The Multi-domain Modeling and Optimization of Aircraft Electrical System Based on Modelica

Jin Xiao*
State Key Laboratory of Virtual Reality Technology and Systems
Beihang University
Beijing, China
xiaojin_ck@126.com

Yue Li
State Key Laboratory of Virtual Reality Technology and Systems
Beihang University
Beijing, China
16231008@buaa.edu.cn

Xiaoguang Hu
State Key Laboratory of Virtual Reality Technology and Systems
Beihang University
Beijing, China
xiaoguang@buaa.edu.cn

2023 IEEE 18th Conference on Industrial Electronics and Applications (ICIEA) | 979-8-3503-1220-1/23/$31.00 ©2023 IEEE | DOI: 10.1109/ICIEA58696.2023.10241598

***Abstract*—Aircraft electrical system includes key equipment such as battery, step-down circuit, filter, motor and so on. It is a comprehensive system integrating machinery, electronics, control, thermodynamics and other fields. However, many current modeling and simulation methods are aimed at specific problems in a single domain or subsystem, and it is difficult to consider the coupling relationship between different domains. To solve the above problems, this paper uses the multi-domain physical system modeling language Modelica to establish the aircraft electrical system model library on the simulation platform Mworks, and simulates the electrical characteristics of each model, some parameters are optimized. The results show that the multi-domain modeling of aircraft electrical system based on Modelica language can realize the simulation results close to the actual, and the optimization of related parameters can effectively improve the system performance and improve the design efficiency.**

Keywords—Modelica、aircraft electric system、 modeling and optimization、multi-domain modeling

I. Introduction

Aircraft electrical system is an important part of aircraft, including power system and electrical equipment, responsible for the whole process from electricity generation, conversion, transmission to use. With the rapid development of modern science and aviation technology, all kinds of electronic equipment on aircraft are increasing day by day, the electricity consumption is increasing, and the structure and control of aircraft power supply system are becoming more and more complex. In this case, the accurate modeling of the electrical system and electrical characteristics of the aircraft can realize the optimization of the system design method and process, restrain the voltage and power fluctuations, so as to maximize the elimination of failure factors and greatly reduce the probability of failure[1].

Electrical system is a comprehensive system integrating mechanical, electronic, control, thermodynamics and other fields. It is difficult to realize cross-software use and high reuse of single-domain model in modeling and subsequent iteration. For example, Matlab/Simulink is mainly suitable for modeling control systems; ANSYS can model magnetism and heat, but not electrical systems. Multisim can simulate circuits, but it has insufficient support for mechanical and magnetic fields. In addition, the different protocols and interfaces used by different software make it impossible to realize the co-simulation with good performance.

For this situation, Modelica, a multi-domain physical system modeling language, can be used for modeling. Modellica language is object-oriented and non-causal.The characteristics of object orientation can ensure that the model based on the language has high reusability and simplicity. Non-causal modeling means that the model can be modeled without deducing the relationship between model output and input, and only need to use mathematical language to describe the behavior of the model. These two characteristics make Modelica ideal for modeling electrical systems.

The Mworks software developed by Suzhou Tongyuan Soft Control Information Technology Co., Ltd. supports Modelica language modeling, has a built-in professional library of machinery, hydraulics, motors and other functions, and also has a toolbox that can carry out batch experiments and other functions, so as to facilitate the optimization of system parameters. Mworks has also been widely used in the modeling and simulation of aviation, aerospace, vehicle and other fields, so this paper builds the corresponding model based on Mworks[2][1].

Based on Mworks software and Modleica language, this paper selects the appropriate power supply system and type according to the requirements of the aircraft electrical system, establishes the electricity model of products and equipment, and finally builds the model library to simulate and analyze the electricity characteristics of each system and equipment. And through the preliminary design and simulation optimization to improve the performance of the integrated electronic system, but also to provide a basis for the physical development of the performance appraisal.

II. Aircraft Electrical System Composition

Aircraft electrical system is a comprehensive system, which can transform the study of complex system into the study of relatively simple submodules through modular decomposition. In this paper, electrical system is divided into motor, battery, cable, voltage reduction circuit, constant power module, general equipment and other modules for modeling, and finally establish aircraft electrical system model library.

