Research on Vector Control Simulation Based on Field-Road Coupling

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Abstract. In vector control simulation, the MATLAB/Simulink model of the permanent magnet synchronous motor cannot fully simulate the inherent characteristics of the motor. It leads to problems such as reduced simulation accuracy and limited applicability of analysis results. In order to solve these problems, this paper designs a joint simulation model. This model is established based on the direct field-circuit coupling equation and the vector control strategy. It can take into account both the analysis of the electromagnetic characteristics of the motor and the analysis of the control circuit. This paper analyzes the speed, current and electromagnetic field distribution under different working conditions, and these simulation results show that the model is feasible.

Introduction

As the core component of electric car, the motor drive system mainly functions are energy conversion and power output [1]. A suitable motor drive system can not only provide sufficient torque output but also has excellent speed regulation performance. A vector control system composed of a permanent magnet synchronous motor (Permanent Magnet Synchronous Machine (hereinafter referred to as PMSM) and vector control can not only take advantage of the high power density, high precision and high efficiency of PMSM, but also improve the speed and flexibility of the drive system. The performance is in line with the requirements of electric car for electric drive systems [2].

During the design and debugging of PMSM vector control system, it is necessary to simulate it practically and accurately. At present, many scholars have done a lot of work on vector control simulation. Reference [3] designed a parameter adaptive PMSM vector control system based on fuzzy control theory. Reference [4] optimized SVPWM link in vector control. Reference [5] proposed a vector control simulation model without position sensor based on the MRAS principle. These simulation models were established based on mathematical models of various components, which can realize precise modeling of control principles and control algorithms [6]. However, due to the inherent characteristics of the motor (electromagnetic distribution, magnetic pole shape, cogging effect, etc.), this MATLAB/Simulink model based on circuit simulation cannot completely simulate the actual operating conditions, which makes this model simulation analysis accuracy is reduced, and the applicable range is limited [7].

In view of the shortcomings of the above simulation models, this paper established a joint simulation model of PMSM vector control based on the field-circuit direct coupling method [8]. This model takes small PMSM as the research object. First, we built an electromagnetic model of the motor by the finite element analysis software, and established corresponding vector control circuit by Simulink. Then, the interface model of joint simulation is designed based on the solving equation of field-circuit direct coupling. Finally, in order to check the rationality and feasibility of the entire system, this paper analyzes two different operating conditions.

This paper is organized as follows. In Section II, the method of field-circuit and solving equation are given. In Section III, interface model is designed and the co-simulation model are introduced. In
Section IV some data and graphics are analyzes and the model is proven logical. Conclusions are drawn in Section V.

Field-Circuit Coupling Method and Solving Equation

The coupling method uses direct coupling. The finite element model of the motor receives the voltage signal generated by the external control circuit model. Output signals can be obtained by solving the magnetic field equation and the voltage balance equation. The coupling method is shown in Figure 1.

![Electromagnetic Model](image)

**Figure 1. Direct field-coupling method.**

The phase voltage output by the control circuit is $U_m$, the armature phase current is $i_m$, the equivalent resistance is $R_m$, and the leakage inductance of each phase is $L_m$. For a star-connected PMSM, the voltage balance equation can be described in

$$U_m = R_m i_m + L_m \frac{di_m}{dt} + e_m.$$  \hspace{1cm} (1)

Using the induced electromotive force $e_m$ as an intermediate variable, Simultaneous voltage balance equation and finite element expression of induced electromotive force, by the way, the matrix expression of the voltage balance equation can be obtained

$$\{U\} = -2pL_{ef} [C]^T \begin{bmatrix} \dot{A} \end{bmatrix} + [R] \{I\} + [L] \begin{bmatrix} \dot{A} \end{bmatrix}.$$  \hspace{1cm} (2)

In this equation, $\{U\}$ is the phase voltage vector, $p$ is the number of pole pairs of the motor, $L_{ef}$ is the armature length, $[C]^T$ is the matrix coefficient which was decided by the finite element division method, $\begin{bmatrix} \dot{A} \end{bmatrix}$ is the derivative of magnetic potential vector $[A]$ with respect to time.

For the motor model, the Maxwell equations are discretized by the weighted margin method, combined with the electromagnetic field finite element analysis method, and the first-order linear triangle is used as the division unit. its discrete matrix expression can be given

$$[K] \{A\} + [T] \begin{bmatrix} \dot{A} \end{bmatrix} = [C] \{I\}.$$  \hspace{1cm} (3)

Simultaneous equations (2) and (3) can solve magnetic potential vector $[A]$ and current $[I]$. Combining the value by the above equation with the mechanical motion equation of the stator can solve the motor speed and mechanical angle. The equation of mechanical motion is as follows

$$T_{em} = T_L + J \frac{d\Omega}{dt} + D\Omega.$$  \hspace{1cm} (4)
Simulation Model Design

The design of the field-circuit coupling model can be divided into three parts: control model design, interface model design, and finite element model design. Some parameters of the prototype are shown in Table 1.

