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Research on model based design method of permanent magnet synchronous motor servo system based on FPGA

Shimao Yu\textsuperscript{1,3}, Tao Zhang\textsuperscript{1,2}, HuaJiang Zhang\textsuperscript{1}, Peng Zeng\textsuperscript{1} and Xiyou Chen\textsuperscript{2}

\textsuperscript{1}Key Laboratory of Industrial Control Network and System, Shenyang Institute of Automation, Chinese Academy of Sciences. Shenyang, China.
\textsuperscript{2}School of electrical engineering, Dalian University of Technology. Dalian, China.
\textsuperscript{3}E-mail: yushimaosia.cn

Abstract. The ac servo system plays an increasingly important role in modern society. The ac servo drive technology based on FPGA becomes important research direction for its advantages of fast processing speed and flexible designing. A permanent magnet synchronous motor servo control system based on FPGA was model-based designed in this paper. It built three-closed-loop servo control model in Simulink which can simulate the performance of the algorithm, and it completed automatic code generation and configuration in Xilinx Zynq-7000. In addition, it built a complete set of permanent magnet synchronous motor servo control hardware platform. This paper proposes an integrated design and simulation method based on FPGA servo control to improve the efficiency of system design.

1. Introduction
With the progress of science and technology, the application demand of servo control is higher and higher. The traditional servo control scheme based on single chip microcomputer (MCU) and digital signal processor (DSP) has been relatively mature, but the problem of relative shortage of resources is increasingly prominent [1, 2]. The ac servo control board is usually composed of multiple chips. The servo control system based on field programmable gate array (FPGA) is getting more and more attention due to its advantage of resource reconfiguration and parallel computing.

Traditional servo control design requires several parts, including development, simulation, testing, and so on. It is typically developed in code-based form, and tested in entity form [3]. The development process is trivial and difficult to debug. This paper proposes a model-based design method based on Zynq-7000. The permanent magnet synchronous motor servo control model is built, simulated and tested in Simulink, so that developers can verify the algorithm. The model is automatically converted to code through Matlab HDL Coder function. Function can be modified by changing the model parameters, then the code is automatically generated again. The system hardware platform of testing and validation is established. This method greatly improves the efficiency of development and validation.

2. System development method

2.1. System development process
Complete servo control system is composed of position loop, speed loop, current loop and space vector pulse width modulation (SVPWM) module [4]. This chapter introduces the development
method of servo control system based on FPGA. Firstly the complete servo control system simulation model is designed in Simulink. At the same time, the servo model can be converted into hardware code and downloaded to FPGA for function verification through Simulink HDL Coder function. FPGA can utilize the advantages of parallel computing in the complex servo algorithm. Large number of matrix computations are realized by multiple logic gate control, which improves the computational efficiency. The system design process of model development and verification is shown in figure 1.

![Figure 1. System design process.](image1)

### 2.2. Servo control system model
The FPGA-based servo control scheme is shown in figure 2. FPGA mainly realizes the control algorithm part based on model design. The permanent magnet synchronous motor simulation model can be used to verify the function of the servo control algorithm in Simulink. The servo control system is mainly composed of three-closed-loop feedback system. The current loop adopts the vector control method. The input of the torque component Iq is the output of speed loop after PI control. The excitation component Id is 0. SVPWM pulse is generated through a series of coordinate transformation and feedback regulation, which controls six-way insulated gate bipolar transistor (IGBT) to generate variable-frequency three phase voltage to the motor.

![Figure 2. Servo control scheme based on FPGA.](image2)

### 3. System modeling and simulation
This section introduces the detailed modeling method of the servo control function modules. There are some limitations to building the model that can be run with hardware code. Firstly Simulink provides a model library that can be converted to hardware code. Code-convertible model can be built in the library. Secondly the signal form of FPGA is logic level. It is difficult to handle floating-point data in FPGA. All the signals should be set to fixed-point data during model designing.

#### 3.1. Current loop modeling
The current loop is designed according to the current vector control method. The basic idea of the method is to convert the three-phase coordinate system into the d-q coordinate system which is
synchronized with the motor rotor [5]. The excitation component \( I_d \) and the torque component \( I_q \) are controlled respectively. Then the SVPWM wave is generated through the SVPWM control technology. The coordinate transformation is mainly the Clarke transform and the Park transformation. The Clarke transform is to transform the three-phase static coordinate system into two-phase static coordinate system. The \( \alpha \) axis is coincide with a axis, and the \( \beta \) axis is orthogonal with a axis. The formula is shown as in equation (1).

\[
\begin{bmatrix}
U_{\alpha} \\
U_{\beta}
\end{bmatrix} = \frac{2}{3} \begin{bmatrix}
1 & -\frac{1}{2} & -\frac{1}{2} \\
0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2}
\end{bmatrix} \begin{bmatrix}
U_a \\
U_b \\
U_c
\end{bmatrix}
\]

(1)

The Park transformation transforms the two-phase static coordinate system into the synchronous rotation coordinate system. The \( d-q \) coordinate system is synchronized with the motor rotor. The Angle is \( \theta \) with \( \alpha \) axis. The Park transformation matrix is shown as in equation (2).

\[
\begin{bmatrix}
U_d \\
U_q
\end{bmatrix} = \begin{bmatrix}
\cos \theta & \sin \theta \\
-\sin \theta & \cos \theta
\end{bmatrix} \begin{bmatrix}
U_\alpha \\
U_\beta
\end{bmatrix}
\]

(2)

The coordinate transformation module is constructed by basic logic operation module, and the Sine/Cosine calculation is realized by the look-up table module. The current loop model is shown in figure 3.

