A Real-Time Multi Electrical System Integrated Simulator (MESIS) for Validation and Testing of More Electric Aircraft (MEA) Equipment

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Abstract

More Electric Aircraft (MEA) is an innovative trend among aerospace manufacturers. Electrical systems on MEA are designed to replace conventional hydraulics and pneumatics systems, with an objective of reducing weight, maintenance costs, and increasing Mean Time Between Failures (MTBF). However, inadequate electric systems design and integration negatively impacts power quality of the electrical network on the aircraft, and may lead to failures and damage to electrical components. In order to address power quality shortfalls, concepts validation and testing are necessary in the early stages of the electrical systems design process. Conventional testbed cover an increasing amount of tests in order to insure the required technology readiness levels. Alternatively, virtual MEA systems simulation offers a cost effective and time efficient approach. In this context, BOMBARDIER and OPAL-RT are participating with collaborators in the aerospace industry on the development of a Multi Electrical System Integrated Simulator (MESIS) that integrates MEA systems models into a real-time co-simulation platform. This paper provides a high level overview of the MESIS scope and objectives. The practical implementation of MESIS involves key technological aspects and challenges that will be addressed by simulation strategies presented in the paper.

I Introduction

Competitive drivers such as engine power offtake, efficiency, reliability and minimum dispatch interruption rate are pushing aerospace manufacturers to constantly improve and re-engineer their aircraft systems. Heading forward, the new generation of aircraft is focusing on hybrid systems that include more-electric systems. The objective is to increase power density to meet electrical power requirements, while reducing operational costs [1]. MEA is an innovative trend with an increasing amount of applications, and the MEA market is expected to sustain a steady growth in the next decade. Electrical systems on MEA are designed to replace standard hydraulics and pneumatics actuation systems, thus reducing payload, maintenance costs, and increasing MTBF. The removal of pneumatic systems allows moreover MEA power plants to be designed with bleed less gas turbines. This leads to higher engine efficiency and eco-friendly design with a longer system lifespan. Higher frequency operation on MEA allows reduction of electrical transformers and machines, leading to better weight optimization.

However, more electric systems design increases the complexity of the electrical power generation and distribution system (EPGDS) in MEA. This requires considerable focus on research and development activities to reach the required Technology Readiness Level (TRL). Inadequate electric systems design and integration negatively impacts electrical power quality on the aircraft network, and may lead to failures and damage to electrical components. This requires the addition of filtering systems, which increases overall systems' complexity and weight. Electrical power quality is therefore an essential factor to consider for MEA, and is generally governed by stringent requirements within aerospace standards [2].

It is therefore essential to have concrete validation strategies in order to test the new electrical technology used in MEA. New technology testing in aerospace typically involves high cost and high maintenance test rigs. Real-time simulation offers therefore an interesting alternative as it is cost effective, time efficient and flexible solution [3], [4].

In this context, BOMBARDIER is collaborating with multiple MEA equipment designers and OPAL-RT to develop a real-time MESIS within the framework of HORIZON project, which focuses on the technology demonstration streams of advanced systems for the next generation aircraft. MESIS will integrate MEA related electrical systems models into a co-simulation platform provided by OPAL-RT, and will be used to perform real-time aircraft level simulations and conduct studies in multiple operation modes. The main objective of MESIS is to act as a demonstrator for an MEA development program, and will aim at achieving TRL 6. The practical implementation of MESIS requires key technological aspects to be met in order to ensure accurate and reliable behavior in real-time simulation.

The paper is organized as follows: section II describes the technology readiness levels and the importance of real-time simulation in the development of MEA technologies. Section III gives an overview of MESIS objectives and modeling scope. In section IV, the hardware architecture of MESIS is shown along with resource allocations of MESIS models. Main technological challenges and mitigation strategies are presented as well. Section V provides examples of practical implementation strategies that will be used for MESIS. Section VI finally concludes the paper.

II TRL Demonstrator for MEA

MEA include new technologies and concepts requiring extensive validation, as this helps addressing potential design flaws and power quality shortfalls early in the design process. In large and complex engineering systems development such as in aerospace, model-based systems engineering is essential in order to insure successful technology integration [5]. New technologies introduction pass through maturity levels gates, known as Technology Readiness Levels (TRLs). Table 1 gives a description of each TRL [6]. TRLs can be mapped into the typical systems engineering "Vee" model depicted in Figure 1 [7]. TRL 1 and 2 are part of the downstroke activities of the "Vee" model, where basic principles are observed, and requirements decomposition and definition are derived.

