ratio. \( V_d \) and \( V_q \) are the applied stator voltages; \( I_d \) and \( I_q \) are the stator currents; \( L_d \) and \( L_q \) are the d and q direction inductances; \( R_d \) and \( R_q \) are the stator resistance and the rotor electrical position, respectively. \( J_m \) and \( B_m \) are the inertia and damping constant of the motor; \( \theta_m \) is the mechanical position of the rotor. \( P \) is the number of the magnet poles on the rotor. \( \omega_L \) is the electrical speed of the rotor. \( \phi_m \) is the back electromotive force. The term, \( (P/2)\phi_m \), is the torque constant. For more exact simulation, this paper adopts the space vector control method to achieve the current control objective. The realization of pulse-width modulation (PWM) takes the advantage of the unified voltage modulation technique which is described clearly in reference [10]. Fig. 2 shows the simulation block diagram of the PMSM with space vector control in Matlab/Simulink environment. The model includes the PI controllers for the d and q direction by means of the IMC method, a space vector PWM model using the unified voltage modulation technique, a PMSM which is modeled in the rotor coordinate, and a load model simulating the brake effect.

Combining the PMSM model with the EPS system model is helpful to find problems caused by the motor before the implementation.

Matlab/Simulink is an equation-domain modeling tool. It is very complex to model the full car dynamics in this environment. This paper, therefore, uses CarSim to simulate the behavior of the vehicle motion. CarSim can show how vehicles respond dynamically to the inputs from the driver and the immediate environment. It produces the same kinds of outputs that might be measured with physical tests involving instrumented vehicles. For this reason, it is a good tool to simulate the full car behavior while cornering.

### III. CONTROL

For obtaining good tracking ability of current control, this paper applied the IMC method to the EPS control system. The main benefits of the IMC method are as follows. First, the PI current controllers are obtained easily. Second, the control gains are expressed directly in the PMSM parameters and the desired closed-loop bandwidth [11]. According to the benefits mentioned above, applying the IMC method can reduce the trial-and-error process time in PI controller, and, moreover, get the characteristic of the system. The IMC concept is depicted in Fig. 3.

The IMC design procedure consists of two main steps, which provide reasonable tradeoff between performance and robustness. The first step ensures that \( \ddot{Q}(s) \), the designed controller, is stable and casual. In this paper, the electrical dynamics of the PMSM is stated in (6). The back electromotive force term is considered to be a quasi-constant which can be included in the q direction voltage as \( V_q' = V_q + \omega_e \phi_m \). Since there is normally a separation in dynamics of at least one decade between the stator current and the rotor speed, the mechanical dynamics can be disregarded [11]. Equation (6) will be rewritten as follows.

\[
\begin{bmatrix}
V_d' \\
V_q' \\
\end{bmatrix} =
\begin{bmatrix}
R_d & \frac{d}{dt}L_d & -\omega_L L_q \\
\omega_L L_d & R_q & \frac{d}{dt}L_q \\
\end{bmatrix}
\begin{bmatrix}
I_d \\
I_q \\
\end{bmatrix}
\tag{9}
\]

Then the Laplace transform of the (9) is as follows,

\[
\begin{bmatrix}
\dot{V}_d(s) \\
\dot{V}_q(s) \\
\end{bmatrix} = \begin{bmatrix}
L_d & R_d & \frac{d}{dt}L_d \\
\omega_L L_d & R_q & \frac{d}{dt}L_q \\
\end{bmatrix}
\begin{bmatrix}
\dot{I}_d(s) \\
\dot{I}_q(s) \\
\end{bmatrix} = P^{-1}(s) \begin{bmatrix}
\dot{I}_d(s) \\
\dot{I}_q(s) \\
\end{bmatrix} \tag{10}
\]
Figure 3. Internal model control concept.

Figure 4. Equivalence of the ‘internal model’ and the ‘conventional’ structure.

where

\[ P(s) = \frac{1}{\Delta(s)} \begin{bmatrix} sL_q + R_a & \omega_s L_q \\ -\omega_s L_d & sL_d + R_a \end{bmatrix} \]  \hspace{1cm} (11)

and

\[ \Delta(s) = s^2 L_d L_q + s(L_d + L_q)R_a + R_a^2 + \omega_s^2 L_d L_q. \] \hspace{1cm} (12)

Considering the equation (11), the \( P(s) \) is minimum-phase and invertible, and then the IMC controller is defined as

\[ \tilde{Q}(s) = \tilde{P}^{-1}(s) \] \hspace{1cm} (13)

It is stable and causal.

