A Comprehensive Simulation Model and Stability Analysis for Power System of More Electrical Aircraft *

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Abstract— **This paper proposes a comprehensive simulation model for the Electrical Power System (EPS) of More Electrical Aircrafts (MEA). Taking the presently typical MEA model of Boeing 787 as an example, the integrated structure of EPS is firstly illustrated and the operating principles are theorized. The key components of the MEA EPS including generators, rectifiers, loads, breakers, control devices, cables and other supplementary elements are then simulated to build a comprehensive EPS model on the platform of MATLAB/Simulink. Although the model's scale is large, its simulation time is guaranteed thanks to using the built-in blocks provided by Simulink. Finally, the stability analysis in terms of normal operation and different faults are carried out in case studies and power source switching strategies in different situations are summarized. The results showed that the comprehensive model proposed by the paper can be used to simulate MEA EPS and analyze its operational stability effectively and efficiently.**

I. Introduction

A conventional aircraft is mainly composed of electric, hydraulic and pneumatic systems. Various valves and control devices needed to coordinate them make the aircraft complicated; and the heavy ducts equipped in the last two systems make it burdensome. These aircrafts acquire the energy in two ways: the electric power produced by the engine-driven generator and the high-temperature air sent by the engine into the pneumatic system. With the developed MEA, the Engine Bleed Air System has been removed and the generating capacity of the EPS has greatly increased. The energy that used to be provided by hydraulic and pneumatic systems and supports many functions such as environmental controls, engine start-up and wing anti-ice is now partly provided by electric system instead[1]. The obvious advantage of replacing hydraulic and pneumatic systems by electric system are saving the wires and one form of the energy resource (high-temperature air); therefore simplifying the design and maintenance of the aircraft, lowering the operational cost, and improving the fuel efficiency. With the developing of All Electrical Aircraft (AEA), hydraulic and pneumatic systems are completely removed from the aircraft structure, which will further reduce the size and weight of the aircraft. However, the increasing use of power electronics and electric-driven devices make the EPS of MEA and AEA much more complicated and thus impose a big challenge for its modeling and simulation, especially the difficulty in improving the simulation speed in case of large-scale model based on detailed components[2].

A large number of research works have devoted to modeling the EPS of MEA; but most of them focused on either component-wise level, such as Transformer Rectifier Unit (TRU)[3], generators and various kinds of power conversion devices[4], or system-wise level of small-scale. For example, Griffo et al. built a model to analyze the stability of a MEA hybrid power system[5]. Although the model is detailed, it only simulated a single-generator (one-line) system that consisted of a synchronous variable frequency generator and an 18-pulse rectifier. The fuel cell/battery and Auxiliary Power Unit (APU) were further considered in [6] and [7]. These studies made a big progress in modeling the integrated power sources of MEA but did not consider power switch strategy and thus has only one bus.

The key problem of modeling large-scale EPS of MEA is to minimize the simulation time at no cost of sacrificing the accuracy. Therefore the modeling needs to focus on components functionality, i.e., so-called functional modeling, instead of on their detailed structures. Wu et. al. firstly proposed the functional modeling method in [2] and used it to study the single-generator system of the overall EPS[8],[9]. The same approach was employed in [10] to study the A380 type. The EPS was modeled to represent only half of the original one and not all power sources were considered.

Based on functional modeling approach as well, this paper builds a comprehensive model for the EPS and use it to analyze the stability of MEA. In Section II, EPS of three typical large-scale MEAs are introduced and compared with that of the conventional aircraft. In section III, the key components of the EPS including generators, rectifiers, loads, breakers, control devices, cables and other supplementary elements are modeled from the system's point of view and the switching strategies of power sources in different situations are discussed. The stability analyses in terms of normal operation and different faults are carried out in Section IV and the conclusion is given in Section V.

II. EPS of More Electrical Aircrafts

The EPS of MEA is strongly different from that of the conventional aircraft in terms of power sources, voltage levels, and power distribution. These will be introduced in detail as follows by taking the currently available MEA models, i.e., Boeing-787 (B787), A380 and F35, as examples.

B787 is the first long-haul aircraft in aviation history and the most typical MEA model at present. This paper

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illustrates the overall EPS structure according to its functional principles as shown in Fig.1. B787 employs a Variable Speed Variable Frequency (VSVF) power system and the power sources are composed of four Variable Frequency Starter Generators (VFSGs) driven by engines under left and right-side wings and two APU Starter Generators (ASGs) powered by a dedicated battery(or from external ground power). This VSVF system is called "variable frequency" because the Constant-Speed Drive (CSD) has been removed and the generator's frequency is in proportion to the speed of the engine. Among all power source systems having been designed so far, VSVF is the simplest and the most efficient one because of its simplified structure of the generator and reduced procedure of the energy conversion. The total generating capacity of B787 is 1450KVA, nearly four times that of other Boeing models. This large generating capacity makes the EPS extremely reliable. A test showed that B787 could fly on one engine for 5.5 hours with five of six generators turned off, which demonstrated the robustness of its EPS[11].