Table 1. Prototype Parameters.

<table>
<thead>
<tr>
<th>Parameter name</th>
<th>Property</th>
<th>Parameter value</th>
<th>Symbol</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of pole pairs</td>
<td></td>
<td>2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Number of slots</td>
<td></td>
<td>24</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Rated voltage</td>
<td></td>
<td>288 U</td>
<td>U</td>
<td>(V)</td>
</tr>
<tr>
<td>Rated speed</td>
<td></td>
<td>1800 n</td>
<td>n</td>
<td>(rad·min⁻¹)</td>
</tr>
<tr>
<td>Rated current</td>
<td></td>
<td>2.5 I</td>
<td>I</td>
<td>(A)</td>
</tr>
<tr>
<td>Stator phase resistance</td>
<td></td>
<td>3.3 R</td>
<td>R</td>
<td>(Ω)</td>
</tr>
<tr>
<td>Moment of inertia</td>
<td></td>
<td>3.6×10⁻⁴ J</td>
<td>J</td>
<td>(kg·m²)</td>
</tr>
</tbody>
</table>

Control Model Design

This paper uses $I_d = 0$ vector control strategy. The entire control model uses a double closed-loop PI control structure, the feedback signal is the real-time speed of the motor and the dual-axis current. The system obtains the reference voltage signal of the d-q axis by the PI controller of the inner current loop and the outer speed loop. The voltage signal is used as the input signal of the SVPWM link to control the drive signal of the inverter. The DC voltage source outputs a three-phase voltage which is corresponding the speed of real-time, and then this voltage is fed to motor. The control block diagram is shown in Figure 2.

Finite Element Model

The finite element model of the motor can be established by various finite element software. The steps for building a finite element model using JMAG software are as follows.
(1) Draw the geometric model of the motor, divide the fixed rotor area and define the boundary conditions.

(2) Import the finite element parameters of the internal coil. Connect the necessary measuring probes.

(3) Set the motor rotation mode to be driven by the mechanical angle change of the external circuit, and establish the input and output of the electromagnetic model.

**Interface Model**

According to the solving equation and the coupling method, the finite element model needs to accept input voltage from an external control circuit, and it will output electromagnetic torque and current.

Define the three input ports of the interface model according to the above requirements, they are $U_u$, $U_v$, $U_w$. Define four output ports, they are $I_u$, $I_v$, $I_w$ and $T_e$. The three-phase current signal is connected to the internal current loop as the feedback signal of the current inner loop after the coordinate transformation module. Because the motor speed is controlled by an external circuit, the driving signal in the finite element model needs to be an external driving signal. In this paper, the change amount $\Delta \theta$ of the position angle between adjacent sampling times is selected as the driving signal of the motor. The interface design is shown in Figure 3.

![Figure 3. Interface model design.](image)

The submodule in the figure is used to output the position angle and speed. It was built based on the mechanical motion equation of the rotor.

**Simulation Results and Analysis**

**Co-simulation Model**

According to the above design, the field-circuit coupling vector control simulation system is completed, and its simulation model is shown in figure 4.
Results and Analysis

Set the motor reference speed to 1800r/min, add a load of $5N\cdot m$ at 0.6s, and the total running time is 1.5s. The change of the motor speed and d-q axis current are shown in Figure 5.

Before the load is applied, the speed of the motor changes drastically in the time period of 0.05s, then acceleration gradually stabilized, overall speed rises steadily. This system speed adjustment process takes 0.5s, it reaches 95% of the expected speed at 0.3s and there is no overshoot in the entire speed-up process. This shows that the entire system has great accuracy and good rapidity. For the current of q axis, it has the same trend as speed change, and for the current of d axis, it changes around zero, this means that the simulation system conforms to the mathematical model of the control strategy before the load is applied. After load is applied, the steady state is broken. The speed starts to decrease and the q axis current increases. After 0.7s, the system returns to stability, this shows that the model has a certain anti-interference ability.

For the PMSM, when it works in a steady state, its magnetic field distribution should be regular and symmetrical. Taking the electromagnetic field distribution chart at 1.4s and display the magnetic potential of each point. At this time, the motor runs stably, and the magnetic potential distribution and magnetic field intensity distribution conform to its own law. The magnetic potential distribution and magnetic field intensity distribution are shown in the figure 6.
Conclusion

In this paper, a multiphysics simulation model for PMSM vector control is established based on the field-circuit direct coupling method. Compared with the traditional MATLAB / Simulink model, this model replaces the motor circuit analysis model in the traditional model with a finite element model that can reflect the electromagnetic field characteristics of the motor. Make the analysis results have better practical reference value. By analyzing the output results of the model under common working conditions, the rationality of the coupled model is verified. The establishment of this model is of great practical significance to reduce the gap between simulation scenarios and actual working conditions, alleviate the problem of disconnection between theoretical models and actual models, reduce the time required for system joint tuning, and promote the development of electric car drive technology.

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References


