Cross-Platform Comparison of Standard Power System Components used in Real Time Simulation

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***Abstract*—Real-time simulators are an essential tool for the development of new cyber physical power system applications, specially in development and testing of smart grid functionalities. Like in many other fields of research, one of the major challenges when using simulation is that of reproducibility results. This problem becomes even more complex for the case of real time simulation when different simulation targets (i.e. hardware platforms) are considered. In this paper, comparisons between two simulators with different hardware architectures are presented. The targets compared are Opal-RT real time simulators with Intel Xeon quad-core processors and Kintex 7 FPGAs, and the Typhoon HIL 603 simulator with a combination of ARM R-class processors and Xilinx Virtex 6 FPGAs. For this comparison, standard power system components were implemented in these two environments, and simulation results from test models were compared. The current study reports the discrepancies and similarities between from the results obtained using the two platforms, and proposes a practical approach to reduce the differences found between results from both platforms. The work herein provides evidence on the need for the use of open standards for model exchange suitable for real time simulation.**

Keywords - Real time simulation, hardware-in-the-loop, power system modeling, power system simulation, Opal-RT, Typhoon HIL, FMI, model exchange

I. Introduction

A. Motivation

The increased sensing and need of networking of Information and Communication Technologies (ICT) to support 'smart grid' functionalities is transforming power grids into Cyber Physical Systems (CPS). In conventional power system modeling, the grid is represented as a time varying continuous system, updating its state continuously according to *physical laws*; while ICT systems follow *rules of algorithms* that are modeled with different formal isms, such as discrete equation systems, state machines, etc. The major challenge is the integration of models of ICT systems with those of the power grid, typically addressed through co-simulation, [14] and [15]. A complementary approach is the use of real time Hardware-In-the-Loop (HIL) simulation, where real-time simulators are used to model the behavior of an actual power system so to test 'real world' devices or an entire ICT system in HIL configuration. While the HIL approach is difficult to scale it provides an essential tool for development, testing and validation of 'smart grid' functionalities. In such case, the development of one of such functionalities is intrinsically dependent on a *specific* real time simulator, which opens the question: *will the functionality perform consistently if tested with a different real time simulator?*

In typical power grid digital real time simulators, the simulation executes in discrete time with a fixed step, while time moves forward an equal amount in 'wall-clock'. In order to achieve this, the simulator needs to solve the model equations for that fixed time-step, acquire external inputs, and send outputs to the hardware-in-the-loop within the same amount of time as in real life. Thus, the performance of the simulator depends on many factors including the hardware architecture, numerical technique used, and solver parameters (e.g. step size), to name a few. Studying the effect of different numerical techniques and step size can be carried out using a single real time simulator hardware, examples of such experiments are carried out in [6] and [7]. This paper, instead, apprises simulation results from two different hardware platforms and proposes possible design modifications on the model software side to obtain similar simulation results across these two different hardware architectures.

B. Related Work

Cross-platform comparisons have been carried out in other domains of electrical engineering. In the communication and networking domains an extensive study comparing various network simulators was reported in [1], where the authors compared the performance of various network simulators including ns-2, ns-3, OMNet++, SimPy, and JiST. In the area of Magnetics a similar survey was reported in [2], where the Rhombic Wire Simulator and the Harvard EMP Simulator were compared and analyzed. Meanwhile, only a limited number of published studies comparing real time simulators in the domain of power engineering have been carried out [4],[5], to the best of authors' knowledge. Although there are no cross platform analysis published, substantial work has been done on

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both the platforms (Opal-RT and Typhoon HIL) individually, by both vendors and users [1].

C. Contributions

- The current work provides a comparative analysis of how the two different real time simulators perform while simulating similar models and analysis scenarios. For an extensive comparison, basic power system component models (blocks) like synchronous machines, transformers, governors, induction machines and simple loads are considered in this work. All these blocks were implemented simultaneously in both Opal-RT 4520 and Typhoon HIL 603. The blocks are subjected to identical simulation scenarios and their responses were recorded and compared.
- Having verified the individual component models, they were used to construct identical power systems in the two different platforms and the response of those systems were recorded and compared.
- Additionally, some possible measures are proposed to minimize mismatches observed between the simulation results of the two simulators.