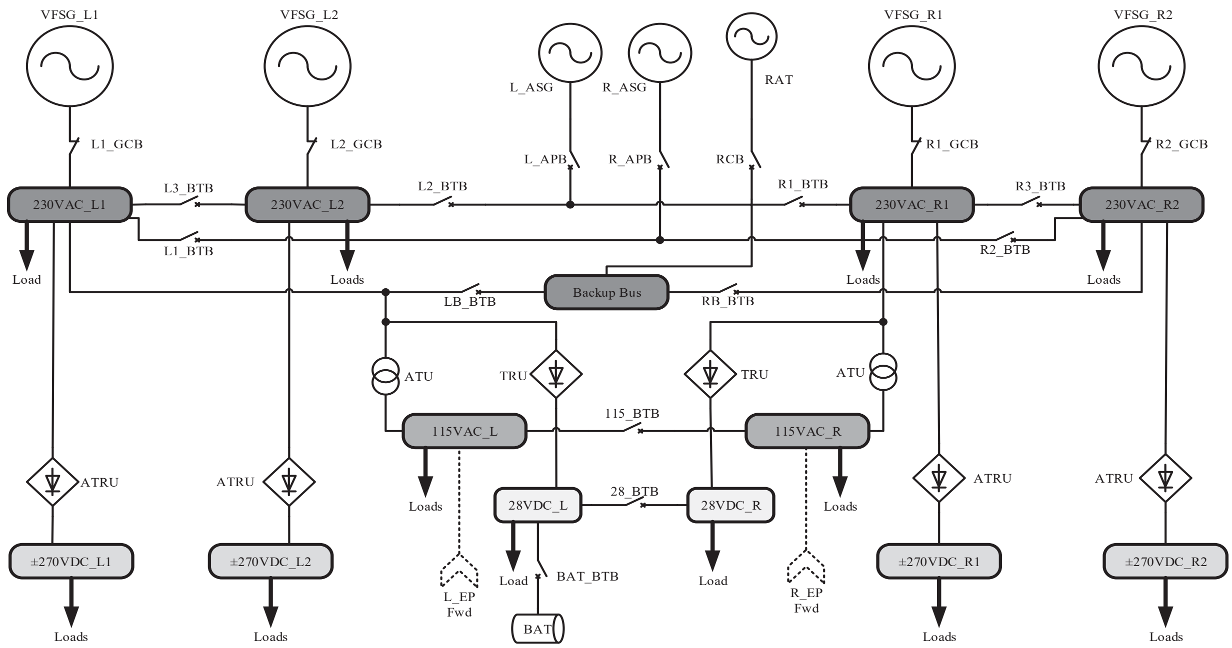

Figure 1. Electrical Power System structure of B787

The EPS of B787 is a multi-level voltage system with hybrid AC/DC networks. The primary 230VAC (with frequency range of 380 - 800Hz) bus is connected to a VFSG by a Generator Control Breaker (GCB). From there, the power produced by the VFSG is either directly distributed to AC loads or transformed to three voltage levels: one is the secondary 115VAC bus by the Autotransformer Unit (ATU); the other two are 270VDC bus by the Auto-Transformer Rectifier Unit (ATRU) and 28VDC bus by the Transformer Rectifier Unit (TRU) respectively. As shown in Fig. 1, the EPS of B787 is left-right symmetric with two 230VAC buses, two 270VDC buses, one 115VAC bus, and one 28VDC bus on each side.

Before taking off, ASGs start up and supply the power to the loads connected to the primary 230VAC buses. After taking off, VFSGs are the primary power sources while ASGs are the backups. If all AC power fails during the flight, the Ram Air Turbine (RAT) connecting to the Backup Bus will be automatically in service and supply the power that will be transformed to 115VAC and 28VDC respectively. In case of emergency when all generators and RAT fail, the Battery (BAT) acts as the last straw to supply the power to the most important DC loads. Although there are many power sources, only four VFSGs function most of the time and undertake the largest load during the smooth flight of MEA. Later we will take advantage of this fact to simplify the modeling.

In the conventional aircraft, the distribution system is centralized so that it takes a long way for the electric wires transmitting the power to all loads. In contrast, the EPS of MEA (such as B787) is so-called solid-state consisting of one Primary Power Distribution System (PPDS), two Secondary Power Distribution System (SPDS), two Bus Power Control Unit (BPCU) and 17 Remote Power Distribution Unit (RPDU). PPDS distributes the power from the primary 230VAC bus while SPDS distributes the power from the secondary 115VAC bus and 28VDC bus respectively. When some of the generators fail, the power-off loads has to be switched to other sources. BPCU controls power transfer functions by switching on/off the breakers including Bus Tie Breakers (BTBs), Auxiliary Power Breakers (APBs), and RAT Control Breakers (RCBs). All AC/DC loads are directly fed from the nearby electrical equipment bays (E/E Bay) or the RPDUs placing around the airplane. The solid-state power distribution system of B787 EPS is shown in Fig. 2[12]. This structure simplifies the wiring structure, improves the efficiency of power utilization, and reduces the maintenance cost of the aircraft.

The EPS structure of A380 is almost the same as that of B787. It is also a VSVF system and deploys the solid-state power distribution. The differences lie in smaller generating capacity (915kVA), using 115V as the primary AC bus, and less efficient than B787.

Being a fighter plane, F35, among the three models, has the smallest generating capacity (250kVA), the most cutting-edge power distribution system, and the most advanced high-voltage DC systems with primary power sources driven by the brushless DC motor and 270VDC as the primary bus. At present, F35 is called the second generation MEA, even AEA sometimes. However, because of its high cost and military importance, there has been not so much research on F35 yet although it definitely represents an outstanding achievement in aircraft technology.

