A Distributed, Real-Time Simulation Platform for Aerospace Power System Design, Testing and Evaluation

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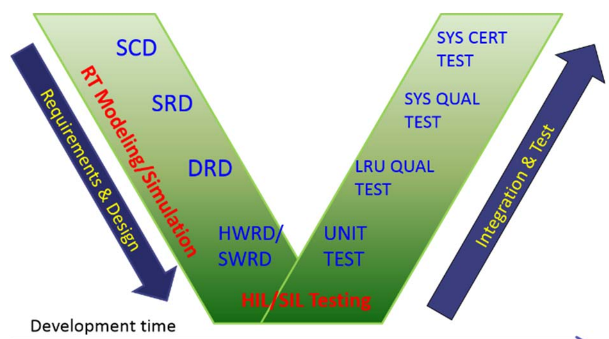
Abstract— **This paper presents a distributed, real-time platform for aerospace power system design, testing and evaluation, which was developed by the University of Dayton, in partnership with GE Aviation's Electrical Power Integrated Systems Center (EPIS Center). This platform is based upon heterogeneous distributed, real-time computing hardware. Also, high-fidelity, physics-based or behavioral models can capture a variety of electro-magnetic transients, electro-mechanical dynamics, aerodynamics, control and thermal dynamics at different time scales, and allow for fault studies as well. A set of real-time computational solvers are used to find the solution to system simulation in a parallel manner, which can help optimize the computational load and simulation step. A simulation time-step as low as 100 nanoseconds can be achieved on the real-time simulator for the model to capture very fast electromagnetic transients, which is especially beneficial for more-electric aircraft where fast-switching power electronic devices dominate. Multiple simulators can be connected together to simulate the integrated operation of multiple systems such as electrical power systems, engines and propulsion systems, and avionics. This paper also elaborates on the various stages of product development and certification for which this platform can be used: real-time simulation, hardware-in-the-loop testing, power hardware-in-the-loop testing and pilot-in-the-loop testing. Two examples of model development and validation and some selected testing results will also be presented in the paper.**

Keywords—real-time simulation; FPGA; more-electric aircraft; power systems; solid-state power distribution; energy storage

I. Introduction

Electrification of aircraft is becoming a future trend of the aviation industry, in both civil and military applications, due to weight, efficiency, noise and environmental concerns [1]-[6]. Before the goal is achieved, there are potentially a variety of design possibilities for system architecture (e.g., more-electric or hybrid electric propulsion) and generation and distribution options (e.g., AC or DC, various voltage levels) [4]-[6]. Trade studies are necessary to reach a wise decision on optimized solutions. This process is typically time-consuming and costly.

To reduce the development time and costs, model-based systems engineering has been used to define and develop a variety of modern industrial systems [7]-[8]. Another benefit of this model-based method is that models can be reused in later design of family products. Fig. 1 shows a "V model" for this approach, which starts from customer specification to system certification. In the requirements and design phases, the top-down process starts from system specification/definition down to hardware/software component design. Real-time modeling and simulation can help verify the system design as well as low-level hardware and software components in this process. Once unit components have been developed, the test procedure may include unit test, LRU test, system qualification test and system certification test. Before the real, final system hardware is integrated, hardware-in-the-loop testing can be used to help reduce the test time and costs in these processes. Among the processes mentioned above, the simulation and testing efforts can generally comprise of multiple incremental steps. If errors or improvement options are identified at any of the inter-mediate steps, engineers may go back to the first design step and make design changes, which greatly reduces design risks.



SCD –Specification Control Drawing
SRD – System Requirements Document
DRD – Design Requirements Document
HWRD – Hardware Requirements Document
SWRD – Software Requirements Document
LRU – Line Replaceable Unit
HIL – Hardware-in-the-Loop
SIL – Software-in-the-Loop

Fig. 1. V Model from customer specification to system certification for the development of highly-integrated more-electric aircraft power systems.

This paper presents our recent work on real-time modeling and simulation and its applications in the model-based system engineering processes. Major challenges in real-time modeling

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simulation and the developed real-time simulation platform will be discussed in Section II. Section III will elaborate on the features and functionalities of the developed platform. Several scenarios of applications will be briefly identified in Section IV. Section V will present two examples of real-time system model development and validation in the context of a representative more-electric aircraft power system. Section VI will conclude the paper and outline the future work.

