Modeling and Simulation of Complex Electromechanical System of More-Electric Aircraft Based on Distributed Simulation Technology

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***Abstract*—This paper proposed the modeling and simulation analysis of complex electromechanical system of more-electric aircraft based on the distributed simulation technology, the heterogeneous joint simulation of multiple environments such as Saber, Matlab, AMESim and Simplorer is adopted to solve the difficult problems of electromechanical system simulation with multi-physical domains and multi-disciplinary coupling, the corresponding properties of slow simulation speed, convergence difficulty and high computing pressure could also be eliminated through the model partitioning and distributed simulation technology. Combined with the actual engineering design requirements of complex electromechanical system of more-electric aircraft, a distributed simulation system comprising electrical control system, power distribution system, energy storage system, power converter and various types of loads is built, and the effectiveness of the distributed simulation technology for the electromechanical system simulation has been verified through simulation results.**

Keywords—complex electromechanical system, heterogeneous joint simulation, distributed simulation, multi-physics domain

I. Introduction

As a necessary process and an important demonstration tool for system design and development, simulation plays a very important role in modern engineering applications. As a typical complex large system engineering, the development cycle of more-electric aircraft is long and technically difficult, so the importance of simulation to its engineering development is obvious. Simulation research for aircraft systems focuses on three main areas such as the accuracy of the simulation model, the adaptability of the simulation environment and the computational power of the simulation [1][2] .

Simulation is a mapping of reality and accuracy is its most important metric. In order to improve accuracy and confidence, the ideas of Hardware-in-the-Loop (HIL) and Software-in-the-Loop (SIL) have been applied to simulation research [3]. HIL simulation has high confidence, but also has the defects of high cost and high complexity [4][5]. In contrast, SIL has a wider scope of application while ensuring confidence. [6] performed software-in-the-loop simulation of a UAV controller embedded in an autopilot protocol in Matlab based on ArduPilot documentation and code. [7] proposed a new approach based on an offline software-in-the-loop simulation technique that allows SIL to be applied to most circuit simulation software that supports Dynamic-Link Library, eliminating the need to use specific high-cost hardware circuits.

For the characteristics of multi-physics domain and multi-disciplinary coupling of more-electric aircraft, joint multi-software simulation can improve the adaptability of the simulation environment and optimize the simulation accuracy and overall convergence. [8] used Modelica language and visualization components to construct models and simulate aircraft power systems by Dymola software, but the model accuracy is still limited by the inherent limitations of Modelica programming. In [9][10], a joint simulation based on Saber - Simulink was carried out to simulate the 270V high-voltage DC power supply system and various power semiconductor devices of a more-electric aircraft, giving full play to the simulation advantages of Saber in the electrical field and Simulink in the control field.

In large and complex system simulation projects, the pressure of simulation computation is so great that a single software cannot meet the demand of computational power. Distributed interactive simulation (DIS) and high level architecture (HLA) liberate the resource supply limitation of computer on simulation software, and greatly improve the overall simulation computing capability [11~14]. Literature [15] developed a distributed simulation platform consisting of UAV, wireless network emulation and integrated parts, and introduced a two-channel approach to achieve the synchronous interconnection required for UAV simulation and wireless network simulation, significantly reducing the processing time delay. A simulation environment for smart grid evaluation system based on information and communication technology is proposed in [16], which can be extended to other simulation domains and various models through HLA applications. In [17], a large UAV distributed simulation platform performed in four simulators was developed, and the system was partitioned into a management module and seven application modules based on the layered design principle of HLA. The system has high fidelity and real-time performance, but the content of the paper is mainly functional description of the simulation platform, lacking specific modelling methods and details.