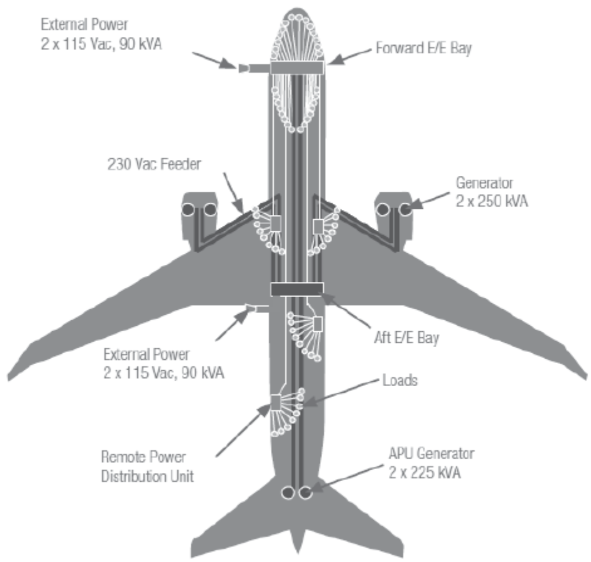

Figure 2. Solid-state structure of B787 EPS

As discussed above, B787 is the most typical and practically-used MEA, so it will be chosen as the representative for modeling and analyzing in this study. Since its EPS structure is the most complex one, the results and conclusions will be applied to the other models as well.

III. Modeling of MEA EPS

Many researchers have built models for the EPS of MEA to study its performance like power quality or stability. The models are usually as simple as a single-generator system and their structure won't change with different working situations of the aircraft. In our study, the complete structure of the most complex MEA B787 is modeled; and the EPS structure will be changed with different switching strategies of the power sources as requested by the flight.

This section describes the modeling of MEA EPS components based on the scheme drawn in Fig. 1 in detail. They are generators (VFSG, ASG and RAT), breakers (BTB, GCB, APB and RCB), ATRU, BPCU, AC/DC loads, cables, and other supplementary elements (e.g., measurements). The modeling focuses on the components' functionality instead of on their detailed structures. The comprehensive model is built on the platform of MATLAB/Simulink and the built-in blocks provided by Simulink are used as many as possible to save the simulation time.

A. Generator

In reality, VFSG is a 3-level brushless generator whose structure is shown in Fig. 3. The Exciter, powered by the Permanent Magnet Pilot Exciter, provides exciting current to the Main Generator through the Rotating Rectifier Assembly, which is installed on the rotor of Exciter and thus the 3-level generator is "brushless". The output voltage can be directly controlled by adjusting the exciting current and its frequency changes in proportion to the speed of the rotor (engine).

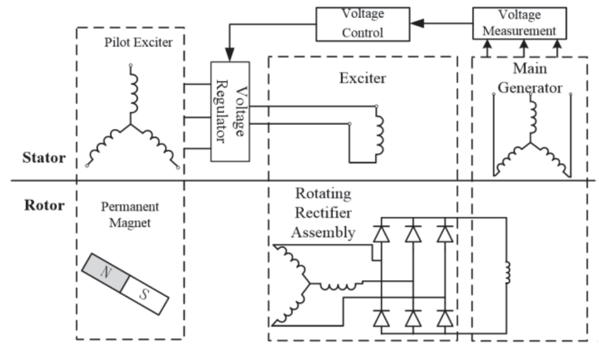

Figure 3. 3-level brushless generator structure

The corresponding Simulink model referring to the Simulink demo "Aircraft Electrical Power Generation and Distribution" is shown in Fig. 4. "Speed" is a programmable signal that can imitate the variable speed of the turbine (so-called "variable frequency"). "Generator" is a simplified generator subsystem and "GCU" controls the output voltage. The Measurement displays the output voltage of the generator. The performance of the output voltage is stable and suitable for the B787 EPS.

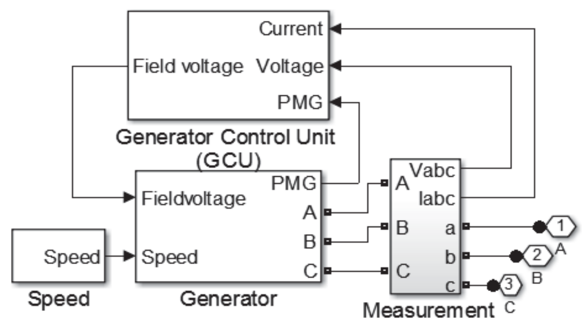

Figure 4. VFSG model

Although the structures of ASG and RAT are different from that of VFSG, they are simple power sources. So they can be modeled in the same way as shown in Fig. 3 with a constant speed of 12000r/min (i.e., 400Hz).

B. Breakers (BTB, GCB, APB and RCB)

Buses are connected together through BTBs. In the event that one generator should fail it is automatically isolated from its respective bus and all associated loads are taken over by the operative generator. A controlled three-phase breaker can achieve this function.

The model of L3_BTB which combines 230VAC_L1 Bus and 230VAC_L2 Bus is shown in Fig. 5. The tag "L3_BTB" is the control signal of this breaker. When one of the left generators turn off, the control signal status becomes TRUE and breaker will switch on to transfer the power source. To avoid the error operations, a time delay block was added in this model. The breaker won't close unless the control signal keeps TRUE for at least 0.5s.

The output of the generators are controlled by the GCB, APB and RCB. These breakers can share this BTB model because they function in the same way. A given disable signal can cut off the generator from the EPS to imitate the generator fault in a simple way.