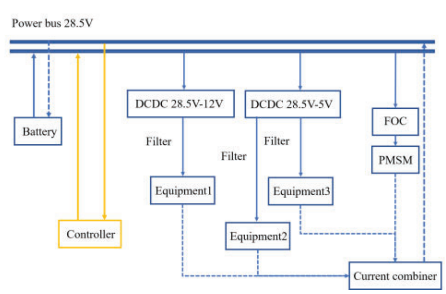

Fig.1. The diagram of electrical system.

As show in Fig. 1, the battery powers the entire electrical system, connecting to the 28.5V-12V DC step-down module、the 28.5V-5V DC step-down module and directly powering the PMSM system. For the part that has been depressurized, it needs to be filtered before being used by various electrical devices. Each electrical device will flow the output current back to the battery through the confluence, forming a closed loop of the electrical system. Electrical control controls the power supply timing and other states to make the whole electrical system run normally.

III. Electrical System Equipment Modeling and Simulation

In this section, the design and modeling simulation of the equipment involved in the aircraft electrical system will be carried out.

A. Design and Modeling of battery and CPL

Battery is an important part of the aircraft power supply system, so it is necessary to conduct accurate modeling of lithium battery to ensure the accuracy of subsequent simulation of electrical characteristics. At present, electrochemical model and equivalent circuit model are commonly used. The electrochemical model starts from the reaction mechanism of the battery and fully characterizes the chemical reaction process inside the battery, but Modelica language is difficult to support the modeling of chemical reaction. It is difficult to directly model the battery from the chemical reaction principle of the battery through the equation. The equivalent circuit model describes the external characteristics of the battery through electrical components such as resistance and capacitance. It has a simple structure, ignores the internal mechanism of the battery, and only considers the external voltage and current characteristics of the battery, which has a good accuracy. Therefore, this paper chooses to establish the equivalent circuit model of Partnership for a New Generation of Vehicles (PNGV)considering thermal effect[3].

The PNGV standard battery model is shown below:

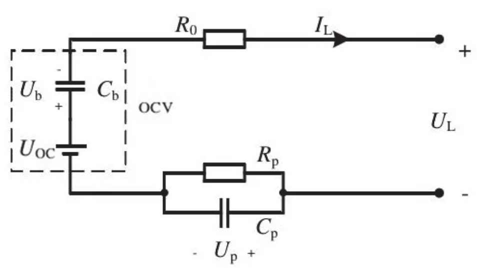

Fig.2. PNGV battery standard model.

U_{oc}-ideal voltage source, equivalent to the open circuit voltage of the battery; R_0-equivalent ohm resistance; C_b-energy storage capacitor can be used to describe the open-circuit voltage change caused by the load current time accumulation; U_L-battery terminal voltage; R_P-equivalent polarization resistance; C_p -equivalent polarization capacitance.

Since this model covers the characteristics of battery polarization and ohm internal resistance, and at the same time adds a large capacitance to express the variation of battery voltage as well as the capacity of the battery, the PNGV equivalent battery model is relatively accurate and recognized as a relatively effective battery model at present.

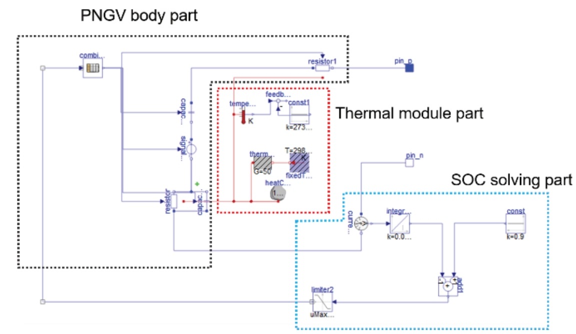

Fig.3. PNGV battery model with thermal module part.

The PNGV model established in this paper considering the thermal effect can be divided into three parts as shown in the figure above, namely, the main part, the thermal module part and the soc solving part. The difference between the main part and Fig.2 is that the above ohmic internal resistance, polarization resistance and polarization capacitance are converted into controlled components, which can change with the change of SOC through interpolation table components. The SOC solution part is used to solve the SOC value of the battery. The calculation formula of this part is shown in Equation (1):

$$\mathrm{SOC} = \frac{C_N - \int_0^t \eta I d\tau}{C_N} \times 100\% \tag{1}$$

C_N is the rated capacity of the battery; I is the battery current; η refers to the charge and discharge efficiency, which is generally equal to 1 and is taken as 1 in this paper.