II. Architecture of Distributed, Real-Time Simulation Platform

A. Challenges in Real-Time Modeling and Simulation

In a typical more-electric aircraft DC power system [4]-[5], two or more main generators can be driven by the engine and generate varying-frequency AC power. Power converters then convert it to a DC voltage. Energy storage can be used to help the main generator meet the transient or peak power demand. Solid-state power distribution circuits can help route electrical power from proper sources to various loads.

Real-time modeling and simulation of these power systems are facing a lot of challenges [9]-[13]. A major challenge lies in high-frequency switching and the associate fast transients in solid-state power conversion and distribution systems. For instance, SiC-based power electronic devices may switch at a frequency higher than 100 kHz, which requires a switching period of below 10 microseconds. Discontinuous conduction mode may exist in the operation of some diode-based power converters, which adds additional complexity to real-time modeling and simulation. To simulate the fast transients, a time-step of lower than 200 nanoseconds would be desirable.

Power generation systems may also operate under high and varying frequencies, for instance, those higher than 1 kHz. Thus power conversion (e.g., in the exciter and main generator) may have complex operating modes, which will demand special care in the real-time modeling and simulation process. In addition, aircraft power systems may contain complex multi-disciplinary subsystems, where different subsystems (e.g., electro-magnetic, electro-mechanical, aero-dynamic, control, hydraulic, thermal, etc.) may have dynamics with multiple time scales spanning 1 microsecond to tens of seconds.

B. Developed Real-Time Simulation Platform

To facilitate the model-based methodology and address the challenges above, the University of Dayton Research Institute (UDRI), in partnership with GE Aviation's Electrical Power Integrated Systems Center (EPIS Center) has developed a new distributed, real-time simulation platform that can be used for aerospace power systems design, testing and evaluation. The real-time simulation platform includes five major components: heterogeneous distributed computing hardware, high-fidelity multi-physics models, mixed real-time computational solvers, heterogeneous communication links, and user-friendly graphic user interfaces (GUI). Fig. 2 illustrates the architecture of the developed real-time simulation platform. This platform builds on heterogeneous, distributed, real-time computing hardware. Distributed computing hardware located at different places can communicate through a common communication network such as a TCP/IP network. Different hardware units (e.g., real-time processors, FPGAs, multi-core CPUs, etc.) can communicate with each other synchronously through PCIe bus or fiber optic links, or asynchronously through analog links. On top of the hardware are real-time computational solvers which are used to solve all the equations in high-fidelity multi-physics models.

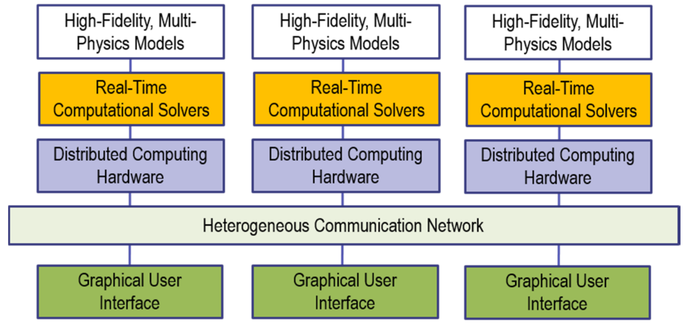


Fig. 2. Architecture of developed distributed real-time simulation platform.

Fig. 3 shows a picture of a portion of the laboratory setup. Running on the real-time platform, a series of high-fidelity physics-based or behavioral models can capture a wide variety of electro-magnetic transients, electro-mechanical dynamics, aero-dynamics and thermal dynamics at different time scales, and allow for fault studies as well. A mixed set of real-time computational solvers are used to find the solution to system simulation in a parallel manner, which can help minimize the computational complexity and simulation step. A simulation step as low as 100 nanoseconds can be achieved on the real-time simulator for the model to capture the very fast electro-magnetic transients, which is especially useful for more-electric aircraft where fast-switching power electronic devices dominate. There are hybrid computational solvers for different subsystems and multi-rate simulation is achieved for the entire system. For example, the simulation time steps could be 40ns, 200ns, 1µs, or 25µs for different subsystems in a single power system. Multiple distributed simulators can be interconnected to simulate the integrated operation of multiple systems such as electrical power systems, engines and propulsion systems, and avionics. To simulate complex multidisciplinary systems all together, we can partition the system into subsystems. Then we can define state variables and use differential and algebraic equations to describe the dynamics of various subsystems.