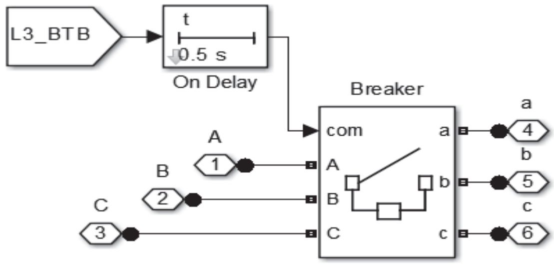

Figure 5. L3_BTB model

C. ATRU (TRU)

ATRUs and TRUs on MEA are normally 12-pulse configuration and usually employ uncontrolled rectifiers[13]. Fig. 6 shows a schematic of a 12-pulse rectifier circuit which employs a three-winding isolation transformer with a Y-Y–Δ connection. An inter-phase reactor (L) is added to connect two rectifiers in parallel. When the output voltages of the two converters are equal, the inter-phase reactor is transparent. However, when the output voltages of the converters are not equal, the winding of the inter-phase reactor presents sufficient inductance to support the voltage imbalance[14]. Due to the existing of power converters, the system contains a lot of harmonics. Filters on the AC side are needed to meet the standards of harmonic contents.

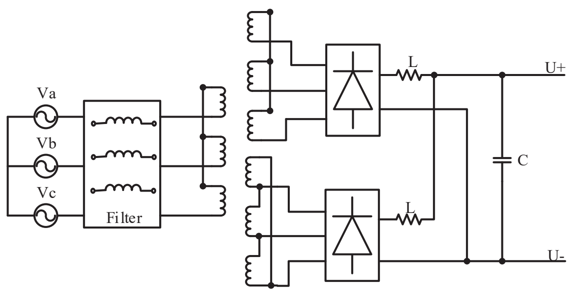

Figure 6. 12-pulse Y-Y-Δ diode rectifier

The following two formulas can be used to calculate the inter-phase reactor and the DC capacity of the ATRU:

$$L=\frac{\sqrt{2}(1-\frac{\sqrt{3}}{2})V_l}{3\omega I_{d\min}},\quad C=\frac{2}{2\pi f R_{ef}}$$

Where, V_l is the input line voltage and $V_l=\frac{\pi}{3\sqrt{2}}V_d$. V_d is the desired DC voltage. $I_{d\min}$ is the minimum load current, nearly 1% of the DC current. R_{ef} is the equivalent resistance on DC side. The final ATRU (TRU) model is shown in Fig. 7.

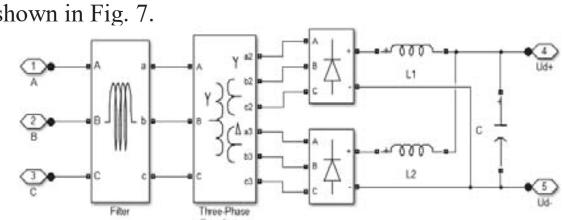

Figure 7. ATRU (TRU) model

D. BPCU

BPCU is used to realize the switchover between the power sources under different conditions by controlling the BTBs. When three or more generators turn off, the ASG starts up and some power-off devices must be transferred to the backup power sources. Appendix 1 shows the power sources switch strategy under different faults. When some of the generators turn off, BPCU would close the corresponding BTBs according to the given strategy. The logic elements were used to implement the switching function. Fig. 8 shows parts of the BPCU logic elements to control 4 of the BTBs. When the logic tag K12 is TRUE, it represents the ground power is on. When 3 out of 4 VFSGs fail, K7 or K8 becomes TRUE.

As an example of R1_BTB, from the switch strategy in Appendix 1, we can see that the R1_BTB would only close under two conditions:

- only the 2 right VFSGs are both out of service (matching the condition K5): in this condition, 230VAC_R1 Bus and 230VAC_R2 Bus both lose power, by closing L2_BTB, R1_BTB, 230VAC_R1 Bus loads are transferred to the 230VAC_L2 Bus and 230VAC_R2 Bus loads are transferred to the 230VAC_L1 Bus closing L1_BTB, R2_BTB.
- 1 left and 2 right VFSGs are out of service (matching the condition K7): in this condition, only 230VAC_L1 Bus is still on work. At this moment, the L_ASG starts to supply the 230VAC_R1 Bus by closing R1_BTB and R_ASG supply the 230VAC_R2 Bus by closing R2_BTB. Meanwhile, the L3_BTB close to supply the left part loads.

But if the ground power is connected, all of the equipment are fed by the ground power and the R1_BTB will not close. The other BTBs work at the same way.

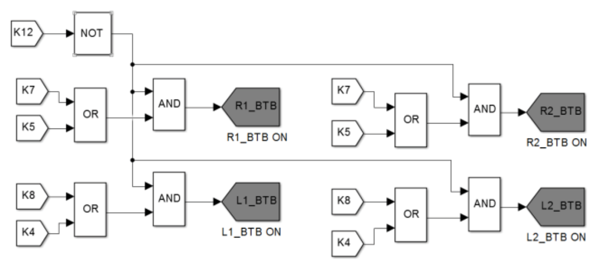

Figure 8. Parts of BPCU model

By changing the working state of the generators, BPCU can imitate the other different generator-fault situations.

E. Loads, cables, and other supplementary elements

There are many kinds of loads in the MEA power system but in this study, different types of loads are not considered. Assume that the power-factor of AC loads is constantly 0.85 and all loads regard as PQ nodes, which data changing with different working periods.

MEA employs the three-phase four-wire system, neutral line on the airframe. The MEA lines are relatively short so we can ignore the capacitive in the PI-type equivalent model and directly represented as an equivalent impedance, using the experimental measured parameters.

Other supplementary elements like buses and measurements can be simply modeled by the built-in blocks of Simulink.

