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作者：　周治国，孙佳恩，于家宝，周学华
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A PMBLDC motor measurement and control system that can be used for ZYNQ hardware-in-the-loop simulation

Zhou Zhiguo, Sun Jiaen, Yu Jiabao, Zhou Xuehua

(School of Information and Electronics, Beijing Institute of Technology, 100081, China)

Abstract: In the modeling of permanent magnet brushless dc(PMBLDC) motor, it is difficult to modify the control algorithm, inconvenient to add and remove the closed loop, and has poor real-time measurement and control capability. Aiming at these problems, this paper uses Simulink graphical modeling platform, based on hall sensor position detection algorithm and PID control algorithm, *combined with piecewise linear method to generate PWM waveform*, proposes a new closed-loop measurement and control method. And then carrying out a sudden load and sudden speed simulation to verify the established PMBLDC motor measurement and control system. The simulation results show that the system has great stability. Besides, it is easy to modify and delete the algorithm module, and it can be quickly deployed in the hardware platform. At the same time, Simulink provides graphical interface for measuring and controlling the hardware-in-the-loop real-time simulation.

Key words: Simulink; permanent magnet brushless dc(PMBLDC) motor; hall sensor position detection algorithm; PID control algorithm; piecewise linear method; PWM

一种可用于 ZYNQ 硬件在环仿真的 PMBLDC 电机测控系统

周治国，孙佳恩，于家宝，周学华

（北京理工大学信息与电子学院，北京市，100081）

摘要：永磁无刷直流电机（PMBLDC）建模仿真存在着修改控制算法困难、添加和删除闭环不方便、实时测控能力较差等问题。针对这些问题，利用 Simulink 图形化建模平台，基于霍尔传感器位置检测算法和 PID 控制算法，*结合分段线性法生成 PWM 波形*，提出了一种新型的闭环测控方法，并对所建立的 PMBLDC 电机测控系统进行了突增负载和突增转速的仿真测试。仿真结果证明了该系统具有很好的稳定性，且可以快速部署在 ZYNQ 平台进行调试，同时 Simulink 提供了可供硬件在环实时仿真测控的图形化界面。

关键词：Simulink；永磁无刷直流（PMBLDC）电机；霍尔传感器位置检测算法；PID 控制算法；分段线性法；PWM

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Introduction

PMBLDC motor has been developing rapidly in recent years and has attracted much attention due to its small size, good performance, simple structure, high reliability and high output torque. With the continuous expansion of PMBLDC motor applications, it is of great significance to develop a higher

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Biography: Zhou Zhiguo(1977-), Male, Hubei Wuhan, Doctor, Associate Professor, Deputy Director of Institute Of Signal And Image Processing (Beijing Institute of Technology), Research direction for the simulation method and application.

standard motor control system. In the development process of motor measurement and control, the focus should be on good control performance, easy to be deployed on hardware platform and short development cycle [1,2,3]. Therefore, how to build a high efficiency simulation model of PMBLDC motor control system has become an urgent problem to be solved.

The research of PMBLDC motor modeling and simulation method is an extremely important process, but there are still some problems such as taking up too much computing resources, poor real-time performance, difficulty in modifying the control algorithm and inconvenience in adding and removing the closed loop[3]. This paper puts forward a new kind of PMBLDC motor modeling method based on Simulink graphical modeling platform, all parts of which are modularized. We respectively established the motor module, the speed controller module, the 3-phase inverter module, the piecewise linear PWM generator module and the core controller module, and then these modules are combined to build a complete PMBLDC motor simulation model. In the process of modeling, how to quickly determine PWM with different duty cycle is very important, which has been solved successfully according to the piecewise linear method. In addition, the modular designed blocks also make it easier to modify, add and subtract algorithms. Finally, the model established by this method can be quickly and conveniently downloaded into FPGA and ARM platform for joint debugging by using the embedded plug-ins of Simulink, which greatly improves the development efficiency of designers.

1 Modeling of PMBLDC motor

The equivalent circuits of PMBLDC motor drive for phase A as shown in below Fig.1-1[4].