TRL	Description	Fidelity	Demonstrator	Environment
1	Basic principles observed and reported	N/A	N/A	N/A
2	Technology concept and/or application formulated	N/A	N/A	N/A
3	Analytical and experimental critical function and/or characteristic proof-of-concept	Low	N/A	Lab
4	Component and/or breadboard validation in lab environment	Low	Breadboard	Lab
5	Component and/or breadboard validation in relevant environment	Mid	Breadboard	Relevant
6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)	High	Prototype	Relevant
7	System prototype demonstration in a target/space environment	High	Prototype	Operating
8	Actual system completed and "flight qualified" through test and demonstration (ground or flight)	Actual technology	Flight qualified	Operating
9	Actual system "flight proven" through successful mission operations	Actual technology	Flight proven	Mission/ operating

Table 1 TRL Scales and Sub-Attribute Description in Aerospace

TRL 3 to 8 form the upstroke part of the “Vee” model, where the new technologies undergo a maturity level progression through systematic integration, verification and validation (V&V) activities. In practical implementations, the “Vee” model implies an interdependency between the downstroke and the upstroke parts. This means that design, integration and validation activities go through multiple iterations along the same “Vee” model.

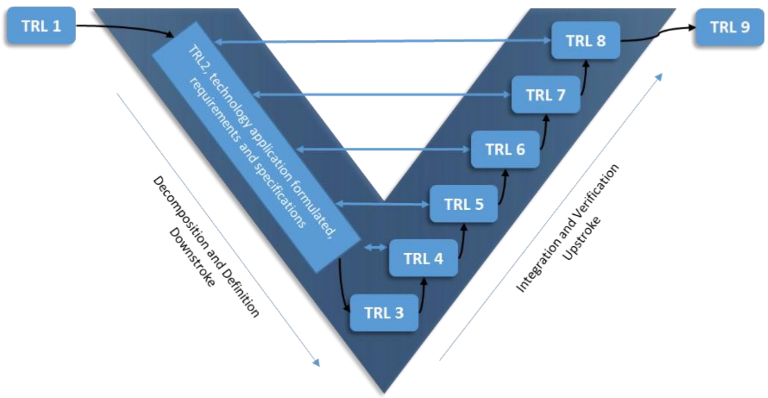


Figure 1 TRL Mapping into “Vee” Model Representation

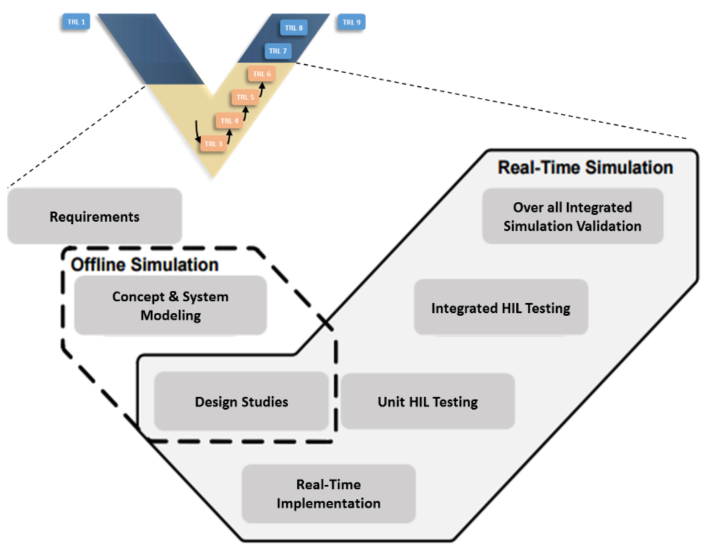


Figure 2 Real-Time Simulation within “Vee” Model

Traditional validation schemes in aerospace involve typically high cost and high maintenance test rigs. Virtual MEA systems simulation becomes therefore an interesting alternative as it is a cost effective, time efficient and flexible solution, and reduces moreover design iterations in the “Vee” model process. MEA systems simulation initially involves the integration of representative simulation models into a fully virtual simulation environment. This configuration allows for validation and testing on a complete desktop simulation setup. Further validation step consists of replacing the simulation models with actual aircraft software and hardware components in the simulation loop. This configuration, also known as Hardware-In-the-Loop (HIL) simulation, enhances the fidelity of the simulation. HIL simulation allows for extensive validation and testing of aircraft hardware and software components and actual controllers’ interactions, as well as transmission delays, in a highly representative simulation environment. HIL simulation setup requires however the simulation models and the hardware components to interact in a time critical manner. This constraint requires the simulation to run in real