![Figure 3. Current loop model.](image)

The PI regulation of the current vector control is incremental PID, which replaces the integral accumulation by calculating the increment. The calculating formula is shown as in equation (3). The model structure of PI adjustment of the torque component is shown in figure 4.

\[
\Delta u[n] = K_p[e[n] - e[n-1]] + K_i\sum_{k=0}^{n} e[k] + K_d[e[n] - 2e[n-1] + e[n-2]]
\]

(3)

![Figure 4. Current vector PI regulation model.](image)

3.2. Speed and position loop modeling

The speed and position loop is an important part of servo control system to realize precise speed and position control. The motor simulation model in Simulink can show speed and position state of the
motor in real time. The speed and position data can be used as feedback parameter for PI adjustments. However, this is limited to the control algorithm simulation, and the actual control system needs encoder values to calculate speed and position information [6].

The synchronous motor used in the experiment is Nanotec company DB42M03. The encoder value is 4000 points per turn. It adopts the form of four times counting, namely 16000 points per turn in the encoder counting program. Figure 5 shows the model of speed calculation and speed PI adjustment.

![Figure 5. Speed loop model.](image)

The velocity is calculated by the delay method. Position difference is obtained and so as the velocity. The formula is shown in equation (4). \( s_1 \) and \( s_2 \) are the coding difference of two moments. \( t \) is the time. The velocity unit is converted to turn per minute. Sampling time of the model is \( 10^{-6} \) s and the delay is 100 sampling points. The function of MATLAB Function is to determine whether the encoder passes zero, and compensate for correct coding difference. The modeling of the position loop is similar to the speed loop.

\[
V(\text{r/min}) = \frac{(s_1-s_2) \times 60}{16000 \times t}
\]  

(4)

3.3. Modeling and simulating of the whole model

After each part of the servo control model is completed, the system-level interconnection and simulation can be performed to verify the algorithm. The servo control simulation model is shown in figure 6.

![Figure 6. Servo system simulation model.](image)

The data type of FPGA servo control algorithm is discrete. External input and output is connected to AD and DA modules. The system output is connected to the permanent magnet synchronous motor model. The system input is position instruction that is in the form of sine. The amplitude is 10 rad and the frequency is 10 rad/s. The PI parameter is adjusted to the appropriate value. The motor is in no-load condition. The simulation output is shown in figure 7.
The first line of the window shows the target position input and the position output of the permanent magnet synchronous motor after servo control. The position control has a slight delay. The second line shows the SVPWM waveform of the unmodulated system output. The servo control function is realized. This method makes it convenient for development and validation of the algorithm, which reduces the difficulty of debugging and modification.

4. Code transformation method and debugging

4.1. Code transformation method and simulation
The modeling and code conversion method is shown in figure 8. Firstly HDL Coder hardware development kit was added in the Simulink model library, and the model was built in the library. HDL Workflow Advisor can set parameters for code generation, hardware platform, and compiler toolchain. After checking the compatibility of the model, the HDL language files and the related hardware test files can be generated, and the complete FPGA project is generated. In order to verify the correctness and feasibility of the generated code, HDL Workflow Advisor function can not only generate the complete algorithm code, but also the matching simulation test files. Code-level simulation tests can be made to verify the correctness of the code.

4.2. Code development and integration
Although the servo control algorithm can be model-based developed, the complete permanent magnet synchronous motor control system still needs the encoder counting function and the current feedback...
AD sampling function. Drivers are written in code form in FPGA. The overall structure of system development is shown in figure 9.

![Figure 9. The overall structure of system development.](image)

The motor type of the design is Nanotec’s DB42M03. The encoder has a dial of 4000 scales. The encoder produces a differential pulse every time when passes by a scale. FPGA receives the differential pulse and judges the direction of rotation by the order of differential signal. At the same time, the zero point correction is performed according to a set of zero-point indicating signals. The AD chip is dual-channel 12 bits AD9226. FPGA provides AD sampling clock and receives 12 bits parallel data. FPGA is the control core, and the servo control algorithm is developed by modeling. The code is verified and generated in Matlab. FPGA program adds encoder counting function and AD driver module. Meanwhile it integrates the code and provides a global clock. Complete motor control program design is completed.

5. System test
After the FPGA servo control project is designed, the system hardware platform is connected including FPGA development board, inverter, synchronous motor, power supply, etc. The testing method is to add debug core in the Vivado development environment. Signal data in FPGA can be sampled in real time to observe system performance. The torque component Iq is sampled in debugging core as shown in figure 10(a). The target input of Iq is pulse of plus-minus 0.2. The output torque component will follow the input target after PI regulation. The step response of current loop control is fast. Position loop test is shown in figure 10(b). The input target is 500 turn, and the final turn of the motor is 499.7. The error is 0.06%. Servo control is realized.

![Figure 10. Real-time sampling results of FPGA signals.](image)

In oscilloscope measurement, the three-phase SVPWM wave of FPGA output is shown in figure 11(a). The three-phase current is shown in figure 11(b), and the phase difference is 120°. The motor runs well.
Figure 11. Oscilloscope measurement of the motor voltage waveform.

6. Conclusions
In this paper, a model of permanent magnet synchronous motor servo control system based on FPGA is designed and simulated through model-based design method. After that, the code is automatically generated through the HDL Coder function. The encoder counting module and AD sampling module are built in code form. The hardware platform of the servo control system is established and the servo control algorithm is verified. This method makes full use of the flexibility and calculation performance of FPGA and improves system extendibility and bandwidth. At the same time, it reduces the difficulty of system development and makes function verification and debugging more convenient.

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