Continuous discharge of battery will release heat and thus increase the temperature of battery, which will also have a certain impact on SOC. Therefore, the advantages of multi-field modeling of Modelica should be used to consider the influence of temperature effect when establishing battery models. In the PNGV equivalent model, polarization resistance and ohm resistance can be regarded as heat generation. Fig.3 shows how to build a thermal module part.

Constant power load （CPL）refers to a class of loads in which the power absorbed from the power supply remains unchanged during the operation of the system. For example, radar, navigation equipment, flight control computer and other equipment in the electrical system of aircraft are all such loads. For some equipment without special professional requirements, constant power load model is adopted instead.

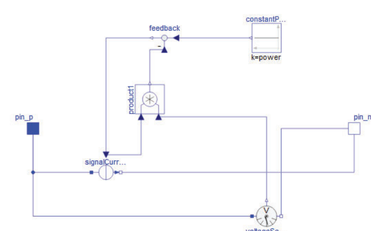

Fig.4. CPL model.

In this paper, CPL is set at 28w and used as the load of PNGV for simulation. The simulation time is 300s. The voltage at both ends of the PNGV battery load is shown in the Fig.5:

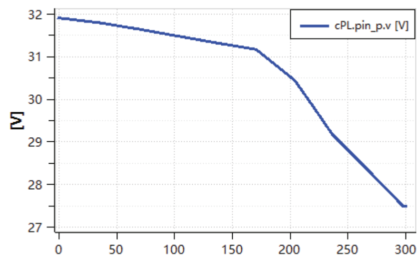

Fig.5. CPL voltage.

It can be seen that the voltage fluctuates around 28.5V in the intermediate long-time range.

B. Design and Modeling of buck and and filtering equipment

DC step-down equipment can convert the battery voltage to the required voltage, but at the same time, ripple and other deterioration of power supply quality exist. Therefore, it is necessary to optimize the modeling. Considering the performance, power consumption and other aspects, mature and stable BUCK circuit is considered to realize DC voltage conversion.

The BUCK circuit can be divided into two parts when working. In the first part, the MOS tube is switched on, and the DC power supply charges the inductive and capacitor of the energy storage to supply energy to the load. In the second part, the MOS tube is turned off. At this time, the inductance is discharged through the diode loop, the current gradually decreases, and the output state is maintained by the filter capacitor.

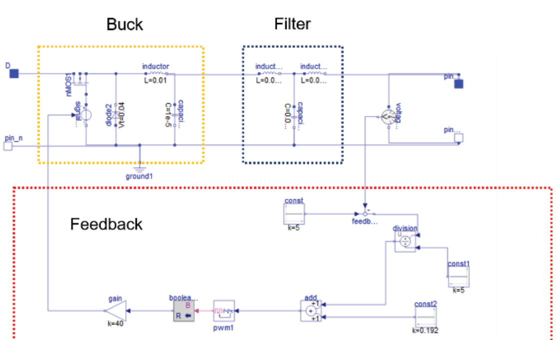

Fig.6. BUCK and feedbak model.

The DC voltage waveform obtained after using DC-DC chopper will have large ripple due to the high frequency on-off of the switching tube. Considering the electromagnetic compatibility design and signal selection, this paper selects the third-order Butterworth low-pass LC filter for filtering, and reduces the electromagnetic interference and the influence of non-target signals. After filtering, the ripple amplitude is less than 0.001V, and the ripple inhibition effect is very obvious.

Due to the different working time sequence of different equipment, the number and power of electrical equipment will be different in time, so it is necessary to add negative feedback device to stabilize the output voltage. On the basis of the basic step-down filter, the output voltage is sampled by voltmeter, and then compared with the reference voltage value. The compensation signal is converted into the duty ratio of current PWM wave. Finally, the current PWM wave is output by the controlled signal source of the drive circuit to control the opening and closing of NMOS tube so as to control the output voltage.

Under the simulation time of 1s, 10 Ω parallel load was introduced into 0.3s and 0.7s respectively, and it could be seen that the voltage could restore steady state and the disturbance time was short.