II. Review of the Simulation Platforms

In this section the basic architecture of the two representative real time simulation platforms are reviewed

A. Opal-RT 4520 Real Time Simulator

Opal-RT 4520 consists of 32 cores intel Xeon quad-core series processor and an array of 7 series Kintex FPGAs providing computational and I/O capabilities, respectively. Connectivity is supported with high speed fiber optical cables with a maximum transmission capability of 5MBit/sec. The schematics are designed using standard MATLAB/Simulink libraries and additional simulink libraries are provided by Opal-RT that enable model compilation and execution on the CPU cores and the FPGAs inside the OPAL hardware. In principle it is possible to simulate systems with a minimum time step of 250 ns in this architecture.

B. Typhoon HIL 603 Real Time Simulator

Typhoon HIL 603 Real Time Simulator consists both Xilinx 6 series Virtex FPGAs and ARM R-class Processors. The communication links are standard ethernet, and this system is capable of simulating systems reliably with a minimum time step of 1us.

III. Test Cases

In order to compare the two different real time simulators, different basic blocks for power system simulation were considered. In this paper, simple system models are designed to test an individual component, including synchronous generator, transformer, governor, induction machines and loads.

[1]There are studies comparing real time simulation tools with offline simulation tools like PSSE and RTDS [13], however, this is out of the scope and interest of this paper.

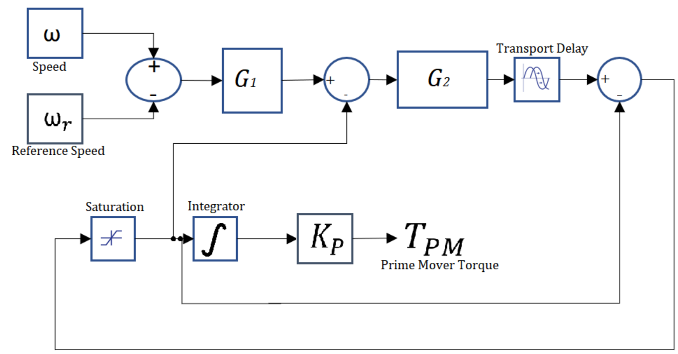

Fig. 1: Simplified Governor Model implemented using Typhoon HIL Schematic Editor

These 'unit-test' models were implemented in the two different platforms and their performances are compared. This part of the work is hereinafter referred to as **unit-testing**. After the successful unit testing, two power system models consisting of those tested units were simulated in the two platforms. These power system models are referred to hereinafter as **Microsystem** and **Microgrid**.

A. Components for Unit-Testing

1) Unit 1: Synchronous Generator: A 3 phase, 50MW, 20kV synchronous generator was implemented in both Opal-RT/ Simulink and Typhoon HIL Schematic. The parameters of that generator are given in the table below.

2) Unit 2: Transformer: A 3 phase 100 MVA Y-Y 20kV-230kV transformer with both primary and secondary resistance of 0.002 pu and inductance of 0.08 pu was tested in both the real time simulation platforms.

3) Unit 3: Induction Motor: A 3 phase 480V (line to line), 200 kW Induction motor was considered. The parameters of this induction motor are given in the table below.

4) Unit 4: Governor: For this block, the default single mass Tandem compound turbine governor system in the Simulink library was considered. To reduce complexity, all the turbine time constants except T_1 were set to zero, and the turbine torque fractions F_3 to F_5 were set to zero. The speed-and-govern system consists of a proportional regulator, speed relay and a servo motor controlling the gate opening. The associated turbine has a maximum of four stages, while each of them can be individually modeled as a first order transfer function. The detailed modeling of this block can be found in [3]. The simplified model that was used in this work is shown in Figure 1.

TABLE I: Synchronous Generator Parameters

D Axis Reactances	$X_d = 2.2$ $X_d' = 0.3$ $X_d'' = 0.2$
Q Axis Reactances	$X_q = 2$ $X_q' = 0.4$ $X_q'' = 0.2$
Stator Resistance	$R_s = 0.003$
Inertia Coefficient	$H = 2$
Leakage Reactance	$X_l = 0.15$

TABLE II: Induction Machine Parameters

Stator Resistance	$R_s = 0.029\Omega$
Rotor Inductance	$R_r = 0.029\Omega$
Stator Inductance	$L_s = 0.39965mH$
Rotor Inductance	$L_r = 0.39965mH$
Mutual Inductance	$L_m = 0.0346H$

5) Unit 5: Load: A simple constant impedance balanced 3 phase star connected load was implemented in both the simulators . Each phase has a resistance of 1 Ω and inductance of 1 mH.