Fig. 3. Picture of a portion of the laboratory setup.

This platform can be used in various product development and certification stages. For instance, in the design stage, real-time simulation allows for fast verification of system design options and various modes of operation, which greatly reduces the development cycle time. In the component testing stage, controller hardware-in-the-loop testing provides a low-cost and fast way to verify and validate different control functionalities and protection schemes. In the integrated system testing stage, power hardware-in-the-loop testing can help validate and gain further confidence in system design by interacting with real hardware or products. In the certification stage, pilot-in-the-loop testing can provide an option for product conformation and compliance.

III. Features and Functionalities

This section is dedicated to discussing some major features and functionalities of the developed real-time platform.

A. *Distributed, Parallel Computing*

The distributed computing hardware built in the laboratory includes multiple simulator racks from Opal-RT Technologies (e.g., two OP7000 systems, one OP5600 system, two OP4500 systems) [14]-[15], and several dedicated real-time computers. Each OP7000 system contains 4 FPGA (field programmable gate array) cards. FPGAs are semiconductor-based devices that consist of programmable logic components, which may allow the users to reprogram the hardware. A 200MHz frequency allows for a 5ns clock cycle in real-time computing. High-level programming languages such as Xilinx System Generator and MATLAB/Simulink can be used to facilitate and accelerate programming FPGAs. The real-time target is a multi-core CPU and can communicate with FPGA cards. In addition, several dedicated industrial real-time computers with Linux operating system are available in the lab and can be used to simulate some slow systems such as avionics and engine models.

Communication links are important to connect different real-time targets and share real-time data among them. Multiple communication mechanisms can be used in the lab setup.

- The real-time target of Opal-RT simulators communicates with the respective FPGA chassis through a PCIe bus [15].
- Aurora protocols are used for inter-FPGA communications.
- Analog or digital input/output signals, through regular A/D and D/A converters, make direct connection of multiple simulators possible. These signals are synchronized by the individual simulator, but the signal delay/latency between different simulators may vary, but in general should be lower than the sampling period, e.g., 1 microsecond.
- TCP/IP protocol: The simulators may also communicate at a lower rate (e.g., 1ms for an engine model) with other real-time simulators located at different locations, where TCP/IP protocols may be sufficient. Another situation is to use TCP/IP protocol for communications between the host computer and real-time target of Opal-RT simulators [15].

Fig. 4 illustrates a snapshot of the graphical user interfaces. The Power System model will simulate the operation of an entire power system. The Engine model can calculate the speed and send it to the generator in the Power System model, and receive a torque or power extraction signal from the generator. Control signals from the Avionics model are sent to the Engine and Power System models, while the visualization information will be collected from these models and displayed on the GUI.

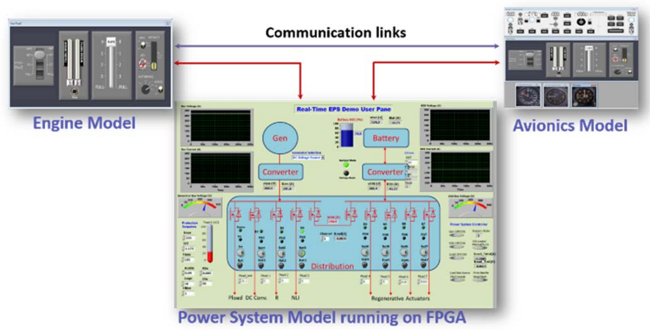


Fig. 4. Snapshot of graphical user interfaces used for the real-time platform.

B. *High-Fidelity Models*

This platform features high-fidelity, multi-physics models of entire aircraft electrical power systems, allowing for control, protection and power quality evaluations and different stages of testing. These models can capture electromagnetic transient and electromechanical dynamics, facilitate fault studies and thermal modeling, and allow for parametrical sensitivity analysis. After models are developed and validated, they can be used in power system analysis and evaluation to verify various control and protection functions, analyze power quality and down-select test cases for lab testing, as shown below.

