FMI based Multi-domain Modeling and Simulation for Aircraft Power Distribution System

Beilei Yang, Xiaohua Wu, Weilin Li

Abstract—**The aircraft power distribution system is a combination of electrical, mechanical, magnetics, and control system. Traditional professional software can only simulate one specific domain, in order to study the coupling characteristics of aircraft power distribution system, a multi-domain simulation tool is needed. A FMI (Functional Mock-up Interface) based multi-domain simulation method is proposed in this paper to utilize the advantages of different software and their professional model libraries. As a case study, this paper built the controllers of aircraft power distribution by Simulink, and then exported as the FMU (Functional Mock-up Unit) model to Dymola platform according to the FMI standard for the modeling and simulation of whole systems. Those models which exported according FMI standard can be independent from the original simulator and applied to other platforms corresponded FMI standard, which realize multi-domain modeling and simulation.**

I. INTRODUCTION

With the development of the aircraft power distribution system toward "more electric", professional software in various fields was unable to meet the requirements of the system level multi-domain modeling, so Multi-domain Unified Modeling and Simulation is considered as the development direction of simulation technology for aircraft power distribution system.

In order to avoid the repetitive modeling of partial controllers, and combine with the advantages of other software, it is necessary to packaging the model through special methods, which is convenient for engineers to call models and helpful to protect some special business models.

But different modeling and simulation software has their own model description format and data storage format, so it is necessary to define a common model that implements the interface to achieve information exchange between the different simulation models. In view of this, The Information Technology for European Advancement (ITEA2) proposed MODELISAR (Modelica - AUTOSAR integration to support vehicle Functional Mockup) project, which aims to a definition of the functionality encapsulated interface standard to support system for simulation, testing and embedded software development. This model package interface standard is called FMI (Functional Mock-up Interface).

The following two simulators were selected for FMI based model exchange in our paper: Dymola and Simulink. Among the numerous existing multi-domain simulation modeling platform, the Dymola platform based on Modelica language is widely used in automotive, aerospace, energy and other industries. In the study of aircraft power distribution system, many aspects, such as mechanical parts, electrical system, control method, fault detection, load management and so on, which can be realized in Dymola.

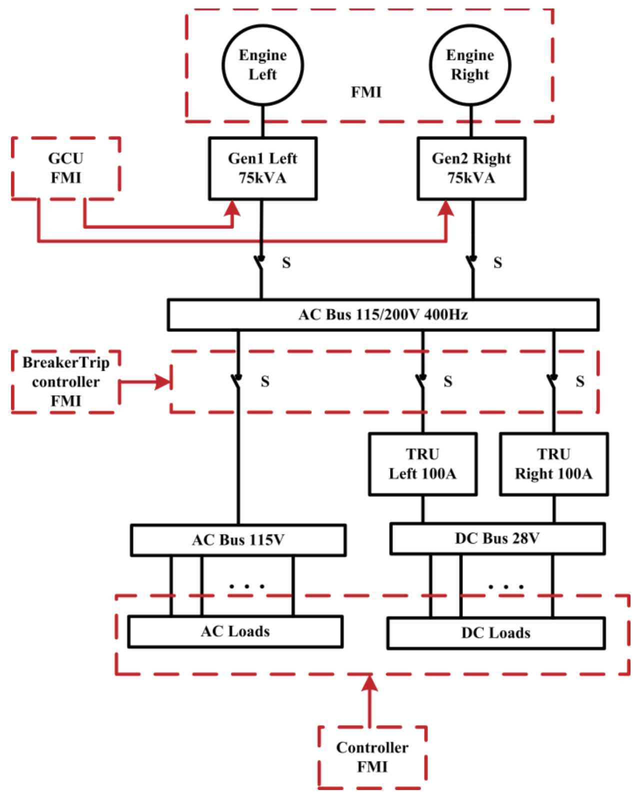


Figure 1. The configuration of aircraft power distribution system with FMI

Simulink has the advantage in modeling complex control algorithms. The advantages of Simulink are wide range, clear structure and procedures and fine, close to the actual and high efficiency for simulation, and so on. Simulink has been widely used in control theory and digital signal processing of complex simulation and design. At the same time there is a large number of third-party software and hardware can be applied to or required to be applied to Simulink. So Simulink is selected for controller simulation in this paper.