Finally, combined all the key component models referring to Fig. 1, the comprehensive MEA EPS model is shown in Fig.9. Though the scale of this comprehensive model is very large, it does not need too much computing time using the original Simulink models.

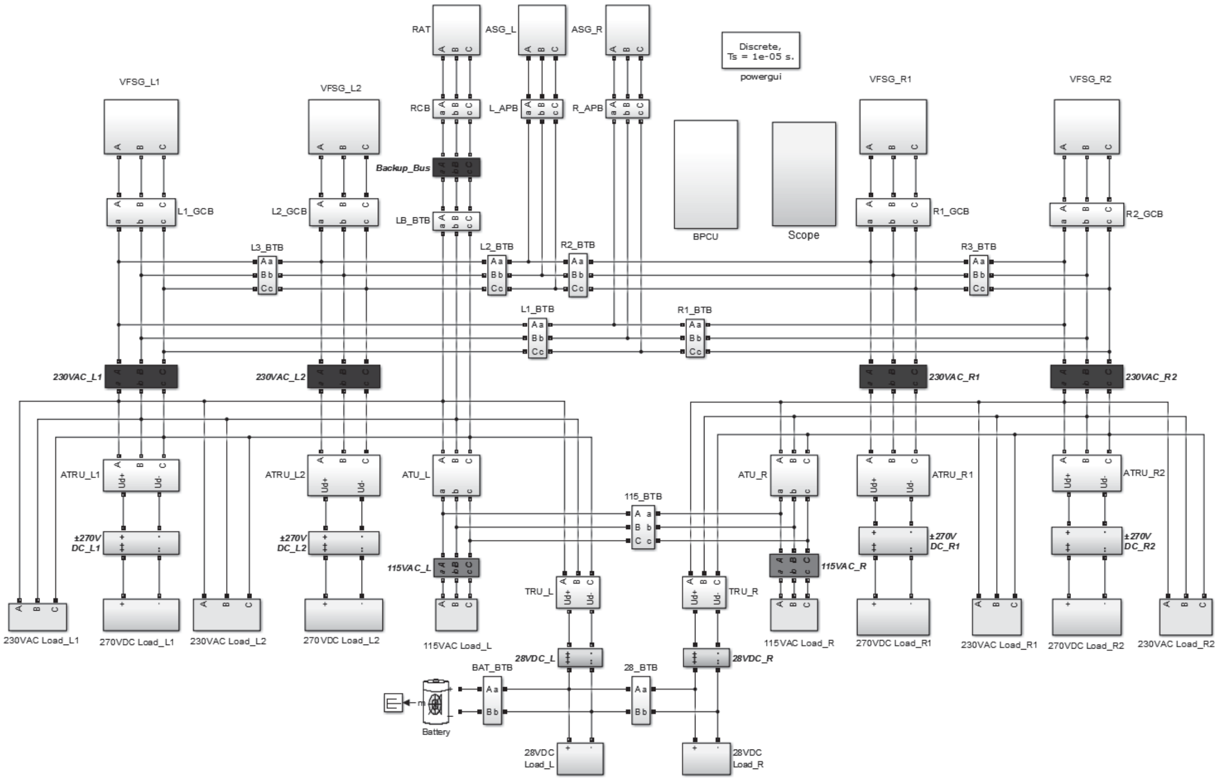

Figure 9. Comprehensive EPS model of B787

IV. Case Studies

This section will assess the performance of the comprehensive model for simulation study under two different conditions: the normal operation and the fault cases. The parameters for this study are list in Appendix 2. All simulations were carried out on a computer with AMD A10 (2.50GHz) CPU, 8GB RAM.

A. Normal Operation (Steady-State Analysis and Load Disturbance)

In most cases, the EPS is running under normal operation. All the BTBs are off and the system operates in a 4-line isolated configuration. The VFSGs running at variable frequency between 366Hz~466Hz. Each single line of the EPS is independent and either one of them can reflect the simulation performance. The line VFSG_R1 -- 230VAC_R1 -- ATRU -- 230VDC_R1 (ATU -- 115VAC_R/TRU -- 28VDC_R) is chosen to study the steady-state performance of MEA EPS. All the loads are under full power conditions. Simulation results in Fig. 10 shows the response of the 230VAC_R1 Bus, 115VAC_R Bus, 270VDC_R1 Bus and 28VDC_R Bus voltage and current when the EPS runs under normal operation. It took 2 minutes 20 seconds to finish a 3 seconds simulation.

The waveforms show a good performance of this comprehensive model when simulating the MEA EPS under normal operation. The Root Mean Square (RMS) line voltage of the 230VAC_R1 Bus is 396.7Vand the Total Harmonic Distortion (THD) of the current on the AC side is 4.301%. The RMS line voltage of the 115VAC_R Bus is 200.9Vand the THD of the current on the AC side is 3.68%. The ATRU and TRU show good performance too. The voltage of 270VDC_R1 is 271V and 28VDC_R is 28.55V, and the voltage ripples on DC side all meet the power quality standards of MIL-STD-704F.

The loads of the MEA do not remain a constant value because the system have to change the power of different devices to adapt to the environment changes in flight. So the load disturbance of the MEA EPS in flight is a good method to verify the stability of this comprehensive model. At the beginning of this case, only half of loads are working. This process last for 2s and then at t =2s, the other half loads are online and last for another 2s, then at t = 4s, the added half loads are removed and return to the initial state. The response results of the 230VAC_R1 Bus and 270VDC_R1 Bus are shown in Fig. 11. It took 3 minutes 50 seconds to finish a 6 seconds simulation.