- Control - verify steady-state and transient performances of the entire control system.
- Protection - verify protection schemes or algorithms under different abnormal conditions.
- Power quality - analyze power quality of system operation.
- Testing - reduce the number of test cases on final hardware in the lab by down-selecting from real-time simulations.

C. *Hybrid Real-Time Computational Solvers*

While the hardware provides a basis for the simulator, real-time computational solvers are the core of real-time simulators, which will solve all equations of the models. This work focuses on a mix of solvers to achieve real-time, multi-rate simulation of multi-disciplinary, nonlinear, dynamic systems. A popular method is the state-space solver, which is suitable for linear systems [16]. The dynamic system can be described as a set of differential and algebraic equations in the state space.

$$\dot{X} = AX + BU \qquad (1)$$

$$Y = CX + DU$$

where X is a vector of state variables, U the control variable vector, Y the output variable vector, A, B, C and D the system matrices. The main challenge is to properly discretize the state-space equations to reduce the errors and increase stability.

Another method that is useful for solving electric circuits is nodal analysis [17]. Each circuit element can be represented as a current source in parallel with a resistor (i.e., Norton equivalent) and the system equation can be expressed as

$$I = Y * V \qquad (2)$$

where V and I are node voltage and injection current vectors respectively, Y the system conductance matrix. The challenge in real-time implementation lies in calculation of the inverse of system conductance matrix.

For nonlinear systems, a typical method is to use iteration-based solvers, where Newton's method can be used to solve the nonlinear equations [18].

$$f(V, I, t) = 0 \quad (3)$$

where f is a nonlinear function of V, I and time t. The challenge lies in computing the Jacobian matrix at every time-step, which needs to be updated to find the solution to the equation above.

In addition, it is sometimes more convenient to use discrete integrator solvers for some special components, for instance, passive components in power converters based on a switching-waveform model. Different integration methods can be chosen for different components or subsystems.

D. Low Simulation Step

Fig. 5 shows representative curves illustrating how low the simulation time-step can be, compared with other time scales in the simulated system. The first curve shows a representative flight profile, which may last a couple of hours. If a particular phase (e.g., climbing phase) is of interest, the power profile, as shown in the second curve, can be used, which has a time scale of minutes. While the transients within several seconds are of interest to power electronic engineers, pulse-width-modulation (PWM) signals may have a period of a few microseconds. To maintain an acceptable resolution of PWM signals in the simulation, a time-step of 100 nanoseconds could be achieved on the developed real-time platform, which is synchronized by a 5ns-long pulse signal of with a period of 100 ns.

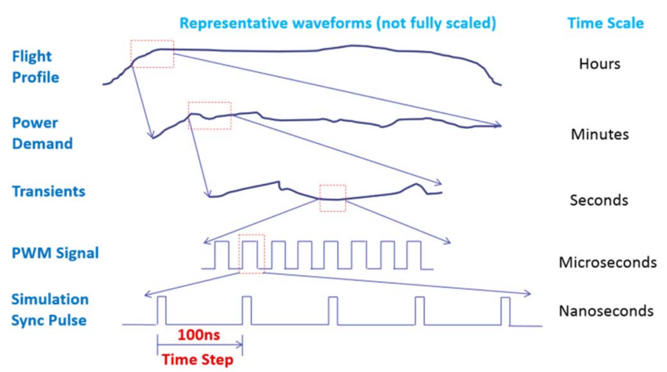


Fig. 5. Illustration of the low simulation time-step, compared wth other time scales in the simulated system.

IV. Scenarios of Applications

The developed real-time platform could be possibly used in different scenarios, which are delineated as follows. Note that some applications have been realized, while others are planned.

A. Design Stage - Real-Time Simulation

The immediate scenario of application is to perform real-time simulation of components, subsystems or entire power systems in the design stage. Fig. 6 shows an example that different components of a power generation system could be simulated on multiple FPGAs. Different subsystems could also be simulated on multiple FPGAs. A main benefit is that real-time simulation is running much faster than offline simulation.