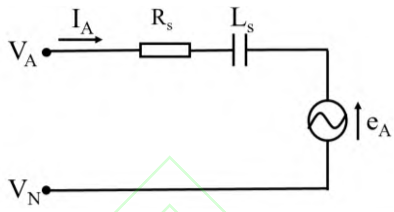

Fig.1-1 Equivalent circuits of PMBLDC Motor

We can get the voltage from:

$$V = I_A \cdot R_S + L_S \cdot \frac{dI_A}{dt} + e_A \quad \ldots\ldots(1)$$

Where, Ls is the inductance respectively, eA is back emf of the motor and Rs is the stator winding resistance for phase A.

We can get these conclusions applying KVL[4],

$$V_a = R_a I_a + L_a \frac{dI_a}{dt} + M_{ab} \frac{dI_b}{dt} + M_{ac} \frac{dI_c}{dt} + e_a \quad \ldots\ldots(2)$$

$$V_b = R_b I_b + L_b \frac{dI_b}{dt} + M_{ba} \frac{dI_a}{dt} + M_{bc} \frac{dI_C}{dt} + e_b \quad \ldots\ldots(3)$$

$$V_c = R_c I_c + L_c \frac{dI_c}{dt} + M_{ca} \frac{dI_a}{dt} + M_{cb} \frac{dI_b}{dt} + e_c \quad \ldots\ldots(4)$$

Where Ia, Ib and Ic are three phase currents. Va, Vb and Vc are three phase voltages. La, Lb and La are three phase self inductances. Ra, Rb and Rc are three phase resistances. Mab, Mac, Mba, Mbc, Mca and Mcb are the mutual inductances of the stator windings. What’s more, ea, eb and ec are the back emfs in motor.

So we can get the matrix form,

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} R_a & 0 & 0 \\ 0 & R_b & 0 \\ 0 & 0 & R_c \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} + \begin{bmatrix} L_a & M_{ab} & M_{ac} \\ M_{ba} & L_b & M_{bc} \\ M_{ca} & M_{cb} & L_c \end{bmatrix} \frac{d}{dt} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad \text{...........(5)}$$

The equation of electromagnetic torque is,

$$T_e = \frac{(e_a I_a + e_b I_b + e_c I_c)}{\omega} \quad \text{................................(6)}$$

The equation of motion is,

$$T_e = j\frac{d\omega}{dt} + B\omega + T_l \quad \text{.....................................(7)}$$

2 The architecture of PMBLDC motor measurement and control system

In this part, we proposed the method of establishing the BLDC control system simulation model based on the analysis of hall sensor position detection algorithm and PID control algorithm, combined with the idea of piecewise linear to generate PWM waveform. The model is built in the Simulink environment of Matlab2018b and SimPowerSystem Toolbox were used. The framework of this system is shown in Fig.2-1.

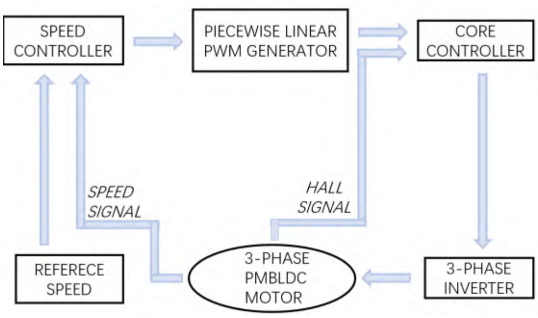

Fig.2-1 Block diagram of the system

The complete model of the whole motor measurement and control system is shown in Fig.2-2. In addition to the motor and load, there are speed control module, piecewise linear PWM generation module, core control module and 3-phase inverter module. This system adopts speed closed-loop PID control algorithm and the modulation mode of PWM is H PWM-L ON.