Thus, in this paper, the simulation technology for the complex electromechanical system of more-electric aircraft is researched, and a complete two-channel distributed simulation platform for electromechanical system is built with the multi-environment heterogeneous simulation platform with Saber simulation software as the core, and it also includes Simulink, AMESim and Simplorer. The SIL technology is also adopted to control energy configuration and load operation. Section II of the paper introduces the simulation ideas and technical advantages of the platform. Section III illustrates the modelling details in combination with the actual simulation models. Section IV discusses the simulation results, and Section V is the summary of the full text.

II. DSITRIBUTED SIMULATION TECHNIQUES

The electromechanical system of more-electric aircraft is a large multi-domain, multi-disciplinary and multi-coupled system, it features the complex system composition, complex development process and complex system behaviour. In order to achieve the simulation analysis, the multi-domain coupling, multi-behavioural work and dynamic verification should be taken into consideration. Therefore, the hierarchical engineering modelling techniques for simulation analysis of electromechanical system are necessary.

As the architecture of electromechanical system is analyzed and designed from three aspects, such as functional architecture, logical architecture and physical architecture, and on this basis the simulation model is reasonably partitioned to make full use of computer computing resources. The functional architecture analyses the operation scenarios of the electromechanical system, identifies the core functions at the top of the system and the functions of each level and sub-component from top to bottom, on this basis, it sorts out the functions of the electromechanical system at each stage of aircraft operation, and it also designs the complete system composition, determines the overall system partitioning arrangement and the functions of each partitioned model. The logical architecture identifies the logical components within the system and the relationships between them, uses the V-model approach to determine the top-down level-by-level requirements of the system, and clarifies the hierarchical structure between the models and the operational dependencies of the interfaces between the models. The physical architecture focuses on the design of physical nodes, networks, software units, data units and other aspects. It requires rational allocation of computer resources in the simulation process, avoiding bandwidth resource conflicts in the network between physical nodes to reduce the overall system operation pressure and improve the simulation operation speed.

In order to achieve the simulation analysis of the electromechanical system, the adaptability of the simulation environment should be ensured, then the reliability of the simulation results and the convergence of the model algorithm could be achieved. From the top-level analysis, the software Saber has a clear advantage in the field of hybrid simulation, and the simulation system uses Saber as the main environment to achieve the main system architecture. Matlab with the advantages in terms of control algorithm models, human-machine interaction and system data processing can be easily realized with its GUI subsystem. Simplorer has great advantages in electromagnetic equipment simulation. Therefore, due to the property of the electromechanical system of more-electric aircraft, in this paper the simulation analysis should be based on a multi-physics domain heterogeneous joint simulation environment, which combines the unique advantages of different simulation software, and the complementary resources could be employed to meet the simulation needs of multiple disciplines and fields in complex large system simulation.

In the electromechanical system of more-electric aircraft, it has complex structural compositions involve various forms of energy sources and component parts, thus, the system simulation models have more combination problems and convergence issues, which are usually difficult for model building and analysis in detail directly. On the one hand, multi-resolution modelling, model downscaling and equivalent circuit modelling are used in conjunction with each other to simplify models to the maximum extent possible while ensuring the simulation accuracy and verification reliability, which reduce the computational load of solvers. Therefore, the distributed simulation technology based on real-time routers should be adopted to solve the problems of multi-level model interaction, multi-solver solution and multi-data type cross-linking in the system simulation process. The real-time data interaction and synchronisation of distributed simulation workstations could be achieved through the control of local clock distribution and global clock synchronisation. The corresponding working sketch is shown in Fig. 1.