According to the FMI standard, this paper exported

*This work was supported by the National Natural Science Foundation of China under Grant No. #51407144, the Young Elite Scientist Sponsorship Program by CAST, the Fundamental Research Funds for the Central Universities under Grant No.#3102015ZY052, State Key Laboratory of Alternate Electrical Power System with Renewable Energy Sources under Grant No.#LAPS15018.

Beilei Yang is with the School of Automation, Northwestern Polytechnical University , Xi'an, China, 710129 (phone: +86 029 88494650; e-mail: beley.yang@qq.com)

Xiaohua Wu is with the School of Automation, Aircraft Electrical Systems Research Institute, Northwestern Polytechnical University , Xi'an, China, 710129 (e-mail: wxh@nwpu.edu.cn)

Weilin Li is with the School of Automation, Aircraft Electrical Systems Research Institute, Northwestern Polytechnical University , Xi'an, China, 710129 (e-mail: liweilin907@126.com)

978-1-5090-1087-5/16/$31.00©2016 IEEE

partial models of aircraft power distribution systems as FMU from Simulink to Dymola platform to finish the complete modeling and simulation. As shown in Figure1, it is in the aircraft power distribution system through the FMI package controller to control all aspects of the simulation. The red block diagram in Figure.1 is the packaged model exported from Simulink according the FMI standard. The model retains the characteristics of the original tool modeling, and can be applied to any software that supports the FMI standard.

II. The Functional Mock-up Interface

A. Main Design Ideas

In the process of system level's development and design, the design and analysis of subsystems or whole system all need to integrate models established by different simulators to some extent, and analyze the effect between subsystems. Many simulators, however, has its special model description format and data storage form, therefor it is necessary to defined a common interface standard to implement calculate and exchange between different simulators. According to the supply, Modelisar proposed FMI 1.0 in January 2010, followed by FMI 2.0 in July 2014. Now, FMI standard is affirmed fully by many simulation platforms, such as Simulink, AMESim, Dymola and so on. The advantages of FMI standard are small footprint and small fun-time overhead. FMI employed a simple way by one-dimensional array to storage variables instead of complex variables storage form, which can be convenient to operate and maintain data, thus it is widely used in embedded hardware in the loop platforms and Real-time simulation environment. The two main parts of FMI standard consisted:

(1) FMI for Model Exchange: one simulator can generate a C code block with inputs and/or outputs. This block can be imported in other environment;

(2)FMI for Co-simulation: coupling two or more simulators in a co-simulation. In this process, data exchange between subsystems at a special communication points.

The same structure of Model Exchange and Co-simulation will be illustrated in next section.

B. Description Schema and C-Interface

A component which implements the FMI (both Model Exchange and Co-simulation) is called Functional Mockup Unit (FMU). It consists of one zip-file with extension ".fmu" containing all necessary components to utilize the FMU:

(1)XML-file: The name of file is ModelDescription.xml, which contains the definition of all variables of the FMU, as well as other model information.

(2)C-function: The interface function based on C standard provided in source and/or binary form.

(3)Other information: model icon, tables, maps and so on needed by block, in addition to object libraries or DLLs utilized by model.

It should call the C-function interface in the model file in FMU for simulator to implement simulation. The state solver should be supported by simulator for FMI standard model which does not own it. The simulator also needs to obtain the model information by loading the model description file in FMU, including the variable name, the variable type, the number of states and so on. The process of the simulation based on FMU is shown in the Figure.2.