B. Description of the Microsystem

The microsystem consists of a few of the unit-test models that were already implemented and tested in the first stage of this work. It is shown in Figure 2, that a synchronous generator (Unit 1) is followed by a step up transformer (Unit 2). The HV side of the transformer is floating, while the generator is operating at rated conditions. At time t, a star connected balanced load (Unit 5) is switched on across the HV side of the transformer. The generator is speed-controlled by the simple governor, that was modeled as described in the previous section. The transient behavior of the system during the switching of the load is analysed in the sequel.

C. Description of the Microgrid

This models consists of an 18 bus distribution network as shown in Figure 3. The induction motor used in this system is parameterized as the one used in unit-testing and is connected at bus 13.

IV. Simulation Results

It is to be noted, that for all the unit-tests and the microsystem, the authors simulated the Opal-RT models (which are also used in Opal-RT) as the reference and tried to recreate those simulation results in the Typhoon HIL platform. For

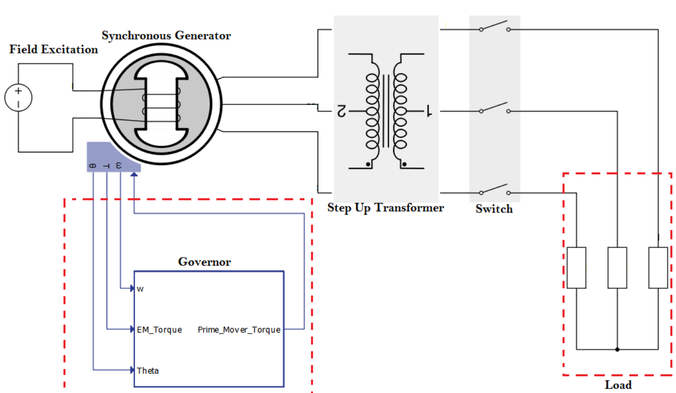

Fig. 2: Schematic of the Micro-system Developed in the Typhoon HIL Schematic environment (Red boxes represent the Governor model and the load model implemented as in Section III.A)

TABLE III: Simulation Settings

RT Simulator	Typhoon HIL	Opal-RT
Solver	Trapezoidal	Trapezoidal
Simulation Execution Step Size	2 us	2 us

Note: Step size is 2 us unless not explicitly mentioned

TABLE IV: Simulation Results for Model Load

Step	Typhoon HIL		Opal-RT		Theoretical	
	P(W)	Q(VAr)	P(W)	Q(VAr)	P(W)	Q(VAr)
4us	201771	76087	201686	76012	201729	76050
2us	201749	76068	201708	76031	201729	76050
1us	201739	76059	201718	76040	201729	76050

the microgrid example, however, the Typhoon HIL model was taken as a reference, and an identical system was modelled in Opal-RT to recreate the simulation results obtained from Typhoon HIL. The simulation specifications are mentioned in table III below. In order to compare both simulators fairly, the same discritization methods and simulation step sizes are chosen across the two simulators.

A. Unit Tests: Simulation Results

- Load: The load as described before, was connected to a fixed balanced 60 Hz, 480V three phase supply voltage, and the active and reactive powers consumed by the load is observed in the two different platforms, for different step-sizes. Observe that the two platforms present a small deviation from the theoretical results.
- Governor: The simplified mass-tandem governor is modeled in Typhoon HIL and its step response is compared to that with the step response of the model implemented in Opal-RT . Figure 4 shows that the responses match with negligible error and hence, the mass-tandem governor implementations are homogeneous in their responses.
- Transformer: The modeled transformer is subjected to its rated primary side voltage and the secondary side voltage is recorded for both simulation platforms. Figure 5 shows that the secondary voltage of the transformer model is the same in the two platforms.
- Induction Motor: The transient response for the induction motor is plotted in Figure 6. Both Opal-RT and Typhoon HIL results are shown in the same plot for comparison. It can be seen that the OPAL-RT does not undergo a oscillation as shown by the Typhoon model. In addition, the initial overshoot for OPAL-RT is lower. A subtle difference can be seen in transient response as well as the steady state value of active power consumption of the motor. These observations, however, are consistent with the results seen in the cross platform transient simulation of Microsystem in the next section.