time. Real-time simulation implies that the execution time of the simulation is within the sampling time interval. This setup requires having a fixed time step based simulation for real-time applications. Figure 2 shows a sub-“Vee” model involving offline and real-time simulation validation [8], encompassing TRL validation activities within the main “Vee”-model process. As per the definition of TRLs in Table 1, HIL simulation represents a high fidelity demonstrator that is expected to bring the technology to TRL6.

III MESIS Description and Scope

MESIS development is part of the framework of project HORIZON, which focuses on the technology streams demonstration of advanced systems for the next generation of MEA. Multiple collaborators from a consortium with BOMBARDIER are involved in the HORIZON project. MESIS will integrate system models from those HORIZON collaborators in a real-time simulation environment, and will act as a virtual test rig to achieve TRL 6. Figure 3 presents the timeline evolution of MESIS covering TRLs 1 to 6. MESIS is planned to evolve from a desktop simulator to a HIL real-time simulator involving the testing of actual aircraft hardware controllers.

The scope of study of MESIS is to conduct V&V activities in order to test transient and steady state performance requirements of more electric systems integration in normal, abnormal and failure test conditions, with the following main objectives:

- Advanced electrical system functions, logical and architectural interactions;
- Power electronic control and protection algorithms performance;
- More electric system interactions;
- Normal and failure mode effects;
- Power quality analysis (harmonic distortion, voltage/current fluctuations, etc...)
- Monitoring of nuisances or erroneous indications.
- Electrical stresses on equipment under normal and transient conditions

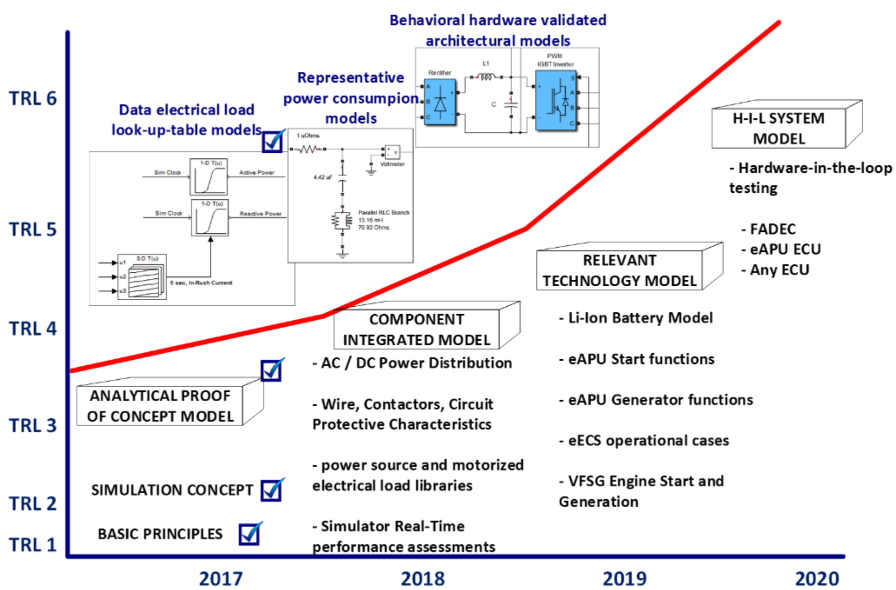


Figure 3 HORIZON MESIS Timeline Evolution

Among the above objectives, a particular focus will be put on power quality analysis. As part of this analysis, MESIS will be used to study and test the following operation modes as prescribed in [2]:

Power Quality Analysis	Requirements Testing
Normal Operation	AC power distribution frequency variations
	Power transfer operation tests
	AC power characteristics
	Wire voltage drop, Contactor time operation and sequencing
	Power distortions and harmonics studies on AC and DC signals
Abnormal Operation	Loss of VFSG Generator (single / multiple), loss of any AC Bus
	Abnormal DC level on AC signals
	Power interruptions
	Load unbalance effect on power generation and stability
	Faults and protection coordination
Transient Operation	Voltage and current transients
	Voltage spike limit
	Inrush current under nominal voltage