The executive part of FMI consists of two header files that define the equations of a dynamic system from a C program. The two main header files are "fmiModelTypes.h" and "fmiModelFunctions.h". The first header file consisted the definitions of input and output for function. The second header file contained the function prototypes accessed in simulation tools.

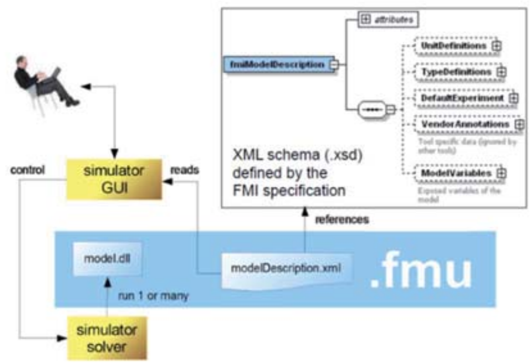


Figure 2. Simulation structure diagram of FMU

C. FMI for Model Exchange

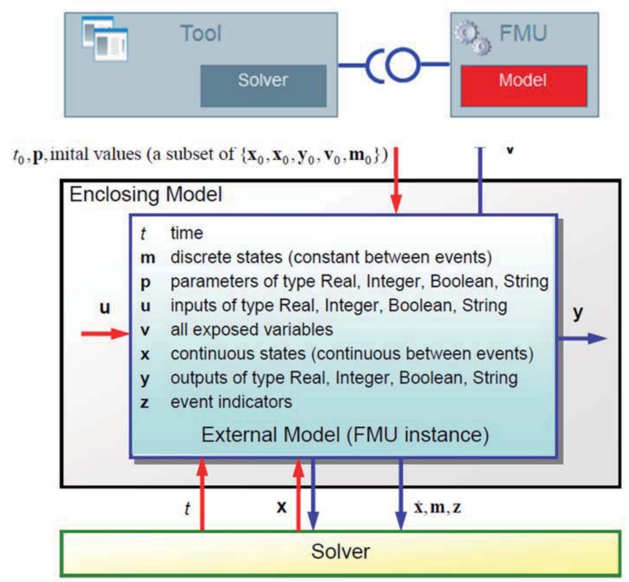


Figure 3. Data flow between the components (Blue arrows: Information provided by the FMU; Red arrows: information provided to the FMU)

A schematic view of a model in "FMI for Model Exchange" format is shown in the Figure.3. It can be shown that the solver is provided by the master and models are consisted in FMU only. The information is communicated by a special interface between master and slaves.

This type of system is described as a piecewise continuous system. Discontinuities can occur at time instants$t_0, t_1, \ldots t_n$, where$t_i < t_{i+1}$. These time instants are called "events". Events can be known before hand (= time event), or are defined implicitly (= state and step events).

The "state" of a hybrid ODE is represented by a continuous state *x(t)* and by a time-discrete state *m(t)* that have the following properties:

x(t) is a vector of real numbers (= time-continuous states) and is a continuous function of time inside each interval$t_i \leq t < t_{i+1}$, where$t_i = \lim_{\varepsilon \to 0}(t_i + \varepsilon)$, i.e., the right limit to t_i (note, *x(t)* is continuous between the right limit to t_i and the left limit tot_{i+1}respectively).

m(t) is a set of real, integer, logical, and string variables (= time-discrete states) that is constant inside each interval$t_i \leq t < t_{i+1}$. In other words, *m(t)* changes value only at events. This means $m(t) = m(t_i)$, for $t_i \leq t < t_{i+1}$.

