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Real-Time Simulation of a More Electric Aircraft Power Generation and Distribution System

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I. Abstract

More Electric Aircraft (MEA) technology is leading aircraft manufacturers to replace traditional hydraulic and pneumatic systems by electrical components, resulting in weight and maintenance cost reduction, and in the increase of Mean Time Between Failures (MTBF). This has for effect of increasing the complexity of the Electrical Power Generation and Distribution System (EPGDS) of the aircraft and degrading its power quality. As a result, testing and validation must be performed early in the design stages, which has traditionally been done via the use of physical testbeds which involve significant amount of hardware. However, because of the electrical nature of MEA, virtual testbeds are now increasingly used, which offer greater flexibility and are less costly than conventional testbeds. As such, OPAL-RT is developing real-time simulators that integrate MEA systems models into a real-time co-simulation platform. This paper provides simulation results that showcase OPAL-RT's real-time simulation capabilities in the context of EPGDS simulation, applied to a generic example inspired from public domain publication regarding the Boeing 787 EPGDS.

II. Nomenclature

ATRU	=	Autotransformer Rectifier Unit
EPGDS	=	Electrical Power Generation and Distribution System
HIL	=	Hardware In the Loop
MEA	=	More Electrical Aircraft
MTBF	=	Mean Time Between Failures
MTC	=	Motorized Turbo Compressor machine
TRL	=	Technology Readiness Level
TRU	=	Transformer Rectifier Unit
VFSG	=	Variable Frequency Starter/Generator

III. Introduction

Modern aircraft manufacturers are in the constant pursuit of more efficient aircrafts, with more reliable, cheaper and lighter components. One way to achieve this objective is to come up with higher power density systems that rely less on pneumatic and hydraulic equipment. In that way, More Electric Aircraft (MEA) designs have become of increasing interest for aircraft manufacturers. Since it replaces conventional actuation systems with electric equipment, MEA technology introduces new types of loads such as switch mode converters in the EPGDS and thus increasing the complexity of its design and analysis [1]. MEA increasingly integrate new generations of electrical machines and converters and their impact on the other systems is not fully known. For example, power quality and protection coordination are affected by MEA technology, which are of critical importance in the aerospace industry [2].

Because of this, considerable time and effort need to be spent on research and development in order for the necessary Technology Readiness Levels (TRL) to be reached. While the conventional approach to aircraft design and validation involves the use of costly physical test rigs, the electrical nature of MEA makes them

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ideally suited for real-time simulation. Real-time simulation provides a low cost and flexible solution that reduces the time to market [3]. It can also be employed to simulate the whole EPGDS or to simulate individual network components such as converters, motors and controllers [4].

IV. MEA studies with real-time simulation

As MEA technology is a newly developing field, in-depth testing and validation must be undertaken in order for the technology to reach the required TRL. When a new technology arises, its evolution from theoretical innovation to flight-proven, actual technology goes through what is known as Technology Readiness Levels (TRL) [5], which are described in Table 1.

Table 1. TRL Scales and Sub-Attribute Description in Aerospace

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

Systems engineering activities usually employ the “Vee” model representation of TRLs [6], as shown in Figure 1. On what is referred to as the ‘’downstroke’’ of the Vee are TRLs 1 and 2, in which initial definitions, requirements and fundamental principles are defined. Correspondingly, on the upstroke section of the Vee are TRLs 3 to 8, which involve the verification and validation stages. It is to be noted that for practical systems, the Vee model is an iterative process, resulting in dependencies between the downstroke and the upstroke phases.