As can be observed, the voltage of 230VAC Bus remains stable. That shows a very well regulation performance of the generator mode. The current of 230VAC Bus has an obvious rise and fall following the increase and derating of loads. The simulation result of 230VDC_R1 Bus voltage in Fig. 11 shows that the ATRU model has a good dynamic response. These two cases demonstrate that the comprehensive model can accurately and effectively simulate the normal operation of MEA EPS and it's useful to study the stability analysis of MEA EPS.

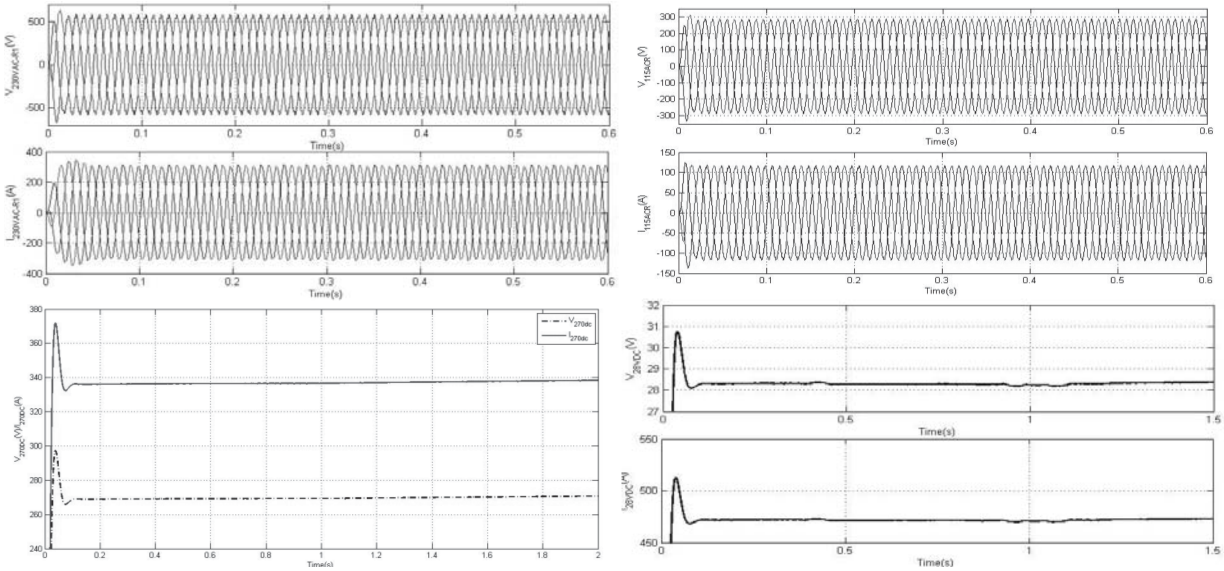

Figure 10. Voltage and current of 230VAC_R1 Bus, 115VAC_R Bus, 270VDV_R1 Bus and 28VDC_R Bus under normal operation

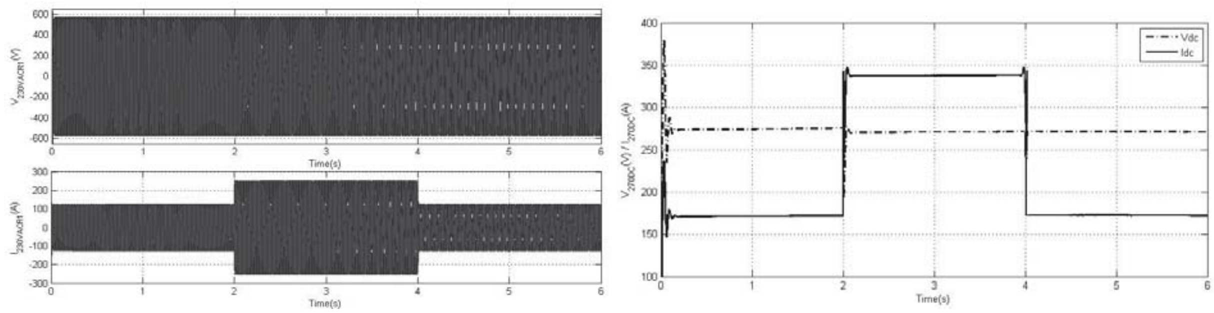

Figure 11. Voltage and current of 230VAC_R1 Bus and 270VDC_R1 Bus when loads changing

B. Fault Case: Loss of VFSG(s)

The power sources switch strategy under different generator faults are shown in Appendix 1. As mentioned above, BPCU controls power transfer functions by switching on/off BTBs under different conditions. In this section, a series of fault cases listed in Appendix 1 will be assumed to observe the response of BPCU and the performance of some important buses.

The whole process is assumed that MEA EPS would run from normal operation to case 3 in Appendix 1, then case 11, finally case 14. The state of associated BTBs is shown in Fig .12, the response of 230VAC Bus is shown in Fig. 13, 28VDC Bus in Fig. 14 and 270VDC Bus in Fig. 15. It took 5 minutes 36 seconds to finish a 8 seconds simulation.