At every event instant t_i, variables might be discontinuous and therefore have two values at this time instant, the "left" and the "right" limit. $x(t_i)$, $m(t_i)$ are always defined to be the right limit at t_i, whereas $x^{-}(t_i)$, $m^{-}(t_i)$ are defined to be the "left" limit at ti, e.g.: $m^{-}(t_i) = m(t_{i-1})$. In the Figure.4, the two variable types are visualized:

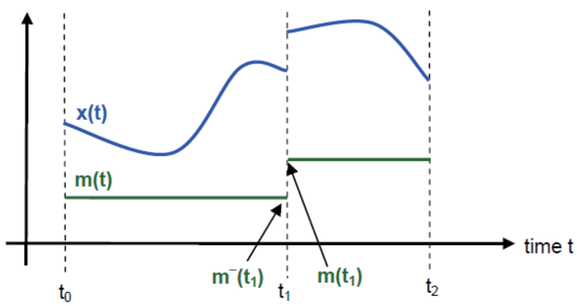


Figure 4. Piecewise-continuous states of an FMU: time-continuous (x) and time-discrete (m)

In this section, a simple content of FMI for Model Exchange is introduced. Due to the fact that lots companies already support the FMI standard, it can be used in multi-domain modeling and simulation widely. Thanks to that, it can be not only avoid repetitive modeling work, and provide convenience for system level engineers, but also strengthen the using of modularization and protection of the original model, which improves the efficiency of modeling. In the next section, partial controllers of aircraft power distribution systems are exported as FMU from Simulink/Matlab to Dymola platform, which can be helpful for people to use those controllers without the need to repeat modeling.

III. The Modeling of Aircraft Power Distribution Systems

A. AC aircraft power distribution systems

The aircraft electrical system is composed of a power supply system and electrical equipment. Among them, the power supply system should provide electric energy to electrical equipment, and electrical equipment consumes the electrical from the power supply system. In order to provide electrical energy to electrical equipment, power supply system must have functions in power generation, transformation, power transmission and distribution. The main link and devices achieve the power generation and transformation are called power supply system, and implement the power transmission and distribution functions are known as the transmission and distribution system.

Taking the traditional aircraft power distribution system as an example, and the structure of aircraft power system is shown in Figure.1. AC power supply system with 115/200V, 400Hz three-phase mechanical hydraulic uses the constant speed power generation system. The main power supply of the F-14A is two power supply devices of 60/75kVA; the secondary power supply is two 100A transformer rectifiers (TRU); the emergency power is a hydraulic drive of AC/DC double input generator, and it can provide a 5kVA 115/200V constant frequency AC power and 1.5kW 28V DC power. The layout of the system is not parallel connection, the two main generators supply power to the main bus power respectively. If one generator breaks and quits automatically, another will supply for whole load to ensure power supply uninterruptedly. On the side of DC, the layout of system is parallel connection, and if one breaks, protections only play a role in the short circuit bus bar, which will not affect another TRU.

In order to simplify the modeling process, one power generation system will be built in Dymola, which consisted by an engine, generator, primary distribution bus, secondary distribution bus and TRU. The loads of the system include various power equipment, including lighting, heater, DC motor and AC motor, etc. The main controllers and engine will exports as FMU from Simulink Matlab to Dymola platform. All models are explained in the following sections in more detail.

B. Controllers exported as FMU from Simulink

Those controllers can be used in many simulations in the field of aircraft power supply system, so it is not necessary to model repeatedly in every simulation, it can be used in many times after the first modeling just modifying their parameters. This goal can be achieved by FMI for Model Exchange standard, which can be implemented trough a special film supplied by Dymola to help Matlab to export models as FMU that can also be applied in any software supplied FMI standard.

It can export models from Simulink as FMU after special process of environmental configuration (the detailed information is shown in Dymola user manual volume2). The Simulink models is showed in Figure.5, which consist Mechanical engine (supplying the mechanical speed to power generator), GCU (a controller of power generator), Breaker Trip (bus control unit) and Breaking chopper controller (a controller of breaking chopper in AC motor).