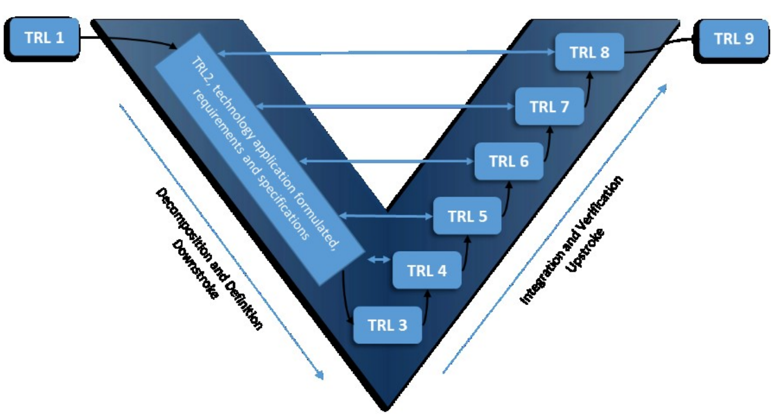

Figure 1. “Vee” Model Diagram with TRL

Conventionally, physical test rigs are built to validate sub sectional designs of the aircraft. While a time-proven way for testing and validation, physical testbeds are costly, do not offer a high degree of flexibility and involve long time scales with regards to assembly and modifications. Real-time simulation, on the other hand, allows for rapid and flexible iterative testing applicable at all steps of the aircraft life cycle, from initial design to validation of modifications on the commercial product. Initial tests are made entirely in software using parameters provided by the equipment manufacturers. They allow to assist in the design of electrical systems, to validate proposed architectures and to acknowledge the effects of normal and abnormal operating scenarios. Once initial designs are accepted and validated via software simulation, actual controllers and software used in the aircraft can be integrated in conjunction with the simulation to perform hardware-in-the-loop (HIL) simulations. HIL simulation allows for more accurate simulation as real equipment and controllers are integrated in the loop with computer models. Based on the definition of TRLs in Table , HIL simulation results in a prototype rig of fidelity level ‘high’, corresponding to TRL 6. Figure 2 shows the Vee model as applied to real-time simulation [7].

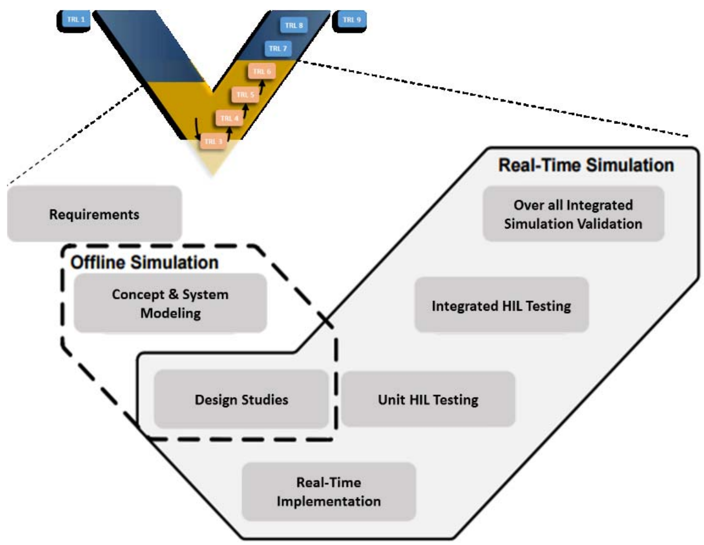

Figure 2. “Vee” Model with Real-Time Simulation

V. Case Study

In this section, the EPGDS of the Boeing 787, as seen in a public domain document [8], is studied. First, the simulator setup is presented with technical challenges posed by this simulation, and proposed mitigations to address those challenges. Then, the architecture of the Boeing 787 is explained along with which simulation techniques are used for specific parts of the network. Finally, some simulation results are presented for two electrical generation frequencies of the network: 400Hz and 800Hz.

A Simulator Architecture

The physical and software architecture of the simulator is presented in this section. First of all, all simulation takes place in the MATLAB/Simulink environment. In order for the simulation to run in real-time, the simulated circuit is compiled and loaded to the physical simulator, as detailed in Figure 3 [9].