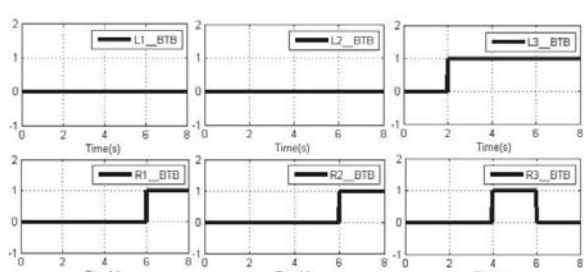

Figure 12. State of BTBs consolidating the primary 230VAC Bus

In initial state, the EPS is under normal operation, then a fault occurs in VFSG_L1 (case3) at t=2s and this generator has to be disconnected from the system. Theoretically, at this moment, BPCU will switch on the L3_BTB to transfer the loads powered by 230VAC_L1 Bus to 230VAC_L1 Bus. The state of L3_BTB in Fig. 12 shows that the BPCU operates correctly. The voltage and current performance in Fig. 13~Fig. 15 demonstrates that the 230VAC_L1 Bus had been taken over by VFSG_L2 after 0.5s delay.

At t = 4s, VFSG_R1 stopped, that lead to case 11. As Fig.12 shows, R3_BTB switched on and transferred the 230VAC_R1 Bus loads to 230VAC_R2 Bus. The voltage and current in Fig.13~Fig.15 demonstrates this too.

Then at t = 6s, VFSG_R2 stopped too. Having three of four main generators out of service, the ASGs started to support the EPS. Using ASG_L to power the 230VAC_R1 Bus and ASG_R to power the 230VAC_R2 Bus, R1_BTB and R2_BTB switched on. Because the frequency of ASG_L and ASG_R are not accurately the same, R3_BTB has to be switched off otherwise it would connect these two generators. The state of R3_BTB demonstrates that BPCU had effectively finished the power transfer functions.