  A corrective measure is proposed here in order to adjust the parameters in the OPAL-RT model in order to minimize the differences between both simulation platforms. The parameter estimation tool (PET) in MATLAB/Simulink is used. The motor behavior in Typhoon can be captured and imported to PET as a reference signal. PET adjusts and optimizes the motor parameters

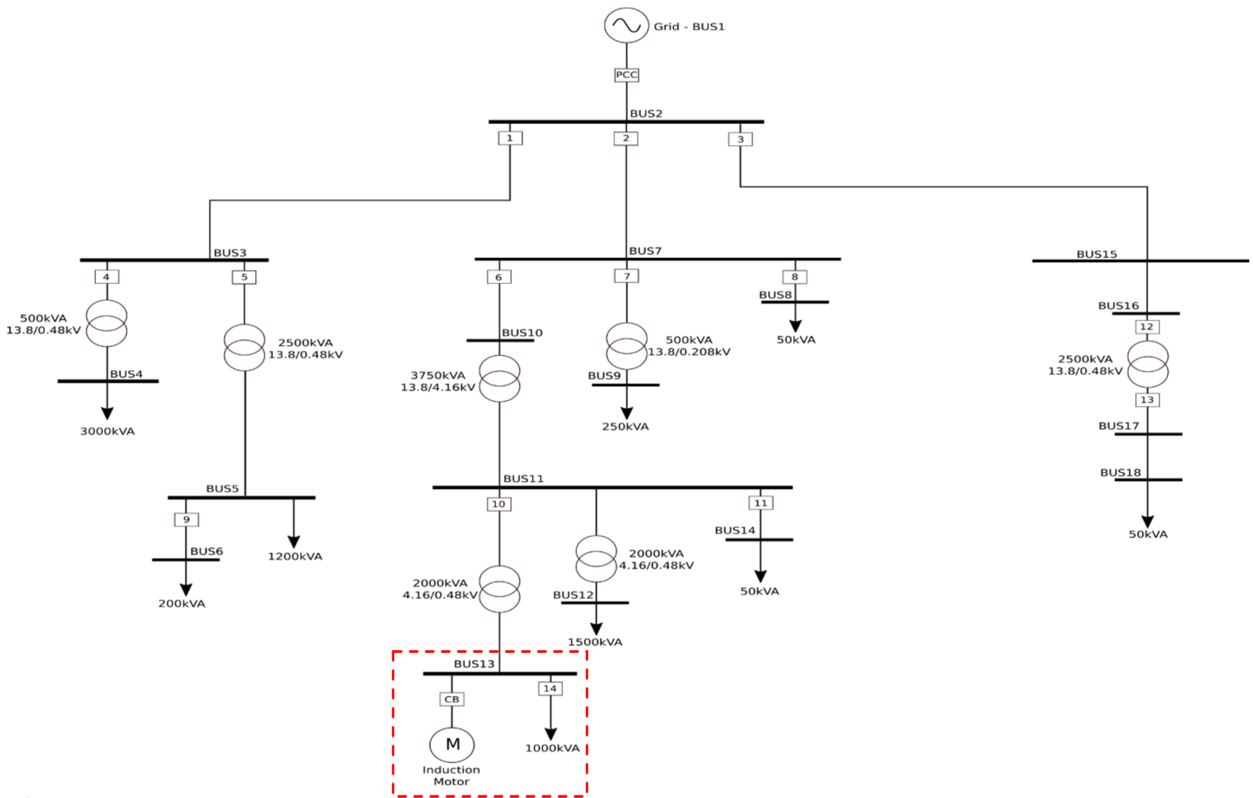

Fig. 3: Schematic of the Microgrid Developed in Typhoon HIL Schematic environment (the red box outlines the induction motor model described in Section III.A)