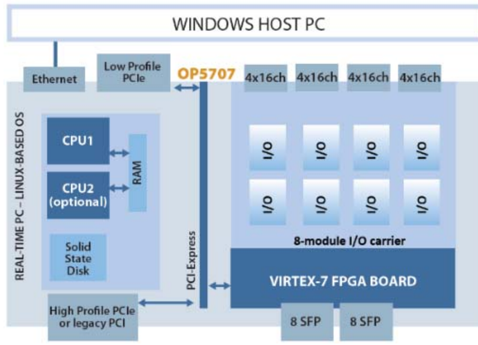

Figure 3. Simulator Hardware Architecture

It can be seen that the modelling takes place on a multi-core CPU. The use of multi-core CPUs enables for the EPGDS circuit to be distributed on the multiple cores, allowing for simulation and resource optimization to take place [10]. While the FPGA boards mainly manage the interfacing with physical signals, they can also be used for simulation purposes. Models requiring reduced time-steps such as switch-mode converters can be modelled on FPGA cards with real-time execution time steps as low as 200 nanoseconds [11]. This means systems with wide-ranging dynamic time-constants, as is the case with the Boeing 787 EPGDS, can be modeled and executed efficiently and accurately in real-time by the simulator using a hybrid FPGA-CPU solution. Table 2 illustrates various types of analysis possible with the simulator, and Figure 4 illustrates typical simulation waveforms.

Table 2. Simulation Capabilities of the Simulator

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

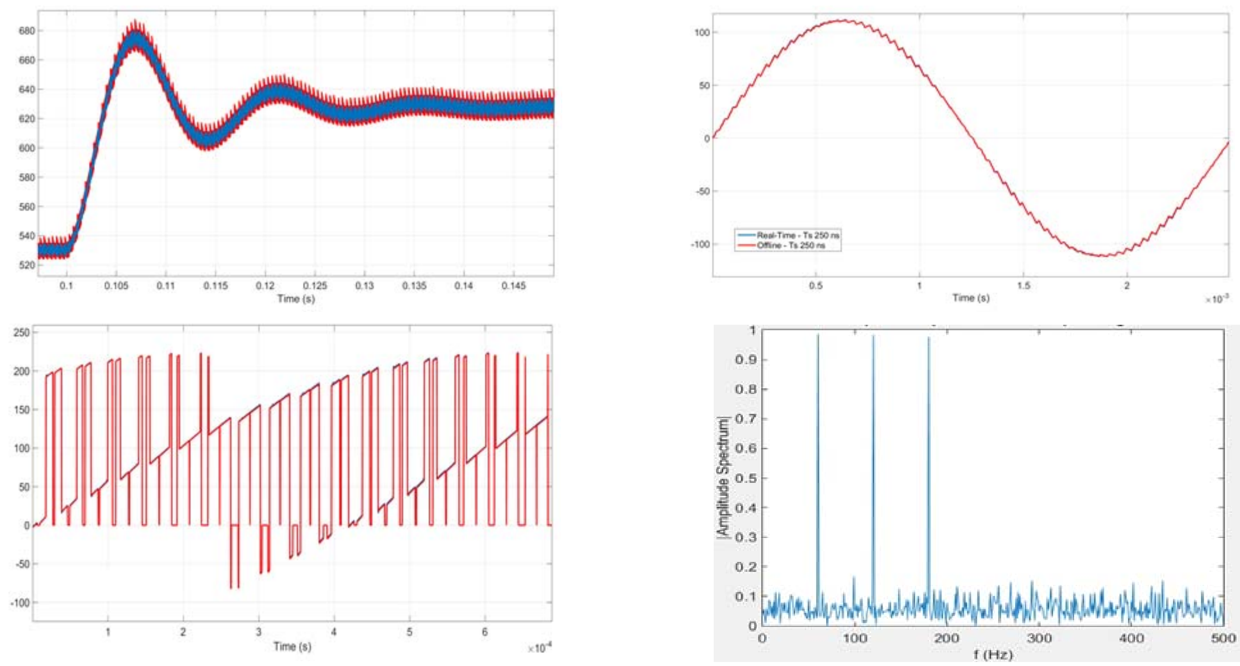

Figure 4. Typical waveforms and associated analysis obtainable with real-time simulation

B Technical Challenges

EPGDS being complex systems, their analysis and simulation present many technical challenges. Below are some aspects of the EPGDS simulation being considered and their proposed solution method.