Table 2 MESIS Operation Modes for Power Quality Analysis

Figure 4 depicts a high-level block diagram that shows the interaction of the models provided by HORIZON collaborators as part of MESIS development. The aircraft and ambient conditions model interacts mainly with the power plants and the EPGDS models. The power plant system encompasses main gas turbine models and the electric Auxiliary Power Unit (eAPU) gas turbine model. The main gas turbine engines drive Variable Frequency Starter/Generators (VFSG) with power electronics based controllers. In motor mode, the VFSGs will perform main engine start, whereas in generation mode, the VFSGs will feed electrical power to the EPGDS. The EPGDS will include power conversion units and MEA / non-MEA electrical loads. The EPGDS architecture has several 230 VAC variable frequency distribution systems, including primary buses, auxiliary bus and essential bus. On ground operation, power source is delivered by external 115 VAC/400 Hz. The EPGDS will incorporate Li-Ion battery models to meet the eAPU start generation and emergency power.

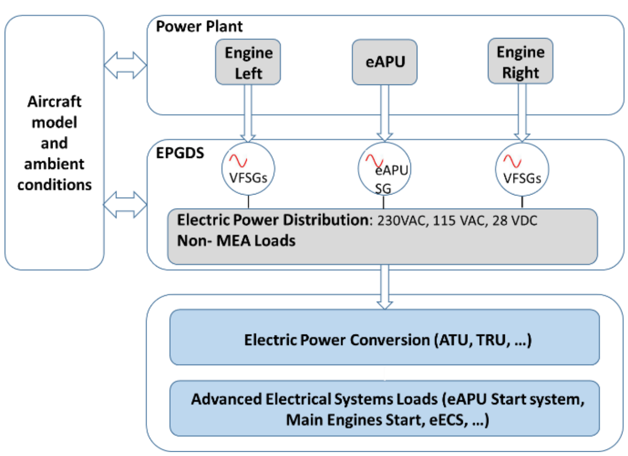


Figure 4 MESIS Block Diagram Structure

IV Practical implementation of MESIS

A Simulator Architecture

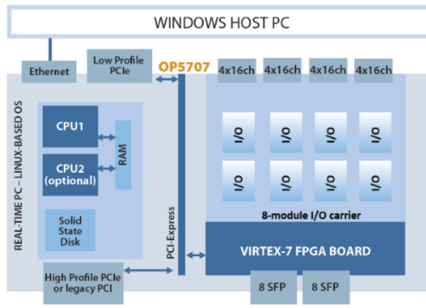


Figure 5 MESIS Hardware Architecture

All models part of MESIS are integrated in the MATLAB/Simulink environment. The overall integrated software model is compiled and loaded to run in real-time on a dedicated platform that forms the hardware part of MESIS. The used hardware simulator architecture is given in Figure 5 [9].The simulator may include multiple CPUs and FPGA cards. CPUs are typically formed by multiple internal cores, and FPGA cards mainly interface with physical I/O signals. In order to optimize the real-time execution of the models, the simulator provides the possibility to allocate separate parts of MESIS models onto different CPU cores. The simulator also offers the possibility to run models requiring lower sampling times on FPGA cards. Several FPGA boards can be linked together using fast optical cables to maintain time step values below one (1) microsecond for large and complex systems. Figure 6 shows the simulator hardware allocation of the MESIS models. For instance, models with relatively slow dynamics such as gas turbines and aircraft models are executed on CPU resources using slower time steps. Electrical models such as the EPGDS can also be allocated to CPU resources with lower sampling times. This is achieved using solvers which optimize the computational resources for electrical models. [10]. Electrical models requiring a sampling time less than 10 micro second are executed on FPGA cards. Those models typically involve the simulation of power electronics devices with high switching frequencies requiring additional simulation accuracy with time steps ranging between 200 nanosecond and 1 microsecond [11].