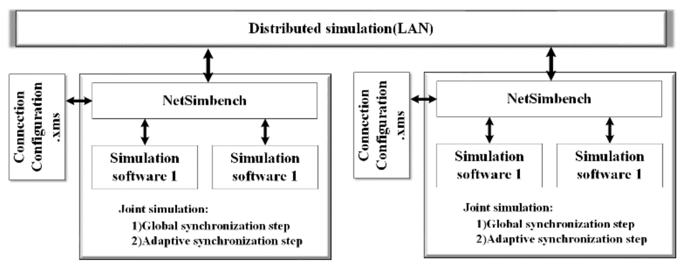


Fig. 1. Working sketch of the distributed simulation system

To further simulate the operation of a electromechanical system of more-electric aircraft, unified functional abstract modeling is carried out for embedded chips such as DSP, and software-in-the-loop simulation is implemented in Saber, which is applied to power load management and electric drive model control. A multi-dimensional approach to the automatic management of electrical loads in aircraft power distribution systems is proposed, and the corresponding program is written in C to achieve dynamic verification of the operation of the electromechanical system. Various hydraulic and fuel pumps in the more-electric aircraft system are driven by electric motors, so in this system, the vector control programed into the embedded processor model to control the permanent magnet synchronous motor system to drive various pump loads.

Thus, the complex components and multi-domain coupling characteristics of electromechanical system of more-electric aircraft have been considered, and the system hierarchical modelling, model partitioning and joint simulation techniques based on interactive information flow have been employed for the complex simulation of proposed system based on complete distributed simulation platform, where the key technical issues are as follows.

(1) The problem of non-convergence and slow simulation speed of complex large system simulation models has been solved by the model partitioning techniques.

(2) A joint simulation technology based on multi-domain heterogeneous models has been achieved to solve the key problem of model data interaction of multiple heterogeneous simulation environments.

(3) The distributed simulation technology based on interface compatibility technology, time synchronization technology and data routing technology has been developed to build a system-level distributed simulation environment for the proposed system.

III. Simulation Platform Design

Based on the above simulation methods and techniques, a multi-environment heterogeneous distributed simulation platform for the electromechanical system of a more-electric aircraft is built. The schematic diagram of the electromechanical system simulation is shown in Fig. 2. The system is based on a dual-channel high-voltage DC power system as the main architecture, including two generators, DC distribution network, DC/DC converters, inverters, load management center, automatic power distribution system, energy storage system and various forms of loads in a behavioural level simulation model. The high-voltage DC generators can be three-stage brushless DC generators or switched reluctance generators. The 270V high-voltage DC bus-bar is connected to the 28V low-voltage DC bus-bar via bi-directional DC/DC converters, which also connects to electric loads, electric pump loads and various types of constant power loads. The 28V low-voltage DC bus-bar connects to pulsed high-power loads and other types of constant power loads. The whole power grid system realizes energy management through the energy management system, and the energy storage system composed of batteries and capacitor banks serves as the energy buffer link of the power grid system.