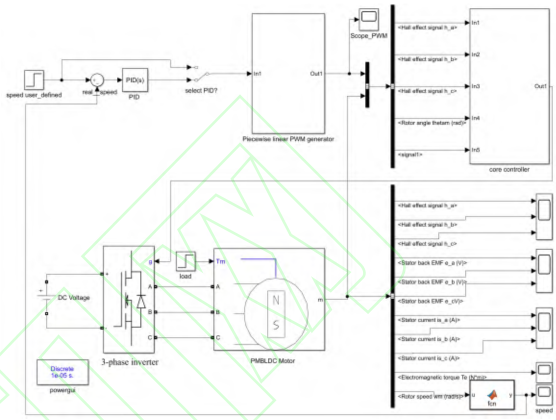

Fig.2-2 The simulation model of PMBLDC motor

2.1 Speed controller

The structure of the speed control module is relatively simple as shown in Fig.2-3.

Dual input: reference speed and actual speed.

Single output: speed deviation value.

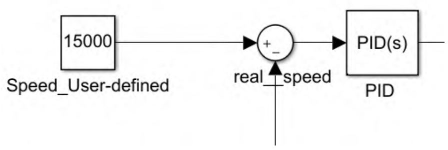

Fig.2-3 Speed controller

The speed control loop adopts typical PID control. The given speed is compared with the actual motor speed to obtain the deviation value, which is used as the input of the PID regulator. After PID adjustment, it is input to the piecewise linear PWM generator module.

2.2 Piecewise linear PWM generator

The piecewise linear PWM generator is shown in Fig.2-4. The piecewise linear module is determined by testing the motor speeds corresponding to multiple sets of PWMs with different duty cycles in an open-loop state, so that the PWM duty cycle corresponding to different speed is linearly fitted. As shown in Fig.2-5, the PWM generator can generate a PWM waveform with a period of 1ms with different duty cycles by receiving the signal from the DC input port.

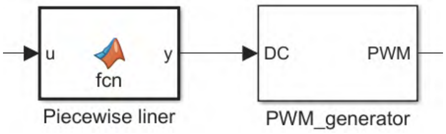

Fig.2-4 piecewise linear PWM generator

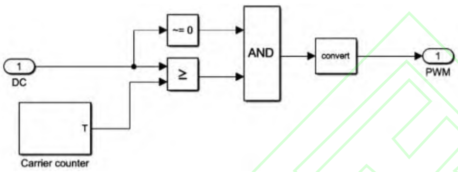

Fig.2-5 PWM generator

2.3 Core controller

The core control system collects input data such as Hall sensor input, PWM and rotor electrical angle to provide control signals for the system. It should generate a modulated PWM signal to control the power switch in 3-phase inverter.

For star-connected motors, the entire working process can be divided into six modes[5,6]. For each stage, two of the three states are conductive, and the third is open. In the presence of a Hall sensor, commutation is based on the input of the Hall sensor, and the order of how the coil should be powered is shown in Table 1.

Table1 Clockwise sensor and drive bits by phase order

PHASE	HALL SENSORS C	HALL SENSORS B	HALL SENSORS A	ACTIVE SWITCH C HIGH	C LOW	B HIGH	B LOW	A HIGH	A LOW
1	1	0	1	0	1	0	0	1	0
2	1	0	0	1	0	0	0	0	1
3	1	1	0	1	0	0	1	0	0
4	0	1	0	0	1	1	0	0	0
5	0	1	1	0	0	1	0	0	1
6	0	0	1	0	0	0	1	1	0

The interior of the module is shown in Fig.2-6, which uses the H_PWM-L_ON PWM modulation mode. The commutation logic part is designed based on the Matlab function.

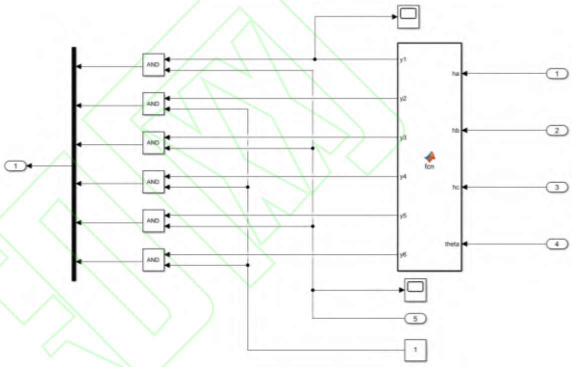

Fig.2-6 The interior of core controller

2.4 3-phase inverter

The 3-phase inverter actually transmits the PWM signal from the control system to the motor[7]. The control system generates a low-voltage signal (up to 5V), and the motor requires high voltage power supply (usually 20-400 V[8] according to the motor usage area). Depending on the type of motor, the inverter bridge components are selected to meet the requirements of voltage and switching speed. Fig.2-6 shows the standard six-switch three-half bridge system which is a typical inverter bridge used for PMBLDC motor control.