- **Multi-Rate Models Integration**: This simulation integrates 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. The validation of such decoupling has been done in previous works [12].
- **Multi-Platform Simulation:** As power electronics converters require very small time steps to be modelled accurately, they are simulated on an FPGA [13] while the rest of the circuit is simulated on CPU. This multi-platform simulation method introduces extra complexity and synchronization issues in the model, and must be addressed accordingly [11].
- **Models Complexity:** Complex electrical circuit models, such as those with a high number of switches, involve the computation of high dimension matrices. This leads to longer computation times, which can conflict with the small simulation time-steps often required to achieve accurate real-time simulation. In order to effectively manipulate those large matrices, dedicated solvers were developed to avoid the computation time taking longer than the desired simulation time step [10]. Such a situation is known as an ‘’overrun’’.

C B787 Architecture

Shown below is the modelled Boeing 787 EPGDS circuit diagram. It includes among other systems four (4) Variable Frequency Starter/Generators (VFSG), four (4) 540VDC 18-pulses Autotransformer Rectifier Units (ATRU), four (4) 28VDC 18-pulses Transformer Rectifier Units (TRU), thirty-two (32) three-phase breakers, two (2) 6-phase inverters, two (2) simplified Motorized Turbo Compressor machine (MTC) models. The total number of switches in the model is 264 switches. Amongst these, two

(2) 6-phase inverters and two (2) simplified MTC models, for a total number of 24 switches are simulated on an FPGA, while the rest of the circuit is simulated on the CPU, as depicted in Figure 5.