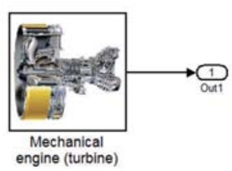
The software and compiler version are:

- Matlab 2010aWin32
- Dymola 2015
- Microsoft Visual C++ 2005 SP1
- The version of FMI for Model Exchange is 1.0

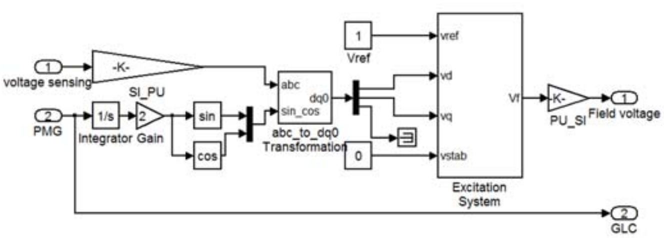
C. Modeling on Dymola platform

Dymoal, Dynamic Modeling Laboratory, is a complete tool for modeling and simulation integrated and complex system for use within automotive, aerospace, robotics, process and other applications. Due to the Modelica modeling language, Dymola users are able to create their own special model libraries or modify the existing models in commercial libraries, which can better meet the unique demand for users. The convenience of Dymola is perfect for users to modeling and simulation in research and studying.

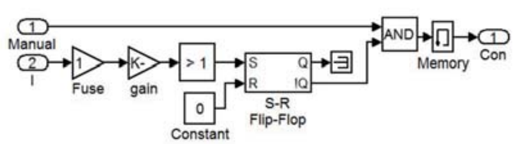
The complete power distribution system is modeled in Dymola showed in Figure.6. The engine is exported as a FMU from Simulink. The sub-model "Power Generation" is shown in Figure.7, which is consisted of a synchronous induction machine and GCU FMU; the controllers in primary distribution control the opening and closing through the speed of the machine; the sub-model "Secondary Distribution" is shown in Figure.8. The data types of two inputs and one output of "BreakerTrip" FMU are determined by the types of input and output points in Simulink models. The red point is Boolean and the blue points is Real. "BreakerTrip" FMU controls the opening and closing of sub-model "contactor" through the current of every load. The Boolean input of "BreakerTrip" FMU is controlled by the driver's control signals. It can be known that, from Figure.8, the first and third loads have a normal operation in whole simulation, while the second loads is cut off in 0.5s by the "BooleanStep" source.



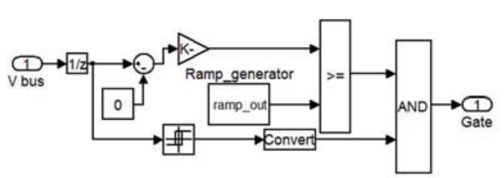
(a)



(b)



(c)



(d)

Figure 5. (a) Mechanical engine; (b) GCU; (c) Breaker Trip; (d) Breaking chopper controller modeled by Simulink

