FPGA based Real time Simulation & Hardware-In-Loop for micro-grids studies and control design

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Abstract-- This paper presents a real-time simulation platform allowing control and protection devices to be designed and tested in virtual power plants, before they can be implemented in a physical system. This platform promotes flexibility of operation with no risk of components failure under any contingency analysis. To demonstrate the effectiveness of the OPAL-RT platform, a Hardware-In-the-Loop (HIL) application is considered. It consists of a virtual Micro-Grid (MG) simulated in real-time, and an MPPT controller running on the OP8665 integrating the Texas Instruments C28335 DSP. Converters with fast switching frequencies are executed on the FPGA simulator. The remaining system, including different distributed energy resources (DER) with low switching frequencies and a distribution network (DN), are run on two CPUs available on the simulator.

Keywords—Micro-grid, Real time simulation, HIL, MPPT algorithm

1. INTRODUCTION

With the increased complexity of modern power grids and the integration of renewable energy sources, industry is relying on simulation tools more than ever for the prototyping and design of power systems. In recent years, digital real-time simulators have become essential to the design of smart grids, as well as for testing control and protection schemes [1]–[4]. However, modern distribution grids rely heavily on power electronics systems, which increase the complexity of power systems containing a large number of distributed generation sources. Hence, the real-time simulation of modern electrical networks faces two major challenges that need to be addressed by a real-time simulator:

1. The simulation of distribution networks comprising a large number of components, modules and buses;
2. The accurate handling of fast switching frequency power converters.

The remainder of this paper is organized as follows: Section II provides background material about real-time simulations, as well as the challenges associated with large power networks and fast switching frequency power converters. Section III discusses the case study considered in this paper. Section IV presents implementation and simulation results. Section V concludes this work.

2. KEY-CHALLENGES OF REAL-TIME SIMULATION

Power grids are complex systems and their electromagnetic transient simulation requires the computation of large matrices. The only way for a real-time simulator to handle their simulation in real-time is to split the grid model over multiple processors. However, distribution networks are lumped by nature, and network decoupling using natural delays (transmission lines) is not always possible. The method used in this paper to split the computation over multiple processors uses a so-called state-space-nodal (SSN) approach [5].

1.1 Real-time simulation of large networks

Large networks are simulated on a multi-CPU platform. SSN automatically splits the grid into subgroups, thus reducing the number of nodes per processor. Moreover, SSN allows the parallelization of the network equations without introducing fictitious delays while keeping the simulation time-step sufficiently low to ensure accurate results during transients.

1.2 Real-time simulation of fast switching frequency power electronic systems

FPGA-based real-time simulators have been proven to be the computing platform of choice for the simulation of power electronic systems [6], [7] because of the high switching frequencies (>10 kHz) targeted by most modern power conversion systems [8], [9]. To avoid the tedious FPGA design workflow, we use eHS, an automated FPGA-based computing engine [10], that consists of a precompiled hardware processor that converts a SimPowerSystems circuit into binary data used by eHS.

1.3 CPU-FPGA coupling

Once the micro-grid model has been split between CPU and FPGA, there is a need to couple and synchronize both models. The issue with this is the
different sampling rates available on both computing platforms: the CPU model will be running at tens of micro-seconds, whereas the FPGA runs at hundreds of nano-seconds (see Figure 1 for an example).

It is one of the contributions of this paper to propose and demonstrate the effectiveness of a decoupling strategy well suited for MG models that consists of a modified ideal transformer coupling with a low pass filter implemented on the CPU side.

3. CASE STUDY

The case study considered for the demonstration of the effectiveness of the proposed method consists of a micro-grid connected to a distribution network comprising 70 three-phase nodes. As shown in Figure 1, a part of the micro-grid is simulated using 2 processors with a time-step of 25 us. This part includes the DN and the DERs connected to the grid through converters with low and medium switching frequencies (<5 kHz). The content of this CPU part is as follow:

1. A wind turbine delivering a maximum power of 10 kW at a wind speed of 15 m/s;
2. A solar panel delivering a maximum power of 5 kW at 1000 W/m2 irradiance;
3. A battery connected to the grid via a 2-level IGBT inverter;
4. Three RL loads representing a neighborhood.
5. A DN with 70 three-phase nodes.

The size of distribution networks is a major difficulty in performing accurate and stable EMT real-time simulations. Large distribution networks, such as the one used in this case study, require a time-step of over 50 µs for EMT simulation using a single processor. To reduce the simulation time-step to 25 µs, the distribution network needs to be decoupled into smaller sub-networks simulated in parallel on multiple processors.

The distribution network considered here includes 70 three-phase buses, 62 short lines represented by series RL circuits, 10 three-phase breakers, and 42 pure resistive loads. The decoupling is carried out without adding artificial single-time-step delays nor artificial capacitors: the network is decoupled using SSN, which creates virtual partitions of the network that are solved simultaneously at the partition points of connection. For this case study, we created 7 such SSN groups.

The second part of the micro-grid is simulated using the Xilinx Kintex-7 FPGA Module integrated in the simulator using a time-step of 500 ns. This second part includes:

1. A solar panel delivering maximum power of 10.68 kW at 1000 W/m2 irradiance.
2. A boost converter regulating the PV voltage to get maximum power.
3. A three-level grid-connected inverter injecting the PV power to the grid.