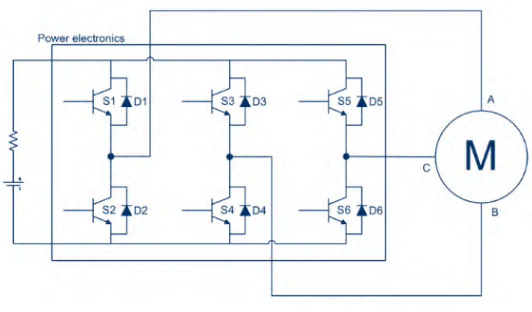

Fig.2-7 Typical inverter drive system for a PMBLDC motor

3 Simulation results and experimental verification

3.1 Simulation parameters

The parameters of the motor used in the modeling process are: motor stator phase winding resistance R=0.0285 Ω, stator phase winding inductance L= 0.000395 H, torque constant T=0.582, rotational inertia J = 0.0027 kg · m2, damping coefficient B = 0.0004924 N · m · s / rad, rated speed n = 20000 r / min, pole pair number p = 4, DC power supply voltage is 200 V.

The three parameters of the discrete PID controller in the speed loop: Kp=3.2, Ki=195, and Kd=0.001. The sampling period of the PWM generator is 1e-6s.

3.2 Sudden increase in motor load

Simulation environment setting: set speed ω=12000 r / min, load TL = 2N · m when the motor starts, when t = 0.5s, load suddenly increases to TL = 6 N · m, and simulation time is set to 1s.

The torque waveform of PMBLDC motor in this system is shown in Fig.3-1. The torque fluctuation is very large in the start-up stage, and the positioning process is basically complete until 0.0035s. Then the torque level gradually stabilizes. During 0.0035 s-0.5 s, the torque is mainly distributed around 2N · m, while the applied torque is 2 N · m. At 0.5s-1s, the torque is mainly distributed around 6N · m, while the applied torque is 6 N · m. The software model simulation proves the effectiveness, rationality and stability of the simulation system modeling.

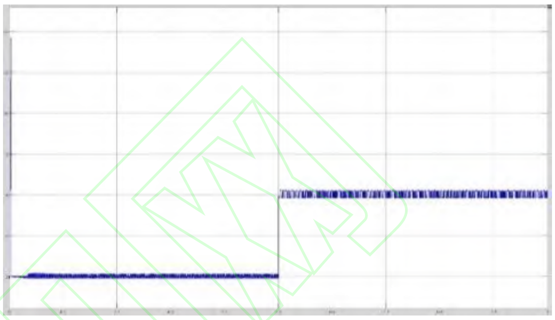

Fig.3-1 Torque waveform

The three-phase currents of A, B and C of PMBLDC motor are shown in Fig.3-2. As demonstrated Fig.3-2, in the initial stage of starting, the rotor starts to accelerate rapidly from 0 seconds, the current increases rapidly, and the sharp change of current can be reflected in the figure. The rotor begins to accelerate slowly, and the increasing speed of the current gradually slows down. After 0.07 seconds, the current alternately appears on the horizontal axis and runs steadily, thus proving that the current waveform conforms to the theoretical analysis.

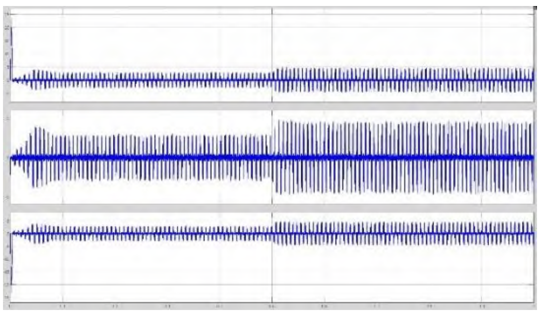

Fig.3-2 The three-phase currents

It can be seen from Fig.3-3 and Fig.3-4 that the back-EMF of the three-phase winding of the motor obtained by the piecewise linear method differs from the angle of the three-phase Hall signal by 120°, which is consistent with the situation of the real motor.