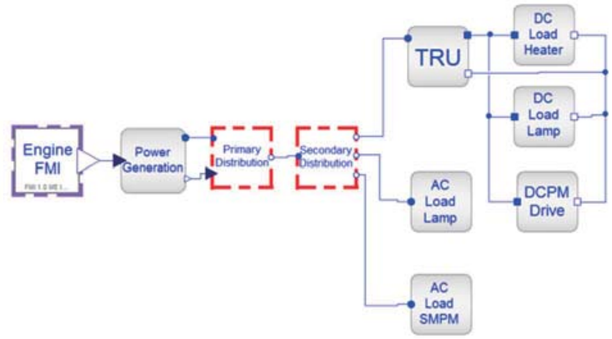


Figure 6. AC power electric distribution modeled by Dymola

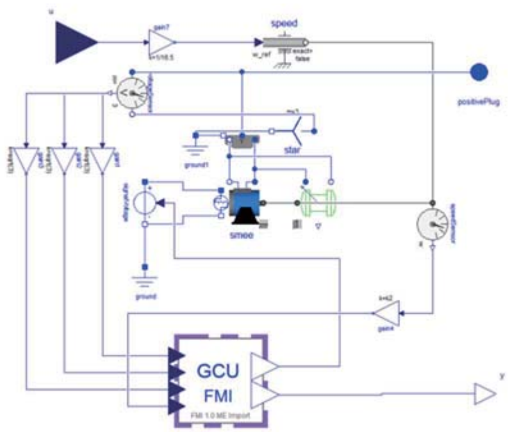


Figure 7. Power generation with GCU FMU

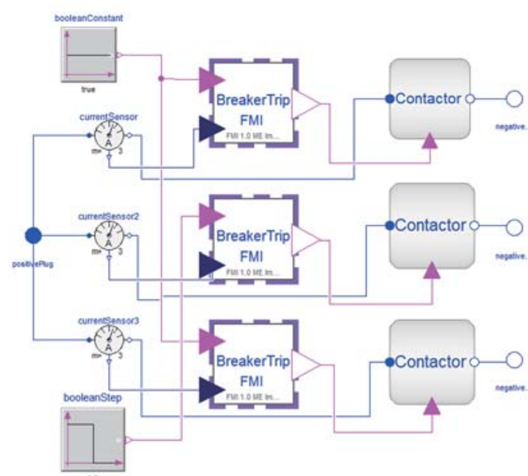


Figure 8. The secondary distribution with BreakerTrip FMU

The "AC Load_SMPM" consists of an AC/DC rectifier, a breaking chopper and a SMPM motor which is shown in Figure.9. The controller of "Breaking Chopper" is a FMU which control the ideal switch to ensure supplying a constant DC for following motor. This model shows a speed controlled transient motor model feed by external power supply. Many components in Dymola are equipped with thermal contact point, which is a true reflection of the status of the actual components. A DC load "Heater" is shown in Figure.10, and the red point on the resister is the thermal contact point which can transfer the heat power of resister to environment. All parameters of models can be shown in Dymola-Simulation-Variables Browser without any sinks just like Simulink.

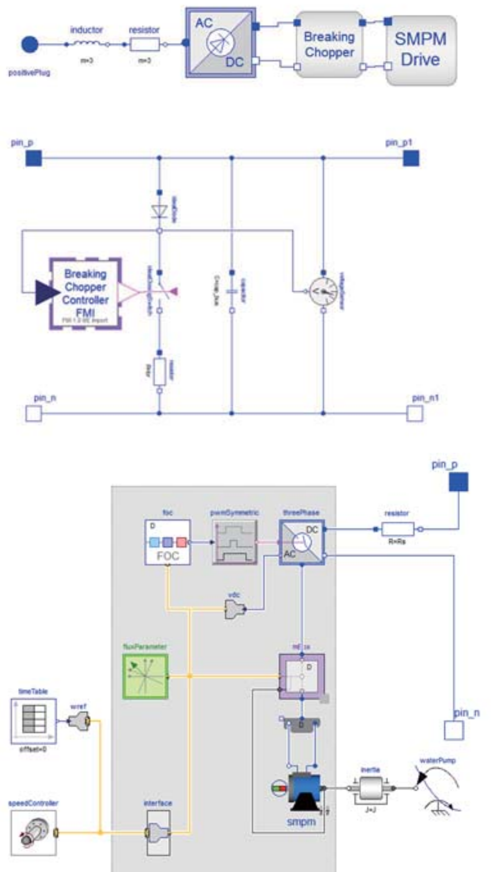


Figure 9. AC load: smpm drive

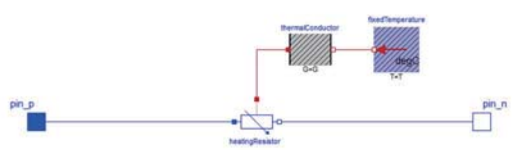


Figure 10. DC load: Heater

IV. SIMULATION RESULTS

The simulation results of aircraft power distribution systems modeled in previous section is shown in following Figures. The output speed of mechanical engine (Figure.11) is shown that the speed of engine reached nominal speed at 0.4s, and the fluctuation of speed appeared at 2s until the speed returned 0 at 6s. The output voltage of power generator kept 115V/400Hz at 0.25s until the end. The Figure.12 is shown that the output voltage of power generator in the first 0.5s.