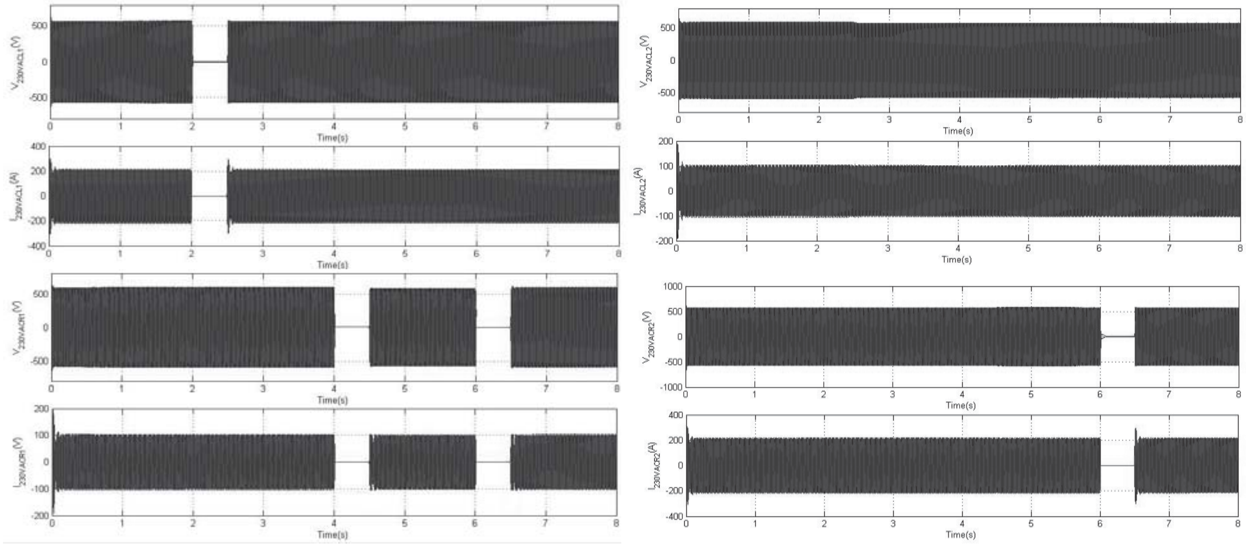

Figure 13. Voltage and current of 4 primary 230VAC Bus during fault

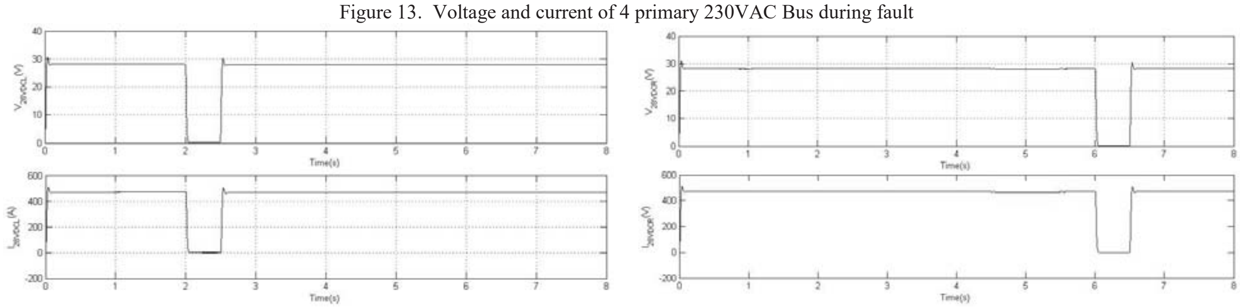

Figure 14. Voltage and current of 28VDC_L and 28VDC_R Bus during fault

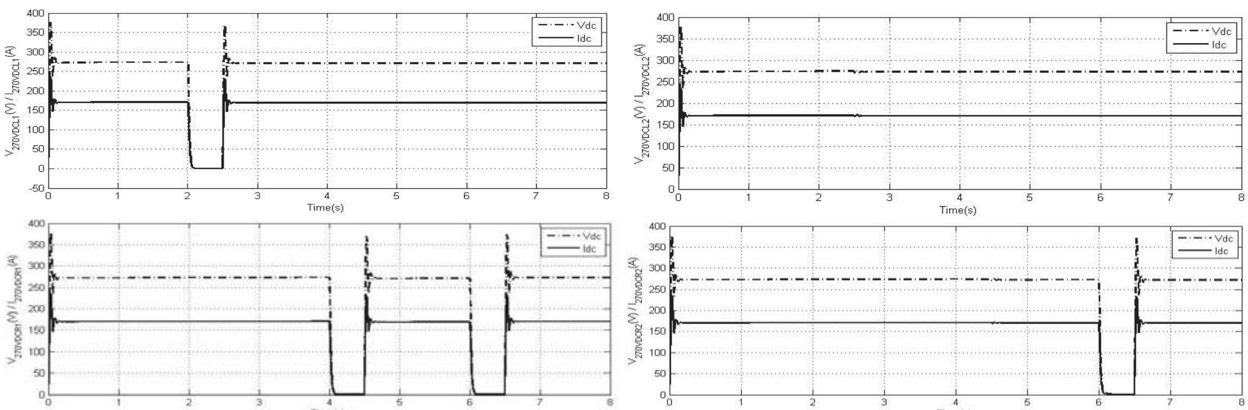

Figure 15. Voltage and current of 270VDC_L1~R2 Bus during fault

V. CONCLUSION

Compared with the conventional aircraft, MEA is lighter, easier to maintain and more efficient due to its hydraulic and pneumatic systems partially replaced by electric system. Having large generating capacity and advanced solid-state power distribution system, the EPS of MEA is reliable but complex. By means of functional modeling approach, a comprehensive Simulink model including generators, rectifiers, loads, breakers, control devices, cables and other supplementary elements has been built to study the performance of the EPS in case of both normal conditions and different faults. The results showed that essential parameters meet the standards required by MIL-STD-704F under normal operation. Besides, the logic procedures representing the control strategies for switching power in case of different faults were implemented. The case study demonstrated that the system can be effectively recovered from different generator faults. All simulations were carried out within acceptable times.

Currently, this study only considers static AC and DC loads with dynamic loads neglected. The impacts of variable loads to MEA EPS along with the security analysis under different conditions will be addressed in the future work.

APPENDIX

Appendix 1: The power sources that the four primary 230VAC Bus get power from under different conditions.

Cases		Available Power Sources	230VAC_L1	230VAC_L2	230VAC_R1	230VAC_R2
Ground	1	L_EP, R_EP	L_EP	L_EP	R_EP	R_EP
Normal	2	VFSG_L1, L2&VFSG R1,R2	VFSG_L1	VFSG_L2	VFSG_R1	VFSG_R2
1 VFSG Fail	3	VFSG_L2, R1,R2	VFSG_L2	VFSG_L2	VFSG_R1	VFSG_R2
	4	VFSG_L1, R1,R2	VFSG_L1	VFSG_L1	VFSG_R1	VFSG_R2
	5	VFSG_L1, L2,R2	VFSG_L1	VFSG_L2	VFSG_R2	VFSG_R2
	6	VFSG_L1, L2,R1	VFSG_L1	VFSG_L2	VFSG_R1	VFSG_R1
2 VFSGs Fail	7	VFSG_L1, L2	VFSG_L1	VFSG_L2	VFSG_L2	VFSG_L1
	8	VFSG_L1, R1	VFSG_L1	VFSG_L1	VFSG_R1	VFSG_R1
	9	VFSG_L1, R2	VFSG_L1	VFSG_L1	VFSG_R2	VFSG_R2
	10	VFSG_L2, R1	VFSG_L2	VFSG_L2	VFSG_R1	VFSG_R1
	11	VFSG_L2, R2	VFSG_L2	VFSG_L2	VFSG_R1	VFSG_R2
	12	VFSG_R1, R2	VFSG_R2	VFSG_R1	VFSG_R1	VFSG_R2
3 VFSGs Fail	13	VFSG_L1, ASG_L,R	VFSG_L1	VFSG_L1	ASG_L	ASG_R
	14	VFSG_L2, ASG_L,R	VFSG_L2	VFSG_L2	ASG_L	ASG_R
	15	VFSG_R1 ASG_L,R	ASG_R	ASG_L	VFSG_R1	VFSG_R1
	16	VFSG_R2 ASG_L,R	ASG_R	ASG_L	VFSG_R2	VFSG_R2
4 VFSGs Fail	17	ASG_L,R	END	END	ASG_L	ASG_R
RAT only	18	RAT	END	END	END	END
BAT only	19	BAT	END	END	END	END

(This table shows the power sources that supply the four primary 230VAC Bus under different conditions. All the 19 kinds of cases are listed. "Available Power Source" means the available power source that can power the EPS in that case. "END" means this bus has been cut off to ensure the flight safety.)

Appendix 2: The parameters of the case study.

Parameter	Value	Parameter	Value
Generator Voltage	230Vrms	Speed of engine	11000~ 14000r/min
Cable resistance	3.71mΩ /m	Cable inductance	3.28nH/m
ATRU Filter reactance	0.1mL	ATRU inter-phase reactor inductance	1.67mH
ATRU DC capacity	0.99mF	TRU Filter reactance	1mL
TRU inter-phase reactor inductance	0.13mH	TRU DC capacity	13mF
230VAC total load	24.35KVA	115VAC total load	56.93KVA
270VDC total load	171.68KW	28VDC total load	22.62KW

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