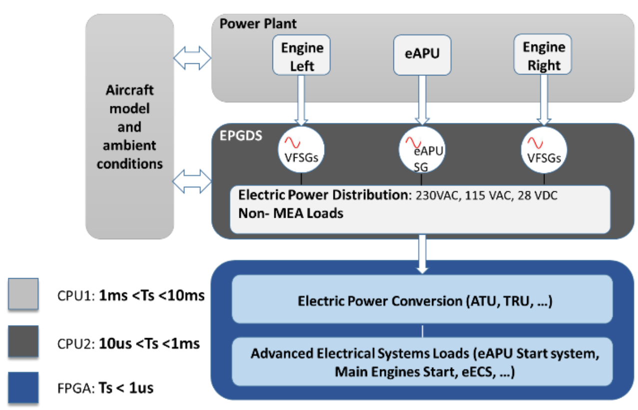


Figure 6 Models Resources Allocation on Simulator

B Technical Challenges

The practical implementation of MESIS implies several technical aspects to be analyzed. The main points below with their mitigation strategy are being considered for the MESIS development phase:

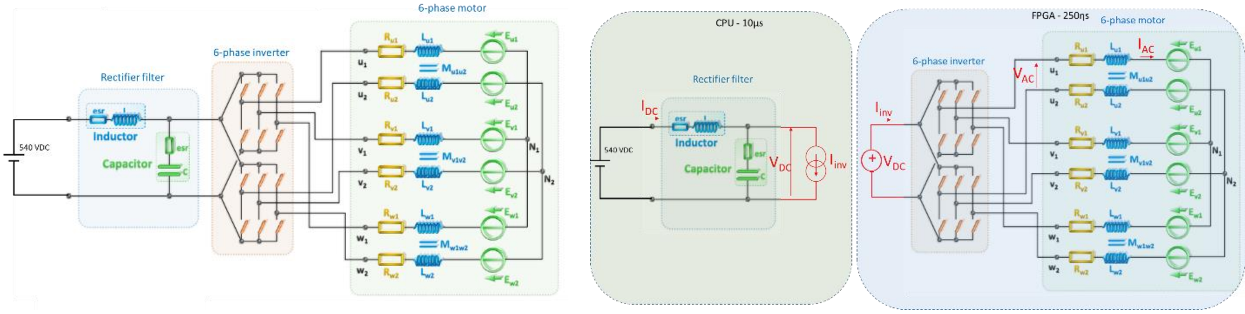
- **Models signals interface management**: MESIS will involve a considerable number of signals interfaces between integrated models. In order to avoid implementation errors, an automated signal interface management system will be necessary for the models integration. This system will be based on the development and management of interfacing signals between all integrated models. Additional functionalities such as malfunction injection and states initialization will also be implemented.
- **Multi-rate models integration**: As per Figure 6, MESIS will integrate models running on distributed simulation resources with different sampling time execution. The development of decoupling techniques between those models is mandatory to insure overall simulation stability and accuracy [12]. Example in section V-A of the paper illustrates this case and presents modeling strategies with validated simulation results.
- **Co-Simulation Environment:** Integrated models received from collaborators may be developed on different simulation platforms. It will be essential to insure simulation compatibility within the integration environment and between models. Harmonization of modeling techniques will be communicated with adequate interface control documentation.
- **Models complexity:** Electrical models with high complexity levels involve computational matrices with higher dimensions. This is especially the case for electrical circuits including a considerable number of switching devices, as discussed in section V-B of the paper. This may jeopardize real-time execution when relatively lower sampling time is mandatory. Specific solvers are used to reduce the computational matrices dimensions and optimize real-time execution without any risk of overruns [10].

V Implementation Examples

In this section real-time simulation examples are presented to illustrate part of the technical strategies that are used to address real-time models integration challenges in MESIS. Example V-A presents a model of power converters and a 6-phase machine part of a turbo compression system. A decoupling technique is applied on the overall model which is separated into sub models that are allocated on CPU and FPGA resources. Example V-B discusses the challenges and potential solutions of real-time implementation of the EPGDS model with a concrete example.