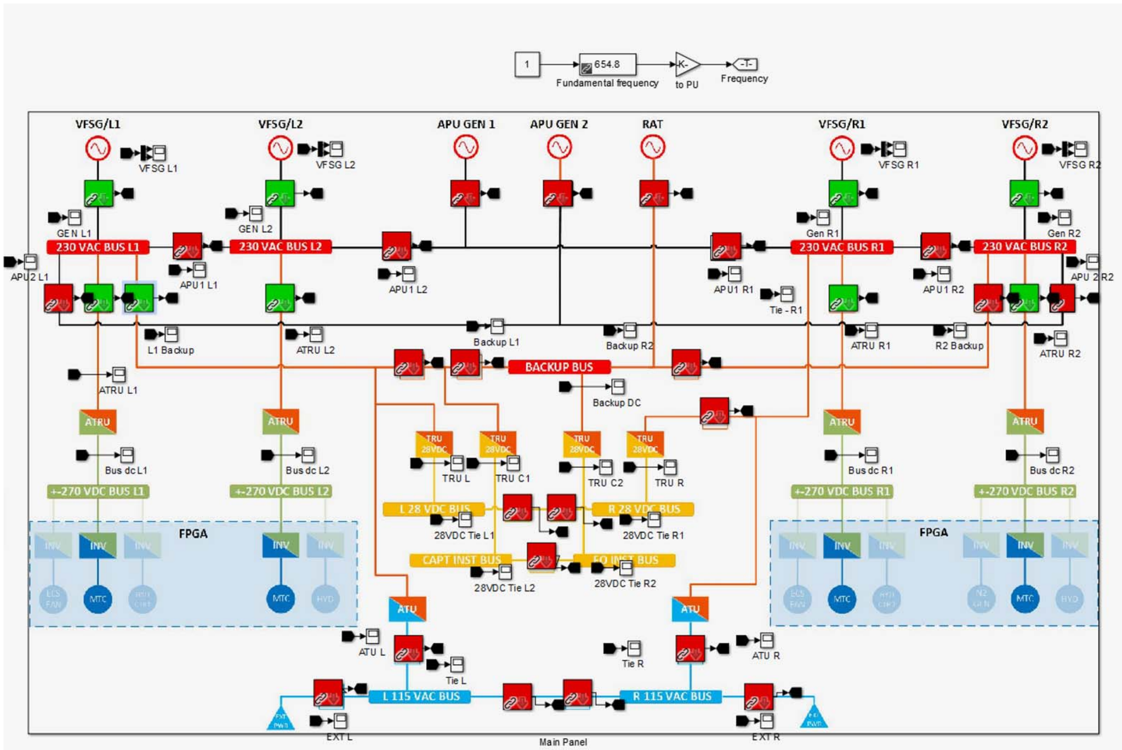

Figure 5. Simulated EPGDS of the Boeing 787

D Results

The circuit was simulated in real-time in a CPU-FPGA co-simulation. Except for the two 6-phase inverters and the MTC loads, which had to be simulated on the FPGA due to their high switching frequency, the entirety of the circuit was simulated on the CPU. CPU sampling time was 25us, while FPGA sampling time was 220ns. Below are some waveforms from the simulation. To replicate the ‘‘frequency-wild’’ nature of an aircraft EPGDS, the system was simulated at its nominal 400 Hz and at its maximal 800Hz. Below are some waveforms obtained from the simulation. Figure 6 shows the current and voltage real-time simulation results for the L1 bus generating at 400 Hz. Figure 7 shows the current and voltage real-time simulation results for the L1 bus generating at 800Hz. Figure 8 shows the FPGA real-time simulation results of the MTC inverters. The inverters are simulated on an FPGA at 220ns. Finally, Figure 9 shows the harmonic spectrum of the motor current, showcasing the precision resulting from FPGA simulation.