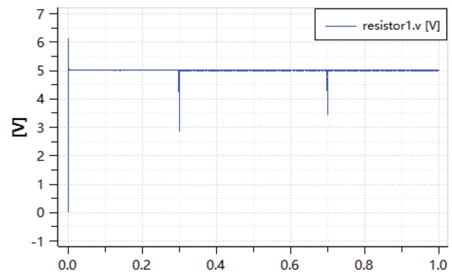

Fig.7. Output voltage of buck circuit after loading.

C. Design and Modeling of PMSM and FOC

In the selection of servo power equipment motor, there are DC motor, permanent magnet synchronous motor, switched reluctance motor and other motors to choose from. Although DC motor is easy to control, it has defects in structure, and it requires higher working conditions. Switched reluctance motor has no permanent magnet and other components, and its structure is simple and reliable. However, its low torque and large noise make it difficult to be widely used. Permanent magnet synchronous motor has the advantages of low loss, high efficiency, moderate price and wide speed control range, so it has been widely used in servo system. According to the requirements of aircraft design, a dynamic system model based on permanent magnet synchronous motor is established in this paper[4].

The electromagnetic relationship of PMSM is relatively complex, so assumptions of complete symmetry of three-phase stator windings, eddy current loss and hysteresis loss are made in the modeling process. Under the above assumptions, the mathematical equation of permanent magnet synchronous motor in three-phase static coordinates can be established, but it is found to be related to the instantaneous position of the rotor. In order to simplify the modeling, Clark transformation was used to transform the three-phase stationary coordinate system to the two-phase stationary coordinate system, and Park transformation was used to transform the two-phase stationary coordinate system to the two-term rotating coordinate system. The schematic diagram is shown in the Fig.8. Finally, the mathematical model under the coordinate system of dq0 axis can be obtained.

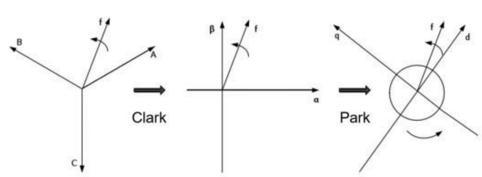

Fig.8. Coordinate axis rotation transformation.

The voltage balance equation of the model is:

$$u_d = R_s \mathrm{i}_d + \frac{\mathrm{d}\psi_d}{dt} - \omega\psi_q \quad (2)$$

$$u_q = R_s \mathrm{i}_q + \frac{\mathrm{d}\psi_q}{dt} + \omega\psi_d \quad (3)$$

The flux equation is:

$$\psi_d = L_{s\sigma} i_d + \psi_f \quad (4)$$

$$\psi_q = L_{s\sigma} i_q + L_{mq} i_q \quad (5)$$

The electromagnetic torque equation is:

$$T_{em} = \frac{3}{2} p\left[L_{md} i_f i_q + \left(L_d - L_q\right) i_d i_q\right] \quad (6)$$

u_d- Stator d axis voltage;u_q- Stator q axis voltage;R_s- Stator winding phase resistance;i_d- Stator d axis current;i_q- Stator q axis current;ψ_d- Stator d axis flux;ψ_q- Stator q axis flux;$L_{s\sigma}$- Stator windings leakage sensing;ψ_f- The flux produced by a permanent magnet in the stator winding;L_{md}- d axis excitation inductance; L_{mq} - q axis excitation inductance.

PMSM also has a variety of losses during operation, such as iron loss, stray loss and mechanical friction loss. Therefore, various loss models are introduced to make the simulation results more accurate. Here, stray loss and iron loss are briefly introduced.

Stray loss, also known as additional loss, does not affect the pressure drop of the circuit and acts on the end of the motor shaft in the form of braking torque. Its calculation formula is as follows:

$$\tau = \frac{P_{ref}}{w_{ref}} * \left(\frac{i}{I_{ref}}\right)^2 * \left(\frac{w}{w_{ref}}\right)^{power\_w} \quad (7)$$

P_{ref} is the stray loss under rated current I_{ref} and rated speed w_{ref}, which is affected by $power\_w$ in an exponential form.