The second step argues \( Q(s) \) with filter \( F(s) \) such that the final IMC controller will state as follows.

\[ Q(s) = \tilde{Q}(s)F(s) \] \hspace{1cm} (14)

It can obtain the final form for the closed-loop transfer function as

\[ C(s) = \frac{\tilde{Q}(s)F(s)\tilde{P}(s)}{1-\tilde{Q}(s)F(s)\tilde{P}(s)}. \] \hspace{1cm} (15)

For no offset to step input, the term, \( \tilde{Q}(0)F(0)\tilde{P}(0) \), must equal to one, which requires \( \tilde{Q}(0) = \tilde{P}^{-1}(0) \) and forces \( F(0) = 1 \). A common filter choice that conforms to this requirement is

\[ F(s) = \frac{\lambda^n}{(s+\tilde{\lambda})^n}, \] \hspace{1cm} (16)

The filter order \( n \) is selected large enough to make \( Q(s) \) proper, while \( \lambda \) is an adjustable parameter which determines the speed-of-response. Increasing \( \lambda \) increases the closed-loop time constant and slows the speed-of-response; decreasing \( \lambda \) does the opposite. The \( \lambda \) can be adjusted on-line to compensate for model mismatch in the design of the control system; the higher the value of \( \lambda \), the higher the robustness the control system [12]. Using the IMC method to design the current controller for the PMSM is proper, since the \( P(s) \) is stable and minimum-phase. It, therefore, can select the parameter \( n = 1 \). The IMC may be considered as a classic feedback control structure shown in Fig. 4. The controller \( C(s) \) can be expressed as follows.

\[ C(s) = [1 - Q(s)\tilde{P}(s)]^{-1}Q(s) = [1 - F(s)]^{-1}\tilde{Q}(s)F(s) \]

\[ = \frac{\lambda}{s} \tilde{Q}(s) = \lambda \left[ \frac{L_d + R_a}{s} - \frac{\omega_s L_q}{s^2} \right] \] \hspace{1cm} (17)

There are two quasi-PI controllers shown in the (17). The quasi-PI gains are shown bellow.

\[ K_{pd} = \lambda R_d, \quad K_{id} = \lambda R_a, \quad K_{pu} = \lambda L_q, \quad K_{iu} = \lambda L_a. \] \hspace{1cm} (18)

Consequently, the \( \lambda \) represents the desired closed-loop bandwidth. The controller designed in Simulink is shown in Fig. 2.

IV. RESULTS

A. Simulation Results

To satisfy the various conditions while cornering, the good current-tracking control method for the EPS system has been developed. This paper integrates the Matlab/Simulink with CarSim to research and analyze the interaction between the vehicle behavior and the characteristic of the EPS system. For shortening the development time and verifying the control algorithm quickly, this paper takes the advantage of MathWorks embedded code generator to generate the C code for the DSP chip directly.

Figure 5. The closed-loop frequency response of PMSM current control system.
This paper takes a surface-mounted PMSM for power assistance. In order to achieve the good current-tracking ability, the IMC method has been adopted to design a suitable controller. Fig. 5 and Fig. 6 are the frequency response and step response of closed-loop respectively. The sampling frequency is set as 5 kHz. The simulation results show that the closed-loop bandwidth is about 500 Hz. The closed-loop rise time is less than 0.355 ms. It is fast enough in the PMSM current control since the current rise times of about 1ms are common.

To simulate the interaction between the EPS and the vehicle, and to confirm the current control performance in the overall system, this paper utilizes the co-simulation technique to verify each models and controllers. Fig. 7 shows that the co-simulation block diagram. In this simulation, the base assist map has been adopted, and the weave test has been applied. The amplitude of the steering input is 250 degree. The speed of steering input is 25 deg/s. Fig. 8 shows that the motor has good tracking performance for current control.

B. Experiment Results

Finally, for realizing the base assist logic and the current control algorithm, this paper utilizes model-to-chip technique to implement the control method on the embedded-DSP. Fig. 9 shows the Matlab/Simulink code that is the source code of the EPS control system. Fig 10 and Fig 11 show the experiment results of the PMSM current control by using IMC method. This method provides a way to obtain the suitable parameter for conventional PI-controller easily and to reduce the trial-and-error procedures in the PMSM current control. The data are acquired from DSP. According to the experiment results, the current control has good tracking ability and response. It means that the IMC method is a very proper technique in the PMSM current control.

Fig. 12 shows that experiment results are compared with the simulation results. The image of Fig. 13 shows the surrounding of the real car test. The experiment results demonstrate that the steering system with the EPS has better steering feel and makes drivers more comfortable. Compared with the simulation results, there are similar responses in the simulation and the experiment. It means that the simulation can predict the system performance effectively before implementation. Furthermore, the control algorithm has been verified on the real car test.
In this paper, the IMC method is adopted to the EPS system with PMSM. As a result, the PI controller is able to provide the good tracking performance and has been shown in the simulation results. The co-simulation technique is helpful to verify the designed controller, and predict the system interaction and response before the hardware implementation. The control algorithm and logic have been confirmed effectively and rapidly on the EPS-equipped vehicles by using the auto code-generate tool. In the future, the various control algorithm and strategies will be carried out on the EPS-equipped vehicles to verify its feasibility.

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REFERENCES