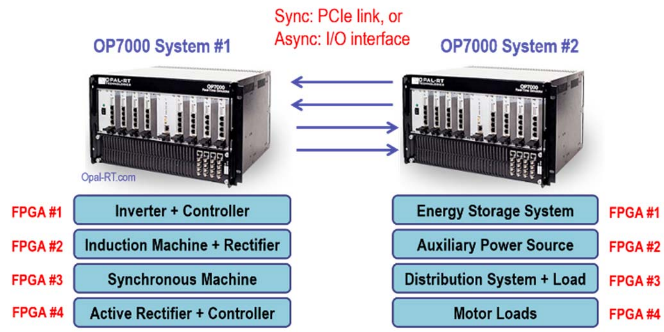


Fig. 6. Example showing that different components of a generation system or different subsystems of a power system could be simulated on multiple FPGAs.

B. Component Testing Stage - Controller-in-the-Loop Testing

Another scenario is to replace some controller models with real or simulated control hardware in the previous scenario. In this case, the measurement and control signals are sampled at actual rates. The controller has full complexity and fidelity, and is running separately from the plant system model. A variety of control or protection functions can be tested under relatively realistic conditions.

C. Integrated System Testing Stage - Power Hardware-in-the-Loop Testing

After some component hardware is available, it is possible to test it together with a simulation model of the rest of the system. Either the generator or the load could be replaced with a simulation model. For example, we could simulate the power generator in the real-time simulator and use the model output to drive a programmable power source. Then we could connect real load and distribution circuit to the simulated generator and test it. Similarly, we could simulate the load and distribution system in the real-time simulator and use the model signal to drive a programmable load, which could be directly connected to a real generator for testing. These two cases are illustrated in Fig. 7.

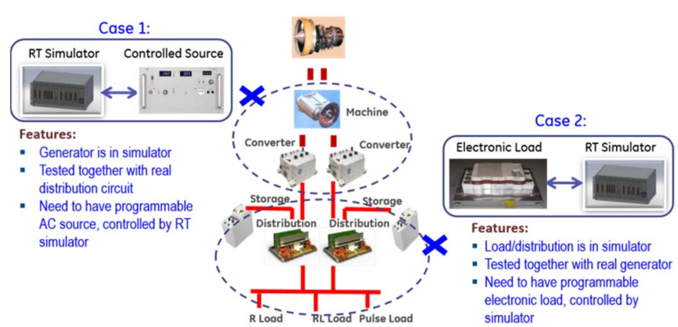


Fig. 7. Cases of power hardware-in-the-loop simulation.

D. Certification Stage - Pilot-in-the-Loop Testing

A further scenario of using the presented real-time platform is to include the pilot in the simulation loop and test the entire power system model with a specific flight profile. In a virtual aircraft integration system as shown in Fig. 8, there are a wide range of real-time simulation models for different components that can be connected to each other and communicate through common communication interfaces (CSIs). When a pilot has inputs to the virtual aircraft system, the power system model running in real time can respond to the pilot operation and interact with other models. While the CSIs can communicate at the same rates, the distributed simulation models can run at different rates. All the simulation results can be interactively visualized and recorded for later analysis.

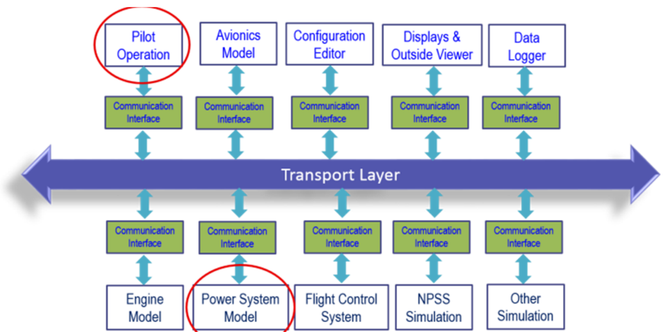


Fig. 8. Architecture of virtual aircraft integrtaion system.