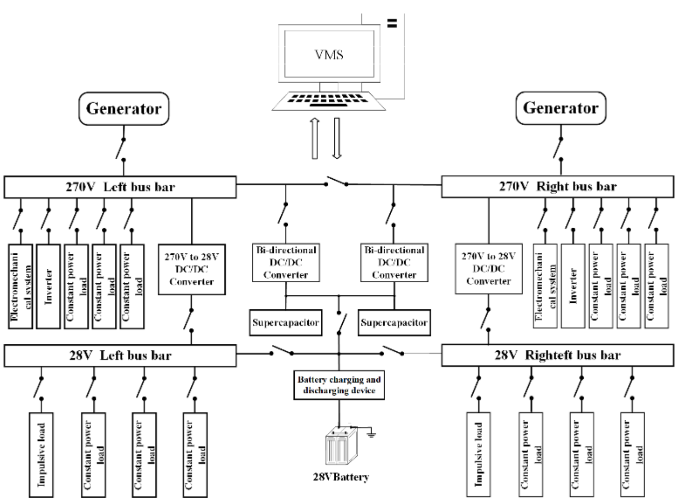


Fig. 2. Schematic digram of the simulation system

The construction of the platform is described in detail in relation to the simulation models. The main system model, namely the left channel main architecture model, is built in the Saber environment, as shown in Fig. 3. In this model, a three-stage motor model as shown in Figure 4 provides 270V high voltage DC power to the electromechanical system, which is stepped down to 28V low voltage DC power via a DC/DC converter. The various loads are hooked up to the high and low voltage bus bars via solid state power controllers. An energy storage module consisting of batteries and supercapacitors acts as an emergency power source for the electromechanical system and also assists in regulating the grid voltage. In addition to the electrical modules, this model also includes a VMS module, a GUI module and a HEAT module. The VMS module controls the solid-state power controller to automatically manage and control the energy distribution, taking into account the power requirements and priority characteristics of the loads. The GUI module transmits the simulation data to Matlab for data processing and display, realizing real-time human-computer interaction. The HEAT module collects the real time power of each part of the power supply system, obtains the efficiency of each subsystem by using the look-up table method, and calculates the real time thermal power to facilitate the access of the subsequent thermal loop control system.

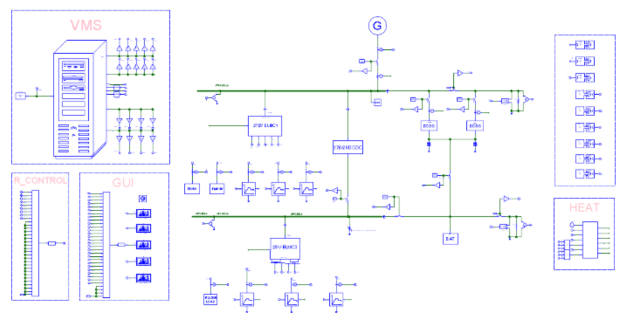


Fig. 3. Simulation model of the the main power system

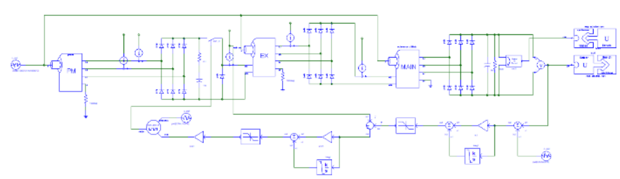


Fig. 4. Simulation model of the three-stage generator

There are four types of typical loads in a electromechanical system of more-electric aircraft , including electric pump loads, constant power loads, high power pulse loads and electric actuation loads. The platform is designed to simulate the actual operating conditions of the electromechanical system by building the above loads through model reduction and other methods.

Since various hydraulic and fuel pumps in electromechanical system are usually driven by permanent magnet synchronous motors or induction motors, the electric pump load models in this platform are shown in Fig. 5 and Fig. 6, which are respectively the embedded processor control model in Saber environment and the permanent magnet synchronous motor model in Matlab environment. The sampling and driving signals are transmitted between them through the distributed simulation interfaces. The algorithm program for the embedded processor is written in the VS project. In Fig. 5, the AD components convert the analogue signals from the Matlab to digital signals to simulate the actual hardware sampling and the embedded processor runs the i_d =0 vector control program to output the drive signals. The DC side of the three-phase bridge in Fig. 6 is connected to the 270V bus bar of the power system. Under the control of the output signal of the processor model, the three-phase sinusoidal current is generated to drive the PMSM to work.