At the 0.5s, the second load is cut off because of external signal, thus the input of sub-model "Contactor" in Figure.8 is false, and the voltage on the second load is zero, which is shown in Figure.13. It should be noticed that the voltage of the load is zero in the first few seconds in Figure.13. This is because the switch of the primary distribution kept turning off until the speed of engine reached 9000r/min. Other loads have the same phenomenon.

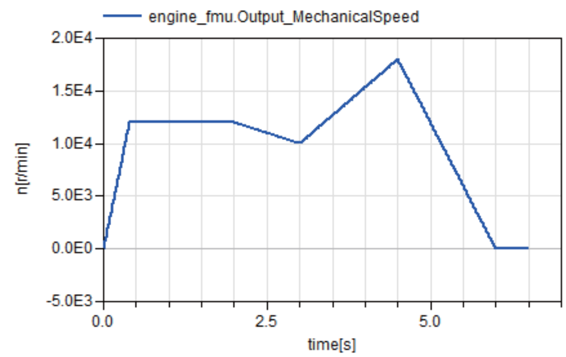


Figure 11. The mechanical speed exported from engine FMU

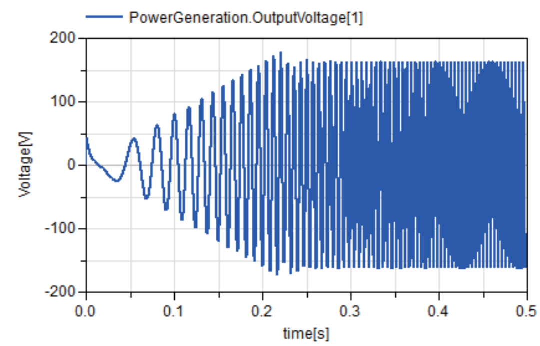


Figure 12. The output voltage of power generation

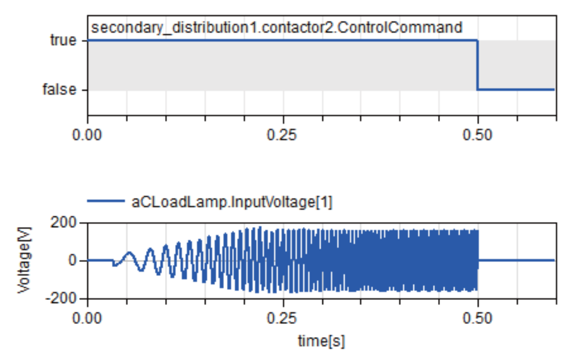


Figure 13. The input voltage of the second load—AC Load_Lamp is cut off in 0.5s

The related wave of AC load SMPM is shown in Figure.14. A reference speed curve is fed to a transient model of the machine which is blue line in the first figure of Figure.14, while the red line is the actual speed. The reference speed reached half of nominal speed at 0.5s (ω=200rad/s) and nominal speed at 0.85s (ω=400rad/s). During that time, the actual waveform basically coincides with the reference waveform. The second figure is the electromagnetic torque of the machine. At the 0.6s, the nominal torque is reached when the speed reached the nominal speed.