V. Example Results

This section will use a couple of examples to demonstrate model development, validation and applications in the context of a typical more-electric aircraft power system. Fig. 9 shows a block diagram of the test system which represents portion of a full aircraft power system. In this system, a diode rectifier can convert varying-frequency AC voltages to a DC voltage and connect to the DC bus through an EMI filter. The battery bank is connected with a three-phase inter-leaved DC/DC converter through an EMI filter. The power converter is connected to the DC bus through another EMI filter. The battery converter can regulate either the output current or bus voltage.

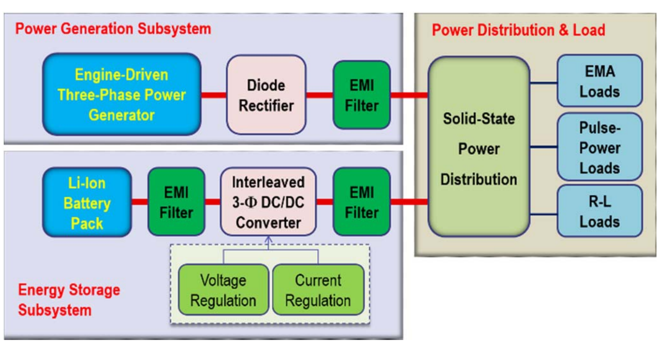


Fig. 9. Block diagram of example aircraft electrical power system under test.

A. Energy Storage

The first example focuses on modeling and control of an energy storage system and its impact on system performances. An equivalent circuit method is used here to model the battery. The model developed in [19] was simplified so as to capture the current-voltage dynamics (with equivalent RC circuit) as well as nonlinear voltage-SOC relationship using lookup tables for real-time implementation. The block diagram of the real-time battery model implementation is shown in Fig. 10. The Charge Calculation block is computing the charge level of the battery based on the charging current and an initial charge level. The SOC Estimation block is to calculate the state of charge based on the charge level, battery capacity and an initial state of charge. The open-circuit voltage is found from look-up tables, depending on the charging current and an average pack temperature. A combined RC network is used to find battery terminal voltage from the open-circuit voltage. The power loss is calculated from the RC circuit and an equivalent thermal circuit is then used to calculate the average pack temperature. All the blocks have been implemented in real time for FPGA simulation, using linear state-space solver, lookup tables, nodal analysis solver, and individual integrator solver, as explained in Section III-C.

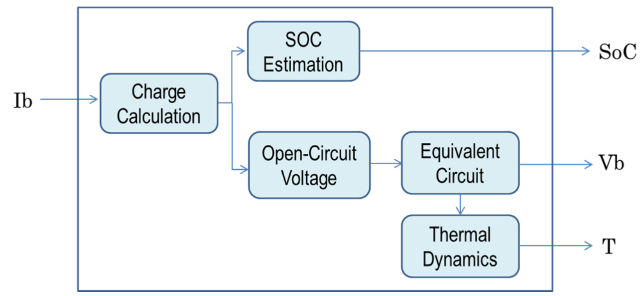


Fig. 10. Block diagram of the battery model.

The battery discharging circuit is modeled as a bidirectional DC/DC converter, which consists of three interleaved synchronous rectification circuits to boost the capacity and reduce ripples. The high-voltage and low-voltage sides of the power converter are connected together, with input and output capacitor filters. The battery converter controller has two major operation modes. Under the load-levelling mode, the battery converter is to regulate its output current to meet load transient requirements and perform fast regulation of DC bus voltage. Under the voltage regulation mode, the battery converter is to directly regulate the bus voltage by injecting an appropriate amount of current to the load. In this test, a DC voltage source in series with an appropriate EMI filter is used to simulate the dynamics of a DC generator. This modeled system is tested under a pulse power load, as shown in Fig. 11. The base power is 8 kW, while the peak power is 72 kW, with a period of 1s and a 50% duty cycle.