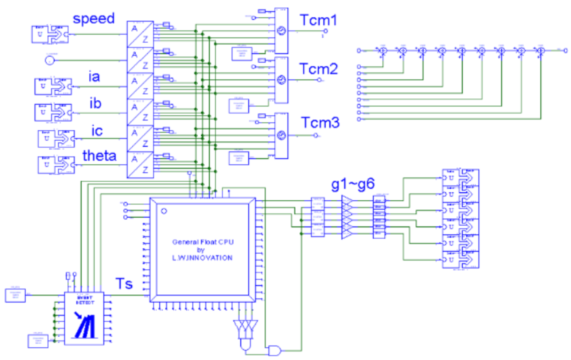


Fig. 5. The controller model based on Software-in-the-loop

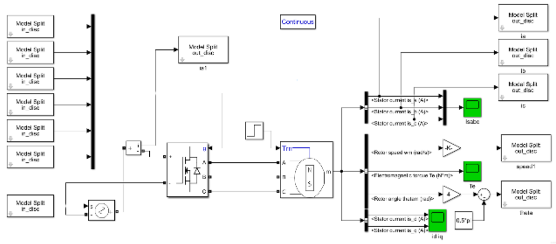


Fig. 6. The PMSM model in Matlab

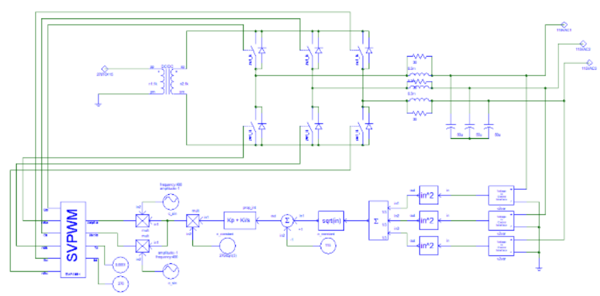
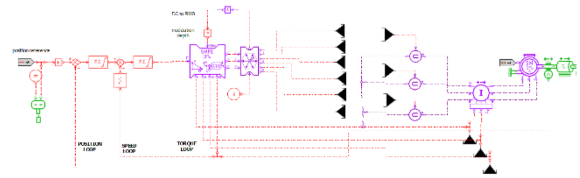


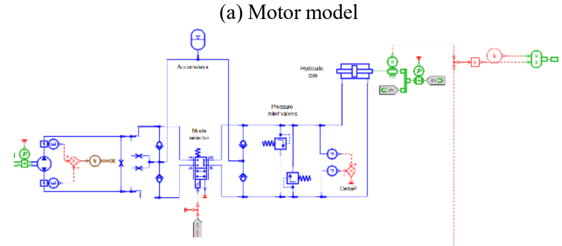
Fig. 7. The constant power three-phase inverter model in Saber

As the constant power loads exhibit negative impedance characteristics for the power system, such as closed-loop controlled power converters and motor speed control systems in electromechanical system, take the three-phase inverter load as an example, as shown in Fig. 7, the DC side of the inverter is connected to the 270V high voltage bus bar via an isolation transformer. The model consists of a power circuit, a single voltage closed-loop control circuit and an SVPWM modulation circuit, which operates at 10kVA constant power and outputs 115V/400Hz alternating current.

There are two main types of high power pulsed loads: one is the DC/DC converter with chopper control, where the voltage or current on the power side is pulsed and the input power is pulsed; the other is the pulsed power load with the secondary power supply, such as the transmitter of airborne radars, which periodically outputs pulsed power. In the platform, a chopper-controlled Buck converter is used as the pulsed load. The input side is set to be connected with 28V low-voltage bus bar. Under the single voltage closed-loop control, the output voltage is 5V and the pulse frequency is 100Hz.



(a) Motor model



(b) Hydraulic model

Fig. 8. The EHA model in AMESim

In this platform, the EHA composed of electrical, motor and hydraulic parts is used as the electric actuating load to participate in system simulation. The electrical part is simulated in Saber environment, and the motor and hydraulic parts are simulated in AMESim environment with higher adaptability. As shown in Fig. 8, in the motor and hydraulic simulation model, three closed-loop controller composed of position loop, speed loop and torque loop is used to output the drive signal required by the electrical model. Then the inverter model in Saber generates electric energy to drive the motor model, and the connection between the electrical model and the motor model is realized through the distributed simulation interface.

To sum up, 13 simulation models are built in Saber, Simulink, AMESim and Simplorer simulation environments. Data interaction among models is realized through the distributed simulation interface, and a complete multi-physical domain heterogeneous distributed simulation environment for electromechanical system of more-electric aircraft, as shown in Fig. 9.