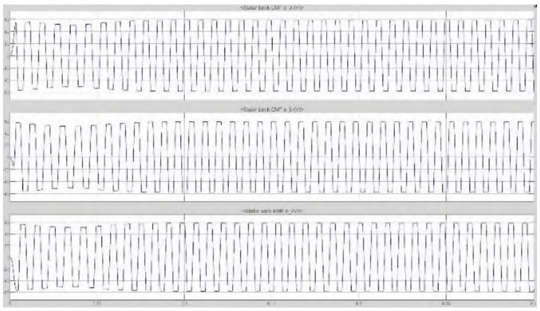

Fig.3-3 The three-phase back-EMF

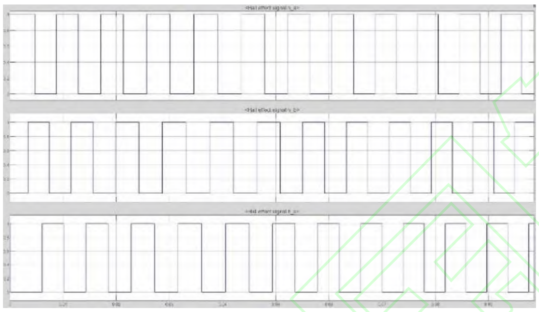

Fig.3-4 The three-phase Hall signal

PMBLDC motor speed response is shown in Fig.3-5. It can be observed from the figure that when the system starts to run, the motor can reach 12000 r / min at 0.07 s, and the system response is fast and stable. When the load suddenly increases from 2 N · m to 6 N · m at 0.5s, the speed drops to a certain extent, but the speed returns to the given value with the impact of regulator in 0.04 s. Although there is a small range of fluctuations, the fluctuation range is only 5 r / min, indicating that the system has good stability.

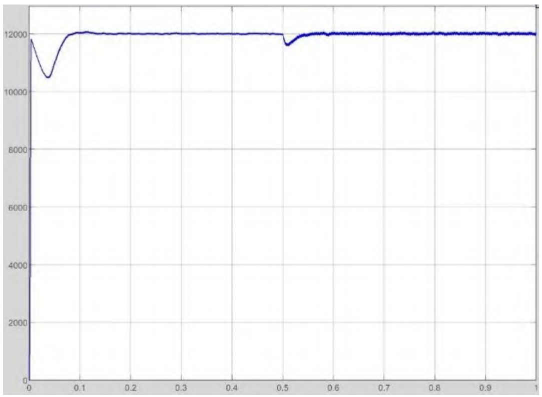

Fig.3-5 speed response

3.3 Sudden increase in motor speed

Simulation environment setting: set the motor load TL = 6N · m. When the motor starts, the given speed is 6000 r / min. When t = 0.5 s, the speed increases suddenly to 12000 r / min, and the simulation time is set to 1s.

Fig.3-6 and Fig.3-7 show the motor torque and three-phase current output When the speed of PMBLDC motor increases suddenly. It can be seen that when the voltage of the three-phase inverter terminal and the motor load are constant, the speed of the motor suddenly increases, which will lead to the phase current to increase, while the motor torque is the positive electric torque. When the motor reaches stability, the phase current and motor torque will decrease rapidly again.