Iron loss is composed of eddy current loss and hysteresis loss, and its calculation formula is as follows:

$$P = P_{ref} * \left(ratioHysteresis * \frac{w_{ref}}{w} + 1 - ratioHysteresis\right) * \left(\frac{V}{V_{ref}}\right)^2 \quad (8)$$

P_{ref} indicates the iron consumption at rated voltage V_{ref} and rated speed w_{ref}, $ratioHysteresis$ indicates the proportion of hysteresis loss in the loss, and can be set to 0 if hysteresis loss is not taken into account.

After considering the effect of loss, because the motor itself is a complex system in many fields, it will involve the coupling between different fields. The modeling method of electrical subsystem and electromechanical and electromagnetic coupling are introduced below.

(1) Electrical subsystem. The electrical subsystem mainly uses the basic components in Modleica. Electric, which is the standard library of Modelica. The basic components such as resistance, capacitance and inductance are developed again by means of parameter differentiation and so on, and the electrical system is constructed by this method.

(2) Electrical and mechanical interfaces. In order to achieve the motors and batteries and other external devices and components, such as electric drive connections, preset Electrical interface, can use Modelica. Electrical. MultiPhase. Interfaces. plug-in components, its potential variables as the voltage, the dependent variable as the current;

The mechanical interface needs to implement torque transmission function of rotating shaft, which can be implemented by flange components in Modelica language mechanics library, whose potential variable is Angle and torque is flow variable, and it follows the rules that Angle is equal at the node and torque sum is zero.

(3) Electromechanical coupling. The main function of PMSM is to realize the conversion of electrical energy to mechanical energy. On the basis of the electrical and mechanical interface mentioned above, the voltage balance equation and electromagnetic torque equation in the equation(2)(3)(6) are used, and the coordinate transformation formula of two-phase stationary transformation to two-phase rotation is used to realize the transformation.

(4) Electromagnetic coupling. The rotor magnetic field generated by permanent magnet is required for PMSM. In this paper, the permanent magnet model in the Modlelica model library of equivalent excitation source is adopted as the electromagnetic coupling part, which mainly provides excitation current, and the magnetic field generated by the current should be used to simulate the magnetic field generated by permanent magnet.

After the modeling of each module is completed, the permanent magnet synchronous motor is encapsulated. First, the electrical interfaces on both sides are used to connect the three-phase power supply, and then the input electrical signals are transformed by Clark into electromechanical coupling components to generate electromagnetic torque and back electromotive force, in which the torque is transmitted from the mechanical part to the outside world. The back electromotive force and cage winding form an electrical loop. At the same time, permanent magnet provides excitation current. Besides the main part, there are loss modules such as iron loss, stray loss and mechanical friction loss. The overall structure diagram and motor parameters are as follows：

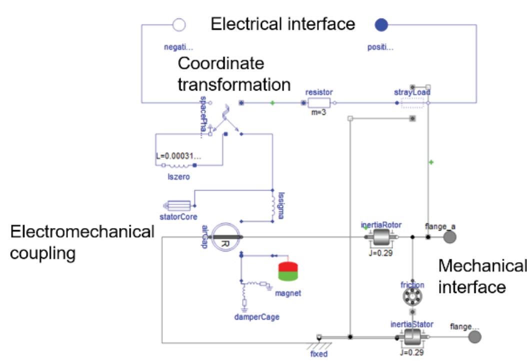

Fig.9. PMSM model.

TABLE I. PMSM PARAMETERS

Polar number	2
Inertia of the rotor	0.29kg.m^2
Rated frequency	50Hz
Rated speed	1500r/min
D-axis inductance	0.159mH
Q-axis inductance	0.159mH

The established model was simulated and verified. The inverter voltage open-loop control was adopted for the motor, the power supply frequency was gradually loaded to the rated frequency, and 200N.m load torque was added at 1.5s.

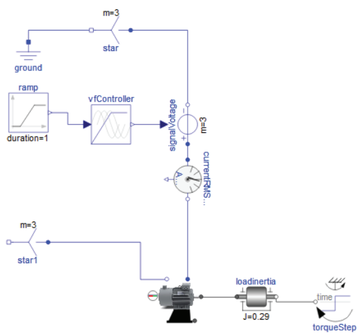

Fig.10. Voltage open loop control mode.

The main simulation results are shown in the figure below.