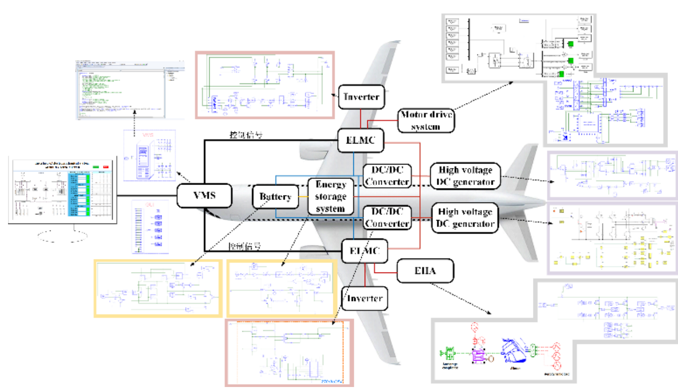


Fig. 9. Heterogeneous distributed simulation environment for electromechanical system

IV. Simulation Results Analysis

Fig. 10 shows the distributed simulation platform built in the laboratory, which is jointly constructed by four high-performance workstations and a high-speed switch. The simulation step size of in the simulator of each model could be set respectively, and the data interaction step size in a single workstation and the data interaction step size between multiple workstations in the relevant configuration file could also be regulated to achieve real-time synchronous simulation in this platform. The power load management and distribution algorithm of more-electric aircraft is achieved by the embedded processor in the VMS model.

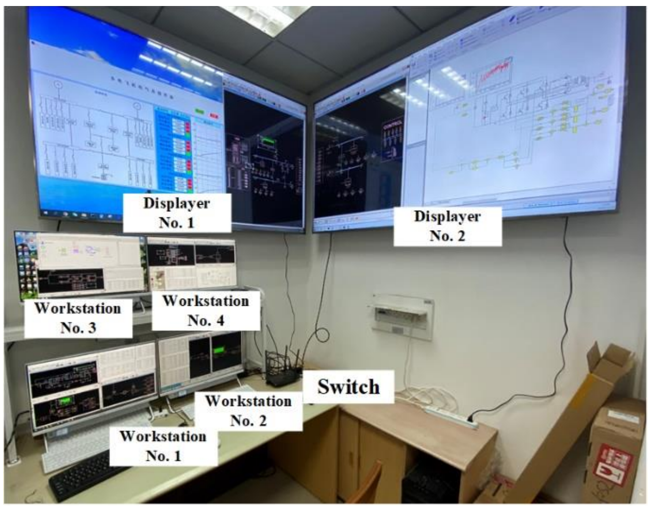


Fig. 10. Physical view of the distributed simulation platform

Fig. 11~16 shows the simulation results of the electromechanical system of more-electric aircraft. Take the left channel as an example to illustrate the stability of the DC power supply system. After 0.075s, the bus-bar voltages of 270V and 28V are stable. At this time, the system loads are successively connected to the power supply system. After loading, the voltages of the two bus bars have dropped to varying degrees, but both are within the allowable range, it can be seen that the working performance of the generator and DC/DC converter is reliable. Fig. 13 shows the A-phase output voltage of the inverter load, which is in high sinusoidal curve, and the operating power also meets the system requirements. Fig. 14 shows the output current of the EHA electrical model in Saber environment, it drives the motor to work and makes the hydraulic pump output displacement stable at the given position. Fig. 15 and Fig. 16 show the simulation waveforms of the PMSM in Matlab environment. When the load of the electric pump is connected to the power supply system at 0.15 s, the armature current of PMSM increases instantaneously to provide enough torque to stabilize the motor speed at 800 rpm. When the load changes at 0.3s, the armature current changes accordingly to achieve the speed stability of the driving system.