The control algorithm for the NPC is implemented on the CPU model and RT-Events is used to generate the gates on FPGA with a frequency up to 10 kHz and a 10 ns resolution. The boost converter is controlled using the TI C28335 DSP and its switching frequency can be varied from 1 kHz to 100 kHz.
The HIL setup is illustrated in Figure 2. It consists of a C28335 DSP from Texas instruments, running an MPPT algorithm of type Perturb & Observe (P&O). The DSP measures the PV voltage and current directly from the FPGA with a latency that is less than 2 µs. Thereafter the DSP generates a PWM signal controlling the boost converter to get the maximum power for a given irradiance.

The controller integrated in the DSP is shown in Figure 3. Three control modes are available based on the configuration of the OP8665 switches:
- Mode 1: the DSP generates a fixed duty cycle controlled either from a LabVIEW console or from potentiometer 1 on the OP8665.
- Mode 2: a PI controller is used to regulate the PV voltage to a voltage reference fixed by the user from the LabVIEW interface or from potentiometer 2 on the OP8665.
- Mode 3: the PV voltage reference is calculated by the MPPT algorithm and input to the PI regulator.

3.1 Test 1: PI controller dynamics
Figures 4 and 5 show the FPGA-based real time simulation results when the DSP controller is operating in mode 2. During test 1, the PV reference voltage follows a saw tooth wave to evaluate the PI controller dynamics:

3.2 Test 2: MPPT algorithm response
During this test the MPPT algorithm is activated. Figure 6 shows the simulated solar panel P-V curve. As can be seen, the maximum power at 1000 W/m2 irradiance is 10.68 kW.
Figures 7, 8 and 9 show the FPGA-based simulation results when the DSP controller is operating in mode 3 (MPPT algorithm activated). As can be seen, the algorithm is generating a PV voltage reference of $1.10 \, \text{pu}/250 \, \text{V}$, which is the voltage we need to get $10.68 \, \text{kW}$ at $1000 \, \text{W/m}^2$.

3.3 Real-time simulation performance

Table 1: CPU performance

<table>
<thead>
<tr>
<th>NB. Cores used</th>
<th>Cores Contents</th>
<th>Model Time Step</th>
<th>Cores Computation time</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>DN + MG</td>
<td>25 us</td>
<td>19 us</td>
</tr>
</tbody>
</table>

Table 2: FPGA performance

<table>
<thead>
<tr>
<th>FPGA module #</th>
<th>FPGA Contents</th>
<th>Circuit Time Step</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>PV + Boost + NPC</td>
<td>500ns</td>
</tr>
</tbody>
</table>

Tables 1 and 2 summarize the real time performance of the presented HIL application. The distribution network and the MG mentioned in red on figure 2 are running using only 2 cores of the simulator with a time step of 25 us. The second PV with the boost and the NPC converter (mentioned in blue on figure 2) are running in the FPGA with a time step of only 500 ns.

3.4 Maximum switching frequency

In order to assess the effectiveness of the proposed approach in reproducing the correct behavior, expected, we have conducted a study where the switching frequency of the boost converter that is simulated on FPGA was varied from 1 kHz to 120 kHz.

Figure 10 presents superimposed measurements of the inductance current on the oscilloscope for four different switching frequencies. It should be noted that the currents are outputted as scaled down voltages.
gain of 3 and an offset of -60 are used. As one can see, as the switching frequency increases, the amplitude of the ripples decreases.

![Image 10: Boost output voltage for various switching frequencies. Black: 10 kHz; Green: 20 kHz; Purple: 40 kHz; Red: 80 kHz.](image)

The ripple amplitude can be computed theoretically. Figure 11 compares theoretical vs measured current ripple amplitude. As one can see, the model follows quite well the theory, demonstrating the effectiveness of the FPGA modelling as well as the CPU-FPGA coupling.

![Image 11: Theoretical vs measurements for switching frequencies ranging from 1 kHz to 120 kHz.](image)

Figure 12 shows the relative error of the measurements vs the theoretical values regarding the ripple amplitude. As one can see, the relative error below 5% for all frequencies below 90 kHz. For switching frequencies ranging from 90 kHz to 120 kHz, the error increases much more. This is explained by the fact that the 500 ns time-step is quite high in regard of such switching frequency. Hence, it is mandatory to decrease the simulation time-step below 500 ns for the higher switching frequencies.

![Image 12: Error in % comparing theoretical ripple amplitude vs measurements for switching frequencies ranging from 1 kHz to 120 kHz.](image)

### 4. CONCLUSION

This paper aimed to explain the encountered challenges in the real-time simulation of microgrids, renewable energy systems and distribution networks, and to explain the state-of-the-art methods used to address these challenges and solve the problems of simulation speed and accuracy. This was illustrated through a case study consisting of a micro-grid connected to a large distribution network with hundreds of nodes. It was shown through this circuit how we solved the two major challenges encountered: difficulty of simulating the large distribution network on several processors/cores, and the accuracy in simulating fast frequency switching power converters.

### REFERENCES