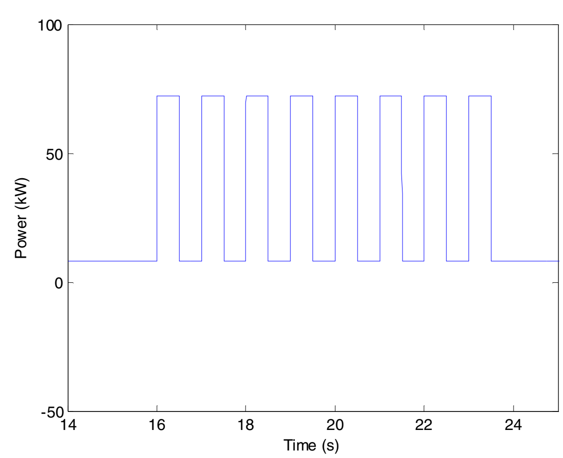
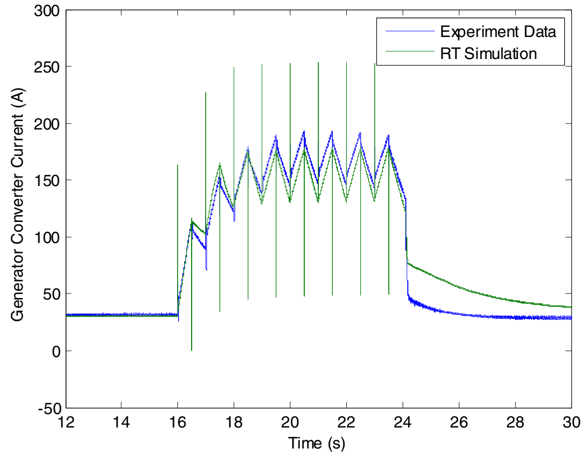
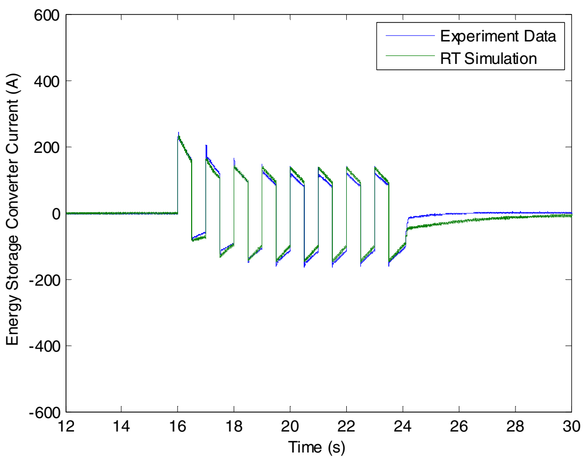


Fig. 11. Profile of load power.

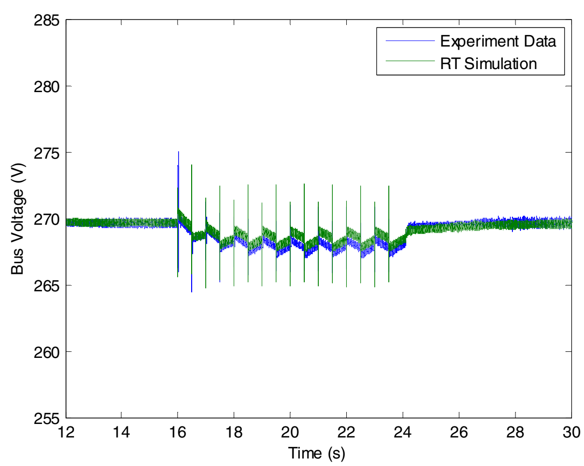
Fig. 12 shows real-time simulation and experimental results of the generator and battery converter currents and bus voltage.



(a) Current from generator converter



(b) Current from energy storage converter



(c) DC bus voltage

Fig. 12. Testing result comparison of current and volatge waveforms between real-time simulation results and experimental tests.

Under the pulse power load, the generator converter current has a saw-tooth shape, while the energy storage converter supplies or absorbs a current of pulse shape. Additional load testing results reveal that the main generator supplies an average current to the load while the energy storage unit can supply or absorb the transient currents under the charging control scheme. It is seen from Fig. 12-c that the bus voltage has only slight variations due to the assistance of energy storage. It is interesting to note that the bus voltage in the high-power interval is even higher than that in the low-power interval. This is because the battery supplies a high positive current when the low power is high, while absorbing a current form the bus when the load power drops. It can be concluded from these figures that the real-time simulation results match the experiment results very well and the model is validated.