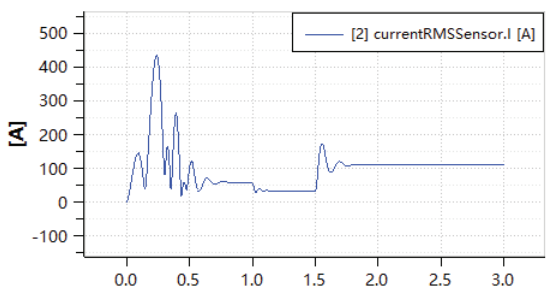

Fig.11. PMSM current.

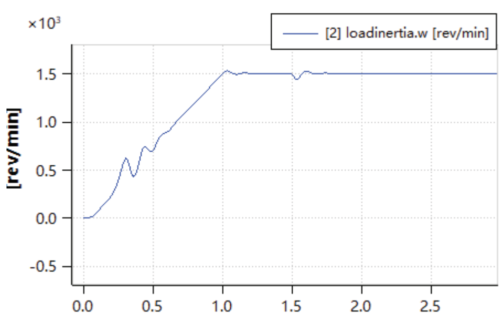

Fig.12. Motor speed curve.

It can be seen from the figure above that the motor speed rises with the increase of voltage and fluctuates briefly after adding the load at 1.5s. It can be seen from the summary of the current curve that the current fluctuates greatly when starting, and the current value becomes large and stable after adding the load. All simulation curves meet the design indexes.

After completing the construction and testing of the motor body model, it is necessary to exert control over it. According to the design requirements, PMSM is controlled by vector control technology, that is, by controlling the stator current to indirectly control the electromagnetic torque to control the motor. The vector control method can make the motor speed range wide and the electromagnetic torque stable. The vector control algorithm model consists of several integral, differential, feedback and coordinate transformation.

SVPWM and vector control algorithm jointly constitute the FOC controller of the motor. Its main principle is to judge which sector area the current voltage vector is in, and allocate the pass time of each switch tube after calculating the action time, so as to generate SVPWM wave as the control signal of the voltage inverter.

Voltage inverter is composed of switch tube, diode and other basic components, responsible for the input DC signal under the SVPWM control signal output into three-phase voltage pulse wave for SMPM use, the following is the FOC controller circuit and the overall motor control circuit diagram.

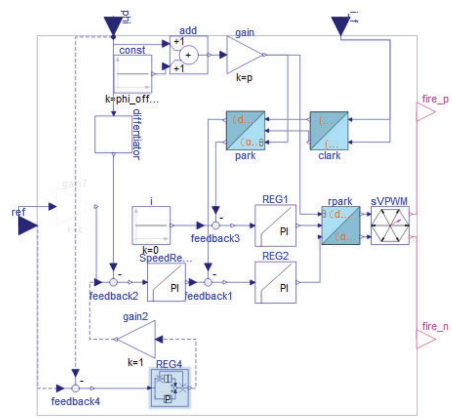

Fig.13. FOC controller.

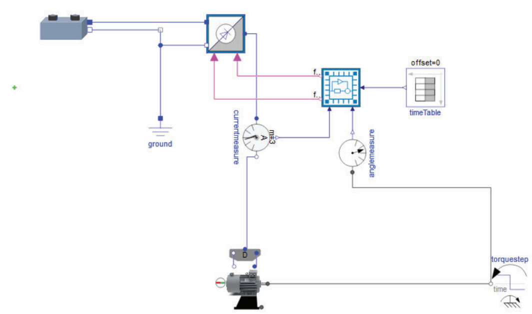

Fig.14. Simulation of control and drive system of PMSM.

FOC controller adopts the position control mode, and input the reference Angle value which changes at any time through time Table. The current value and the actual Angle value are compared as input and reference value, and the output control signal controls the on-off of the switching tube in the inverter. The PMSM receives the time-varying three-phase current from the inverter under the control of the controller to change the output speed and Angle. The main simulation results are shown in Fig.15.

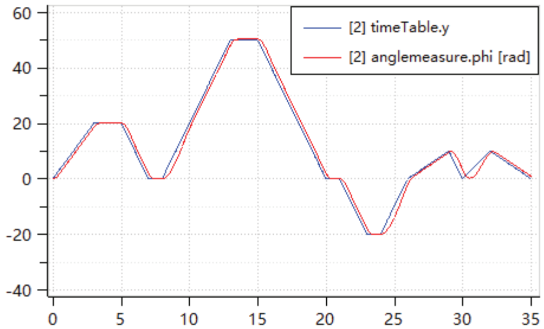

Fig.15. Motor Angle curve.