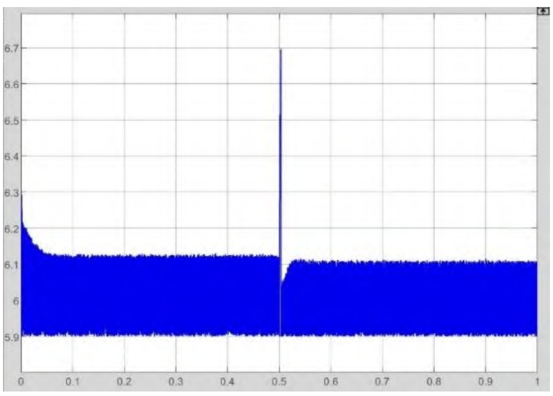

Fig.3-6 Torque waveform

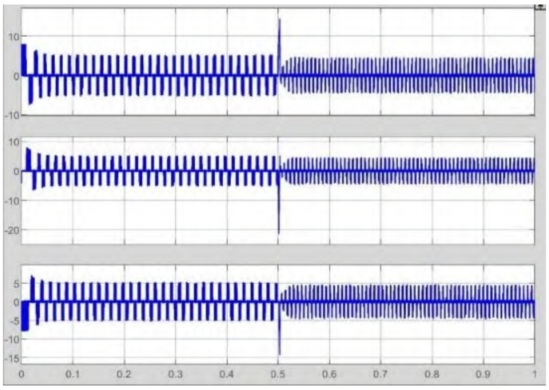

Fig.3-7 The three-phase currents

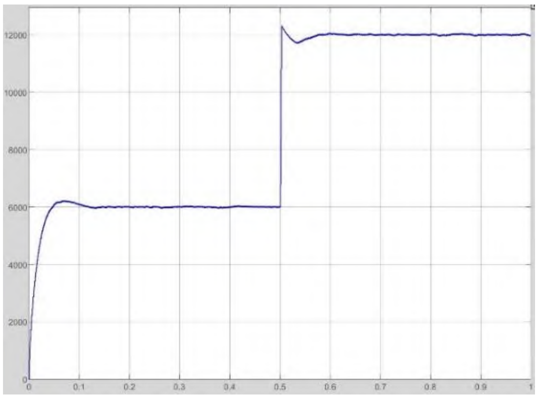

Fig.3-10 speed response

The three-phase winding back-EMF and three-phase Hall signals of PMBLDC motor are illustrated in Fig.3-8 and Fig.3-9. It can be seen from the figure that at 0.5s, the motor speed suddenly increases.

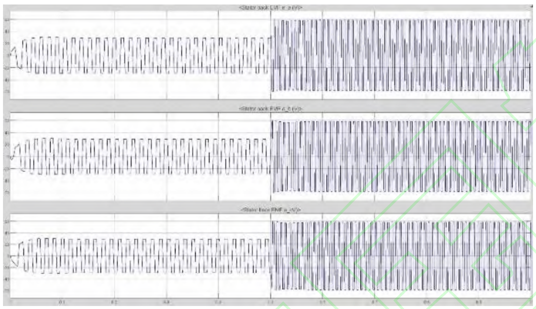

Fig.3-8 The three-phase back-EMF

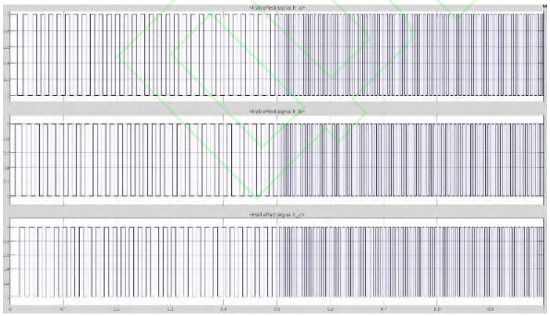

Fig.3-9 The three-phase Hall signal

The speed of PMBLDC motor is shown in Fig.3-10. After 0.5s, the motor speed suddenly increased from 6000 r / min to 12000 r / min just take up about 0.05 s. The system responds quickly with little static error.

4 Conclusion

In this paper, the author adopt the Simulink to simulate and model the PMBLDC motor closed-loop measurement and control system. The piecewise linear method is used to generate PWM control signals, and the H_PWM-L_ON mode is employed to modulate the PWM. We also increase speed and load suddenly to simulate and analyze respectively to verify the effectiveness of the model. This research provides a way for designers to effectively grasp the graphical modeling tools and understand the dynamic process of motor PWM speed regulation. In addition, it is convenient to use Simulink's plug-ins to compile and download this model into ZYNQ for real-time hardware-in-the-loop simulation measurement and control.

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