B. Solid-State Power Distribution

Another example is a solid-state power electronics based distribution system, which may contain multiple channels of solid-state circuit breakers. The equivalent circuit of a single channel is shown in Fig. 13 [21]-[22]. The MOSFET switch is modeled as a variable resistance in the MOSFET's linear control region. An anti-parallel diode is to conduct reverse current when the main switch is off. Another diode branch is to model the metal-oxide-varistor (MOV), which protects the main switch from transient over-voltage. A freewheeling diode is modeled to conduct current when the switch is off and there is a remaining load current. The individual components in the equivalent circuit are modeled in real time using the developed solvers and connected together to derive the real-time model of the solid-state DC circuit breaker (one channel). In the real-time model, the control and protection functions modeled include current limitation, transient over-voltage protection, I2T protection, Safe Operation Area protection.

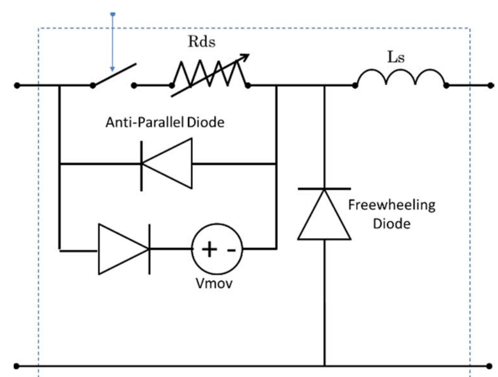


Fig. 13. Equivalent circuit of solid-state DC circuit breaker (one channel).

The test system is similar to the previous one, but with a detailed model of switches. The power distribution system has 2 voltage buses: generator bus and battery bus, and each bus is connected to 7 circuit channels. Some channels are connected in parallel to conduct higher currents. Fig. 14 shows real-time simulation and experimental results of the current of one switch channel. The rated current for this channel is 60A, while the current limitation is set at 2 times the rated value, which is 120A. In the figure, the blue curve is the measured current in the lab test, which oscillates around 120A. It is worthwhile to note that the oscillation is due to the interactions between simulated DC source and EMI filters. It is shown from the real-time simulation result (red curve) that the switch current is limited around 120A under the current limiting control at onset of the inrush current. It can be seen that the current is well regulated. Under the I2T scheme, the protection trips after 0.378s. This matches the experiment result very well, which is 0.38s. The error is less than half percent, which can validate the switch model and I2T protection scheme. Note that the current oscillations in the experimental result can mainly contribute to the difference in the trip time.

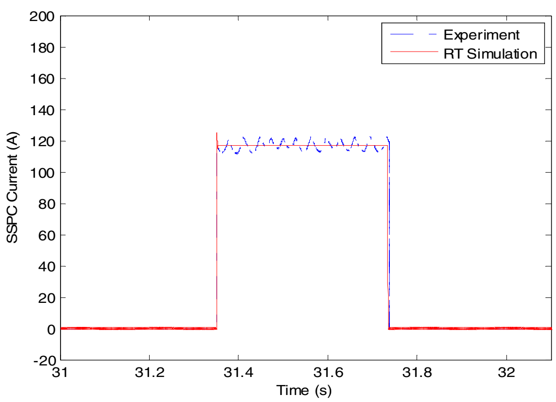


Fig. 14. Current from solid-state circuit breaker (one channel).

VI. Conclusions and Future Work

In this paper, a distributed, real-time simulation platform is presented, which includes distributed real-time computing hardware, mixed real-time computational solvers and high-fidelity models. This platform can be used in various stages of product development and certification. A set of unit component models have been developed for the real-time platform and validated against lab experimental results. An aircraft electrical power system model has been developed and tested. System simulation results show that energy storage can help reduce the size and weight of the main generator. Also, it is revealed that solid-state power distribution provides premier control and protection performances from real-time simulation results.

The future work includes performing controller-in-the-loop testing for a variety of controllers, e.g., generator controllers, energy storage management system, distribution and load management system and power system controllers. It is also planned to perform power hardware-in-the-loop testing, such as connecting a simulated generator (using a real-time model and a power amplifier) with practical loads, and connecting a simulated distribution system (using a real-time model and a programmable load) with a real generator. In addition, a further plan is to interconnect the developed power system models with existing engine and avionics models and conduct power hardware-in-the-loop testing with drive stands in the lab.

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