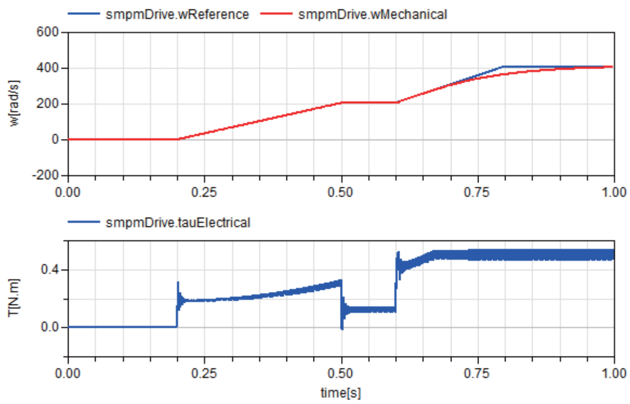


Figure 14. Simulation results of AC_Load SMPM

V. CONCLUSIONS

This paper proposed a FMI based method for model exchange to realize multi-domain simulation of aircraft power distribution systems. Matlab/Simulink and Dymola platforms have been selected to export and import FMU for simulation, thus it is convenient to design various models based on the advantage of these software to finish the system level simulation and modeling. In this paper, the controllers of aircraft distribution were modeled in Simulink, and exported as FMU from Simulink to Dymola platform, where the whole system model was built. Various types of loads, such as lighting, heater, and DC/AC motor, can be easily implemented in Dymola to meet the needs of multi-domain modeling.

Due to the complexity of aircraft power distribution systems, FMI standard can be used to reduce the complexity of the problem, and will be better applied in the multi discipline system level modeling in the future.

ACKNOWLEDGMENT

This work is supported in part by the National Nature Science Foundation of China (Grant No. 51407144), in part by the Young Elite Scientist Sponsorship Program by CAST, in part by the Fundamental Research Funds for the Central Universities (Grant No. 3102015ZY052), in part by State Key Laboratory of Electrical Insulation and Power Equipment (Grant No. EIPE14203)

REFERENCES

[1] Hongfang TIAN, Lizhi SHAN, Chenggong LI. Functional Mock-Up Interface (FMI) Standard[C]. 2011 International Conference on Information, Services and Management Engineering. December 26-28, 2011， Beijing, China.1401-1405.

[2] MODELISAR Consortium: Functional Mock-up Interface for Model Exchange Version1.0 https://www.funciton-mockupinterface.org

[3] Blochwitz T, Otter M, Arnold M, et al. The Functional Mockup Interface for Tool independent Exchange of Simulation Models[C]. In Proceedings of the 8th International Modelica Conference. 2011:105-114.

[4] Blochwitz T, Otter M, Akesson J, et al. Functional Mockup Interface 2.0: The Standard for Tool independent Exchange of Simulation Models[C]. 2012:105-114.

[5] Rajagopalan S, Sastry V V, Ajjarapu V, et al. Object-oriented measurement templates for power electronics education and research using DYMOLA (Dynamic Modeling Laboratory)[C]. Computers in Power Electronics, 2000. Compel 2000.

[6] Tiller M. Introduction to Physical Modeling with Modelica[M]. Springer US, 2001.

[7] Weimer J. Power electronics in the more electric aircraft[C]. Aiaa Aerospace Sciences Meeting & Exhibit. 2002.

[8] Chandrasekaran S, Lindner D K, Boroyevich D. Analysis of subsystem integration in aircraft power distribution systems[M]. 1999.

[9] Liu W, Gong J, Xie S. Aircraft Power Distribution System Large-signal Modeling and Control[C]. International Conference on Electrical Machines and Systems. 2008:4102-4106.

[10] Yang S, Meng L, Ruan L, et al. Modeling and simulation of aircraft automatic power distribution system[C]. 2012 Electrical Systems for Aircraft, Railway and Ship Propulsion (ESARS). 2012:1-4.

[11] W. Li, W. Liu, W. Wu, X. Zhang, Z. Gao, X. Wu, “Fault Diagnosis of Star-Connected Auto-Transformer Based 24-Pulse Rectifier,” Measurement, vol.91, pp.360-370, 2016.

[12] W. Li, W. Liu, S. Liu, R. Ji, and X. Zhang, “Impedance Characteristics Study of Three-Phase Aircraft Power Wires,” Measurement, vol. 78, pp. 235-244, Jan. 2016.