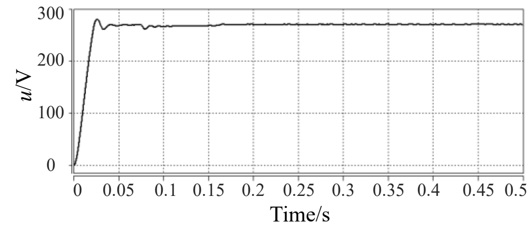


Fig. 11. 270V left bus bar voltage

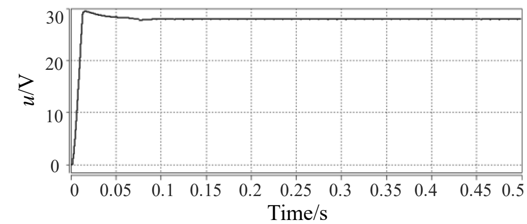


Fig. 12. 28V left bus bar voltage

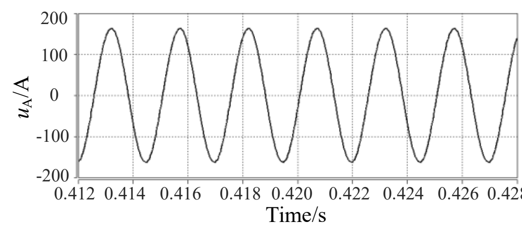


Fig. 13. Inverter load output A-phase voltage

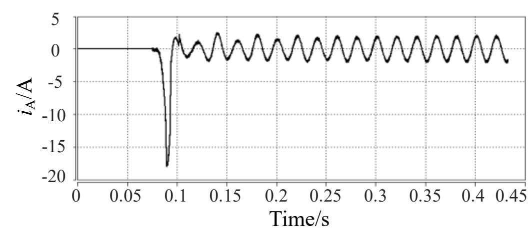


Fig. 14. EHA motor phase A current

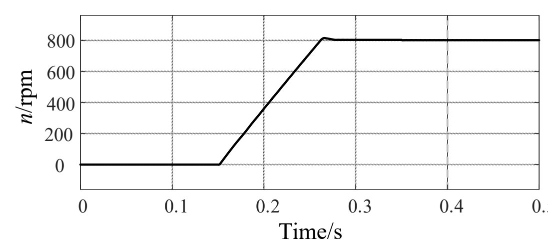


Fig. 15. Speed of permanent magnet synchronous motor

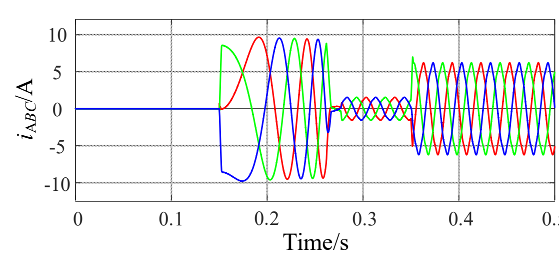


Fig. 16. Phase currents of PMSM

Moreover, based on the distributed simulation technology, the simulation time of the proposed system could also be reduced to meet the expected goals, and it proves the feasibility and reliability of the distributed simulation platform. The platform could also couple models in different simulation environments to give full play to the advantages of each software and improve the accuracy of the large system simulation. It can be seen that the technologies of model segmentation and distributed simulation not only could split the complex systems, but also improve the speed and convergence of the large system simulation effectively.

V. CONCLUSION

Aiming at the important characteristics of multi domain and system complexity of aircraft complex electromechanical system, based on model segmentation and data routing technology, this paper carries out research on key technologies of heterogeneous distributed simulation oriented to multiple physical domains, which solves the fundamental problems of multiple precision requirements, dynamic response and insufficient simulation resources of complex system models, the simulation platform of electromechanical system with the integration of multidisciplinary, multi-level and multi-dimensional simulation models have been built for the verification of the distributed simulation technology. From the simulation results, it can be seen that this platform has the advantages of strong scalability, strong operability and small convergence difficulty coefficient, which can effectively assist the development and verification of electromechanical system.

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