A) Model decoupling of a Motorized Turbo Compressor (MTC) machine

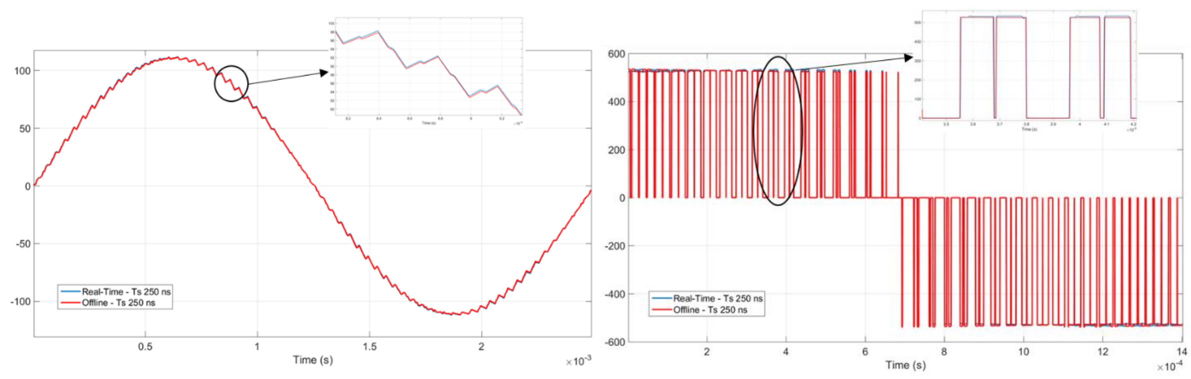
This example presents a multi-rate real-time simulation of a simplified MTC six-phase electrical machine which is part of the air conditioning system in the aircraft. The electrical machine is a non-salient permanent magnet synchronous motor [13]. As depicted in Figure 7 a, the motor is modeled by six mutually coupled stator windings. Back EMFs representing rotor induction and loads are modeled at each stator winding. The motor is controlled by a drive including a 6-phase inverter with PWM control signals. The PWM control signals are sine waves set at a nominal 400 Hz operation, with a carrier frequency set to 25 kHz. As detailed in [13], the motor's power rating is 35 kW and the rectifier which mean value is modeled by a constant DC input voltage of +- 270 VDC (540 VDC). The internal electrical parameters of the machine were tuned to get an operating set point close to the machine's power rating. Figure 7 b shows in red the practical decoupling implementation of the model in the real-time simulator. The rectifier runs on CPU at a 10 micro-second time step, and the machine-inverter group runs on the FPGA, with a time step of 250 nano-second. As shown in Figure 7 b, the model is decoupled by driving the inverter's input with a voltage source fed by the rectifier's DC voltage V_{DC}, and feed back the absorbed current by the inverter I_{inv}, into a controlled current source on the rectifier's side. The motor and power converters are modeled in MATLAB/Simulink environment, using SimPowerSystem (SPS) blockset. FPGA specific solver [14] is used to automatically translate the SPS model of the machine into HDL code that is executed real-time on the FPGA.



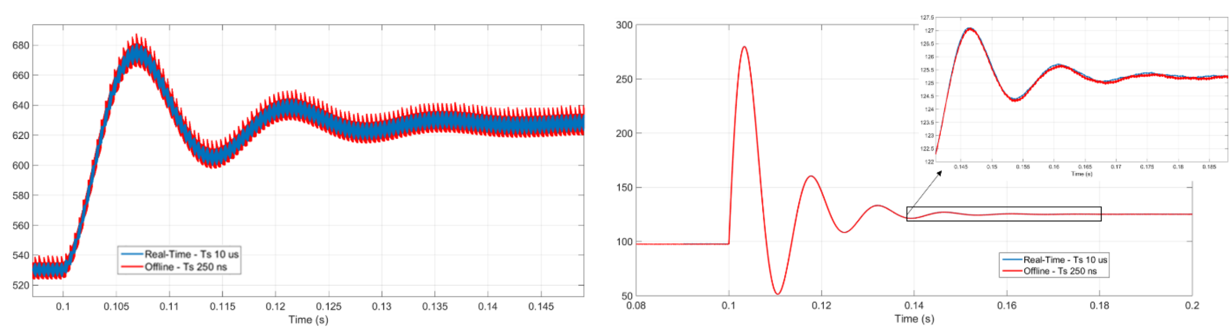
(a) (b)

Figure 7 Power Converters and 6-phase motor Model (a) and Model Decoupling (b)

Figure 8 shows simulation results validated by the layover of the entire model running offline at 250 nano-second without decoupling (waveforms in red) and the decoupled model executed in real-time on CPU and FPGA (waveforms in blue). Graphs (a) and (b) show the overlay of the steady-state AC voltage and current absorbed by the motor for one fundamental period. Graphs (c) and (d) show the overlay of the transient behavior of the mean DC voltage and current for a 100 volt step disturbance on the rectifier's DC voltage. Both the steady-state and transient cases show a very close match between the offline and the decoupled real-time waveforms. Thus the decoupled model preserves both the accuracy of high-frequency switching behavior on the load side, and the dynamic behavior on the electrical distribution side. This is important in the context of an HIL multi-rate simulation, where dynamic interaction of the hardware controllers and modeled systems are validated, while maintaining high accuracy of simulated high-frequency converters, allowing moreover hardware PWM controllers to directly connect to those converter models.