In the figure above, the blue line is the reference Angle, and the red line is the actual Angle of the motor. It can be seen from the comparison that the motor has good followability and can reach the set Angle within the specified time, which indicates that the controller parameter design is reasonable and the drive system is proved to be feasible.

IV. Electrical System Co-Simulation and Result Analysis

The models established in III were connected according to the design requirements. PNGV battery was used as the main power supply to supply power to each electrical equipment. CPL was set as 28w and was connected to the circuit at 3s. CVL with different time sequences replaces constant voltage characteristic equipment after the battery is depressurized. After voltage reduction, the CAN module[5] is connected to analyze the transmission characteristics and electricity characteristics. The PNGV directly powers the motor drive system.

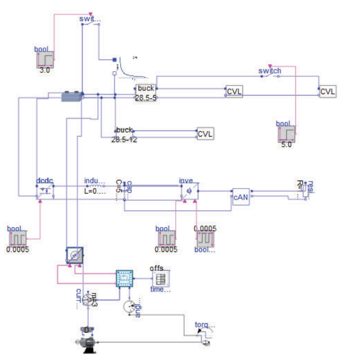

Fig.16. Co-simulation circuit diagram.

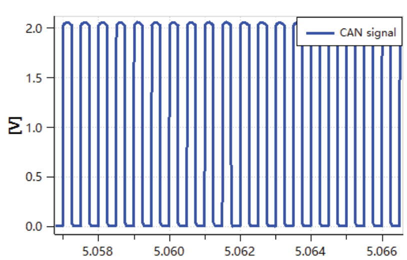

Fig.17. Transmission characteristic curve of CAN module.

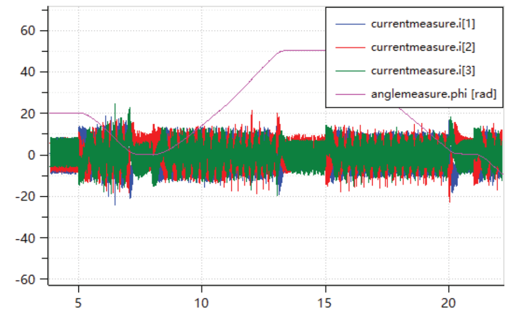

Fig.18. PMSM Angle and three-phase current curve.

As can be seen from Fig.18 and 18, the signal transmission quality is high, the motor current is positively correlated with the Angle change rate, and the equipment of each module works in rated state. The co-simulation results accord with the design expectation.

V. Conclusion

This paper innovatively uses Modelica language to model the aircraft power supply system. The PNGV battery, the step-down filter circuit with feedback, the multi-field coupling PMSM model and the control driver module are constructed, and the design requirements are met through testing. Finally, the correctness and effectiveness of the system are verified by the co-simulation of each equipment. Generate typical electrical equipment model library, enhance model reuse, effectively improves the efficiency of system design iteration.

References

[1] ZHOU Jie-min,SUN Yu,LI Xiao-ming and WU Zai-gu, "Research and simulation on constant powerload of more electric aircraft based on simplorer" [J]. Journal of Chongqing University of Technology (Natural Science),2016,30(05):102-107.

[2] Yizhong W,Fanli Z,Liping C, et al. Domain Library Preprocessing in MWorks-aplatform for Modeling and Simulation of Multi-domain Physical Systems Based on Modelica[J]. The Modelica Associatin,Modelica,2006: 733-740.

[3] US Department of Energy.PNGV Battery Test Manual P B T. Revision 3[R].DOE/ID-10597,February,2001.

[4] Bogomolov M,Kral C,Haumer A, et al. Modeling of permanent magnetsynchronous machine with fractional slot windings[C]//IECON 2012-38th AnnualConference on IEEE Industrial Electronics Society.IEEE,2012:1894-1899.

[5] Xiaolin Xu, "Research on physical layer of CAN network and optimization of signal quality" [D]. Beijing institute of technology, 2018. DOI: 10.26948 /, dc nki. Gbjlu. 2018.000316.