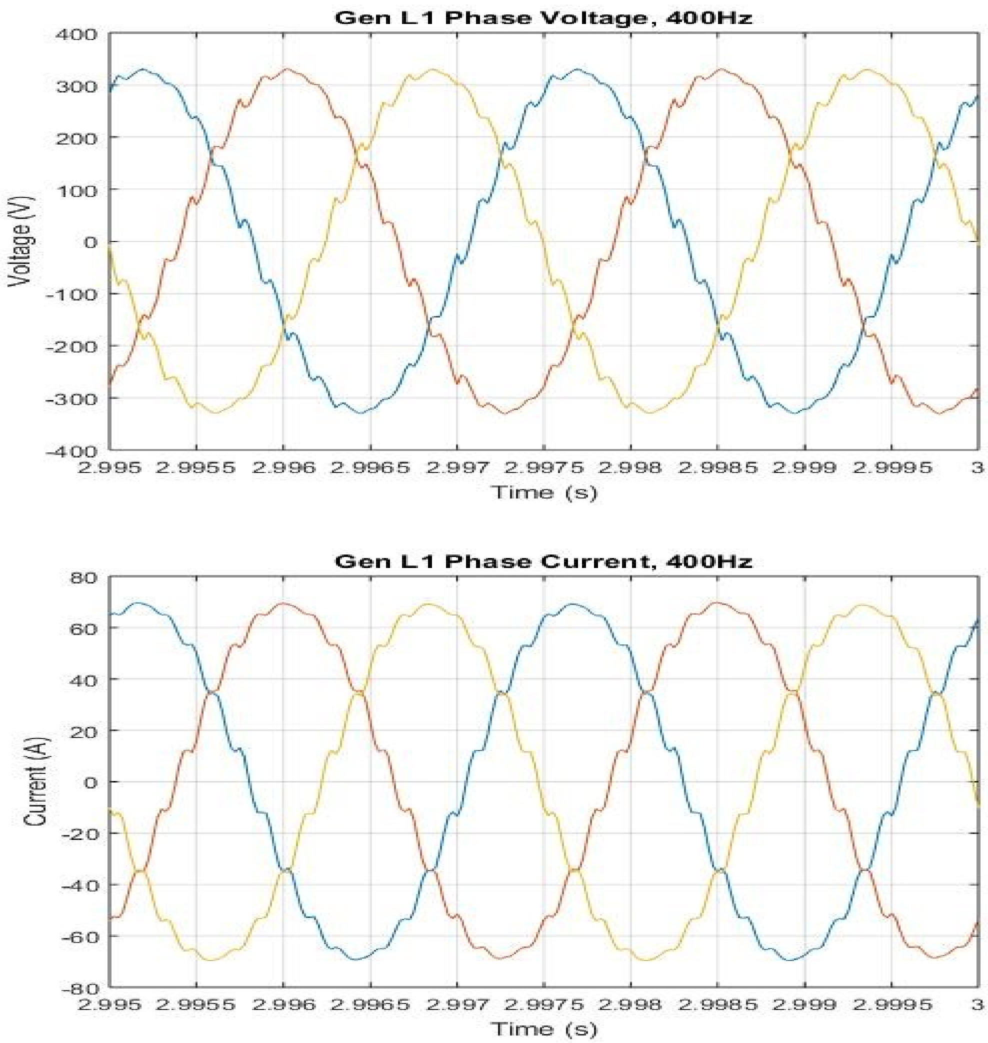

Figure 6. Bus L1 Voltages and Currents at 400Hz – Sampling time of 25us

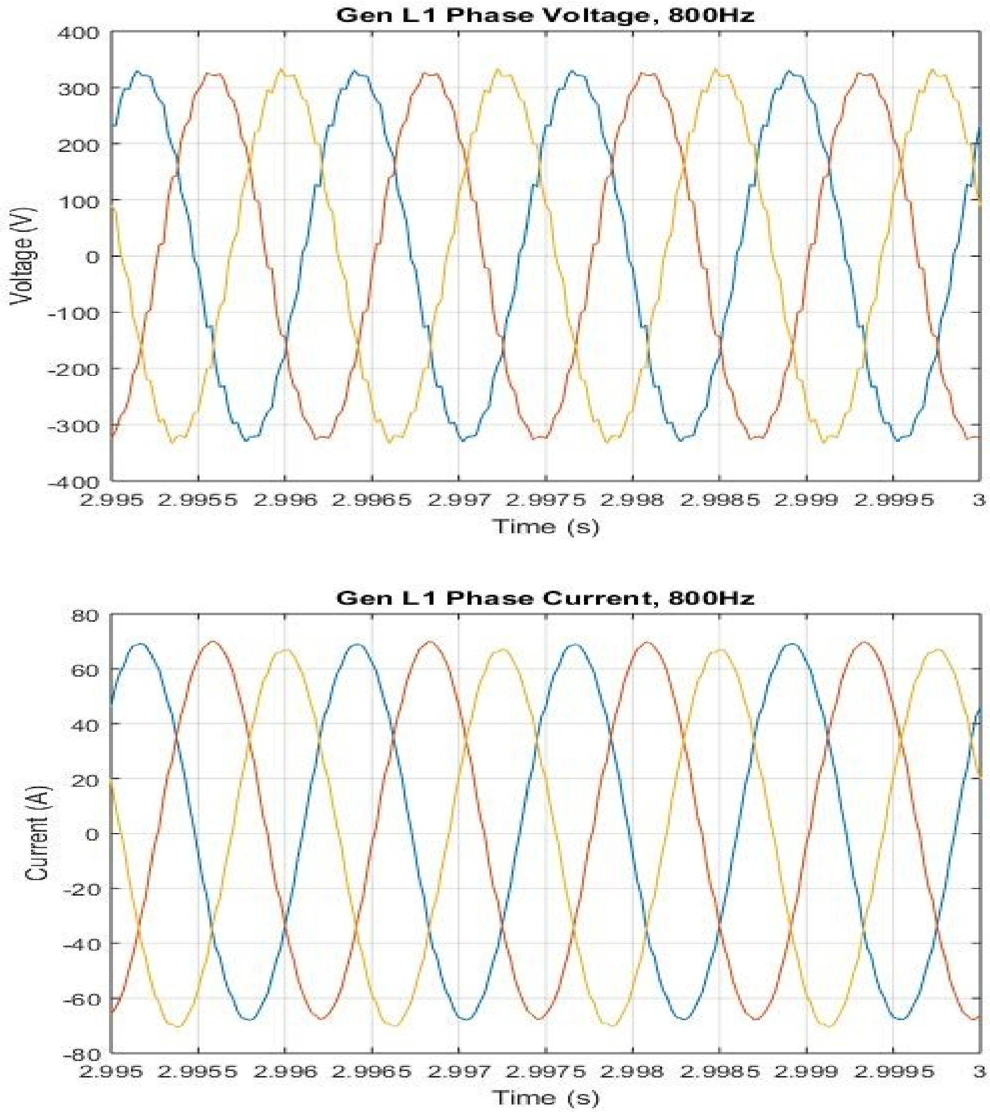

Figure 7. Bus L1 Voltages and Currents at 800Hz – Sampling time of 25us

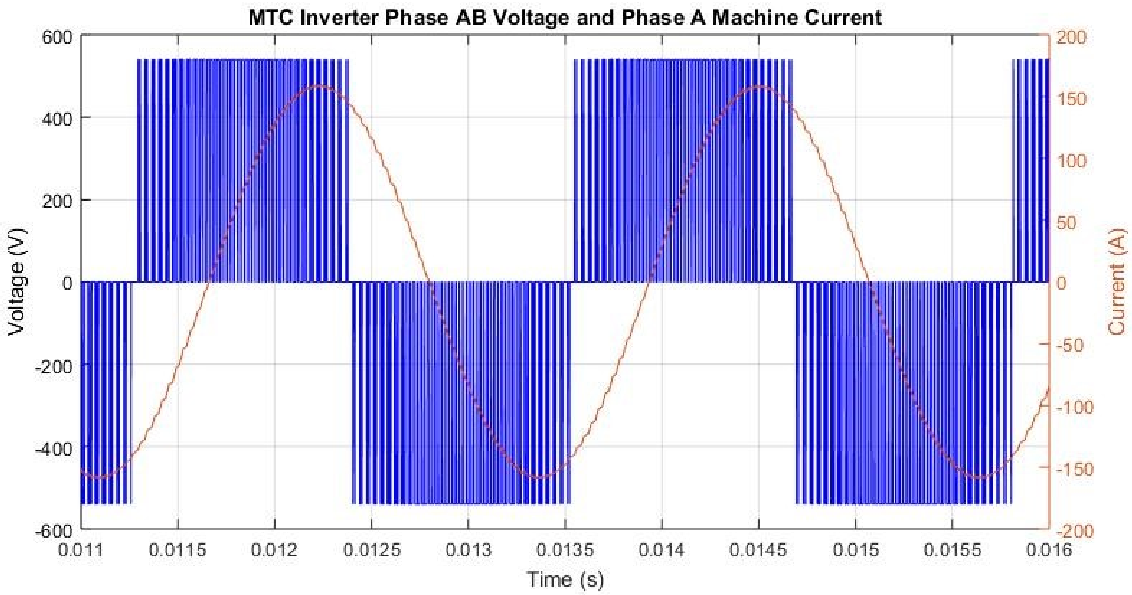

Figure 8. MTC FPGA Simulation Results – Sampling time of 220ns, PWM=20 kHz.

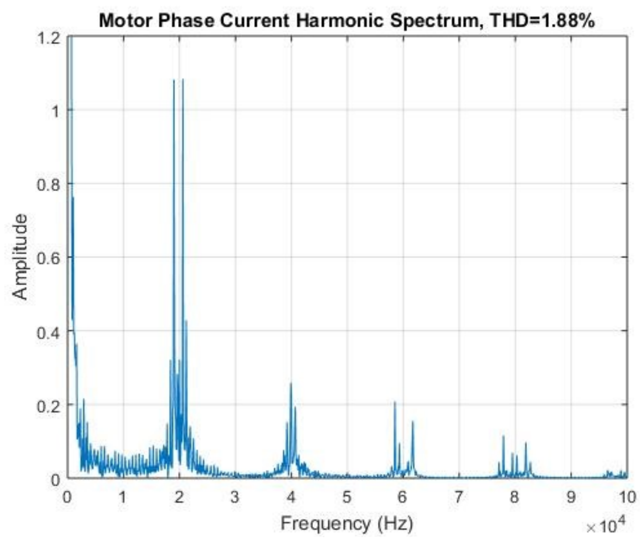

Figure 9. MTC FPGA Harmonic Spectrum

VI. Conclusion

In this paper, the technological considerations and implementation of a real-time simulator for MEA were presented. It was shown the simulator can be used as a technology demonstrator for MEA equipment. The main implementation challenges and mitigation strategies were exposed, and preliminary real-time simulation results were presented. The simulator is able to provide high precision results even for 20 kHz switching converters due to the integration of FPGA co-simulation while guaranteeing real-time simulation.

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