(a) Steady-State AC phase current I_{AC} (Amp) (b) Steady-State AC phase to phase voltage V_{AC} (Volt)



(c) Transient on mean DC voltage V_{DC} (Volt) (d) Transient on mean DC current I_{DC} (Amp)

Figure 8 Decoupled Real-Time Versus Offline Simulation of MTC and Power Converter Models

B) Implementation of the EPGDS model

The practical implementation of the EPGDS model will include numerous component models such as contactors, wires, buses and generators. Figure 9 shows the implementation of a portion of the EPGDS in Matlab/SPS blockset. The component models are implemented with masked subsystems parametrized by technical data sets provided by suppliers.

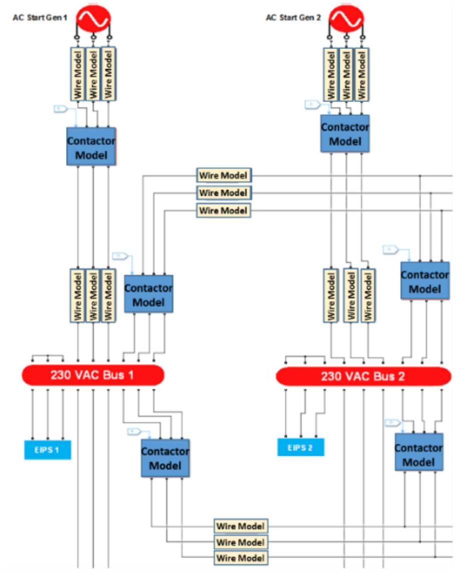


Figure 9 Implementation of an EPGDS Portion in MESIS

The EPGDS includes a considerable number of switching components such as contactors, which makes the real-time execution of the model challenging. The relatively high amount of switching elements increases the computational matrices dimensions, leading to computational limitations during real-time execution. Specific solvers will be used to reduce the computational constraints and optimize real-time execution [10].

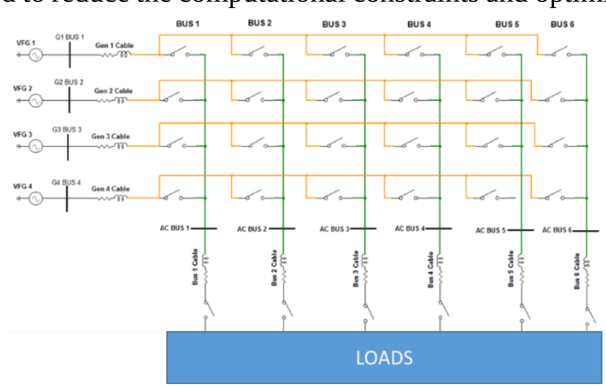


Figure 10 EPGDS Example with a Matrix Structure

Those solvers were already tested on an example of an EPGDS circuit depicted in Figure 10. The circuit includes 90 single-phase switches arranged into a matrix structure. It also includes four generators and six buses. Standard RL loads are connected to the buses. The optimization of the circuit with the abovementioned solvers has led to a real-time execution of the model with a time step of 36 micro-second, and with a maximum execution time of 28 micro-second. Tests on a different type of solvers indicate that a time step of less than 12 microseconds could be reached. FPGA-based simulation of the EPGDS will also be considered.

VI Conclusions

In this paper, the objectives and the technological aspects and implementation of a real-time simulator for MEA were presented. This simulator will be used as a technology demonstrator for MEA equipment introduction for the future aircraft development program. The main implementation challenges and mitigation strategies were exposed, and preliminary real-time simulation results were presented in order to validate some technological implementation concepts. The simulator will follow progressive maturity levels and will evolve into a full TRL 6 test rig demonstrator. Future work will include the integration of additional models and the definition of detailed test plans in support of V&V activities.

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