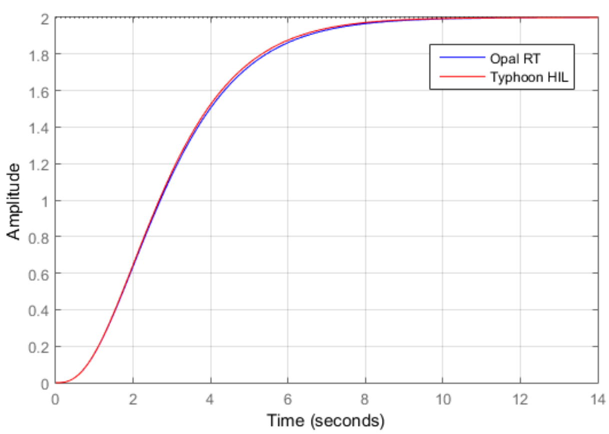

Fig. 4: Step response of the modeled governor

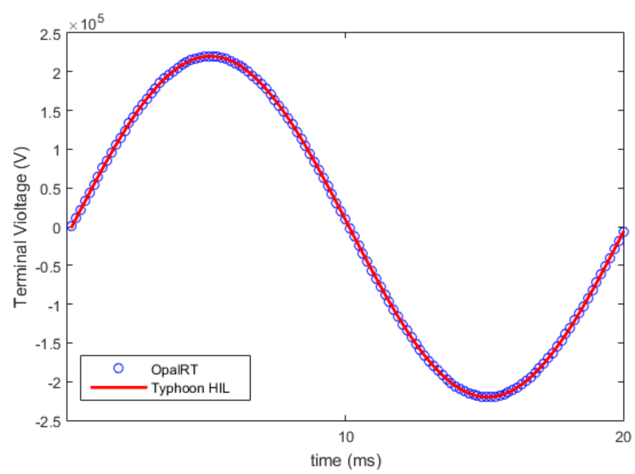

Fig. 5: Response of the transformer model while subjected to rated input voltage

of Opal-RT model to produce a similar response to the reference signal from Typhoon. The parameter calibration results are shown in Figure 7. From this analysis it can be concluded that modifying the snubber resistance helps reducing mismatches between the two real-time simulators.

B. Simulation Results for the Microsystem

A load switching scenario is now used to assess the overall power system model assembly and simulation results. The ratings of the transformer, and the synchronous generator selected are those mentioned in the section III. The load in section III is parameterized to represent a simpler three

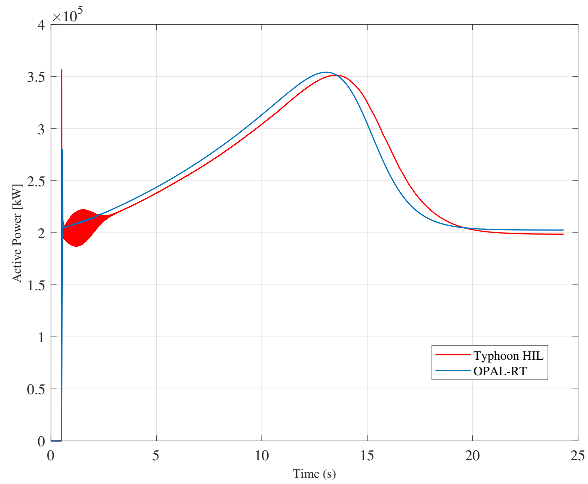

Fig. 6: Transient Response of the Motor

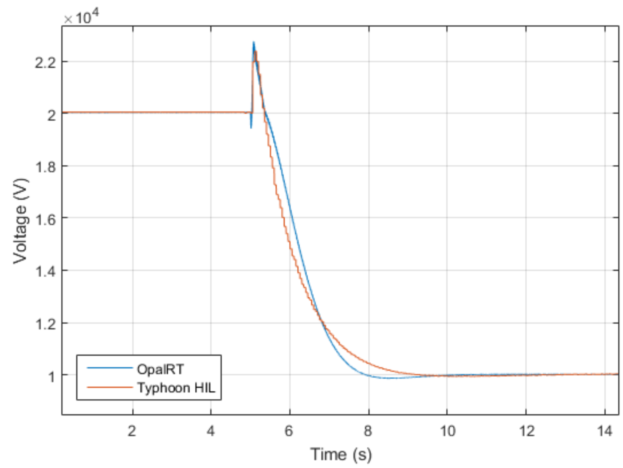

Fig. 8: Transient responses of the generator in the Micro-System

phase resistive load, so as to only consume active power. In Figure 4, at time t= 6s, a balanced resistive load of 35 MW is switched on. The resulting output of the synchronous generator is expected to decrease, as there is no feedback controller to maintain the speed in this simulation scenario. With these results, the outputs from both the platforms were investigated. Both simulators provided almost identical steady state response, but the transient responses were different. This is shown in Figure 8.

It is to be noted that the hardware architecture of Typhoon HIL is significantly different from that of the Opal-RT environment. The signal processing, measurement and monitoring blocks of the Typhoon HIL schematic runs with a time step of T_s, where as the FPGA based circuit solver runs on the FPGA cores with a step size of T_{exec}. In order to run the entire system with a universal step size, multiple rate transition blocks were introduced in the schematic. Even after that, the transient responses of the two simulation results remained different.

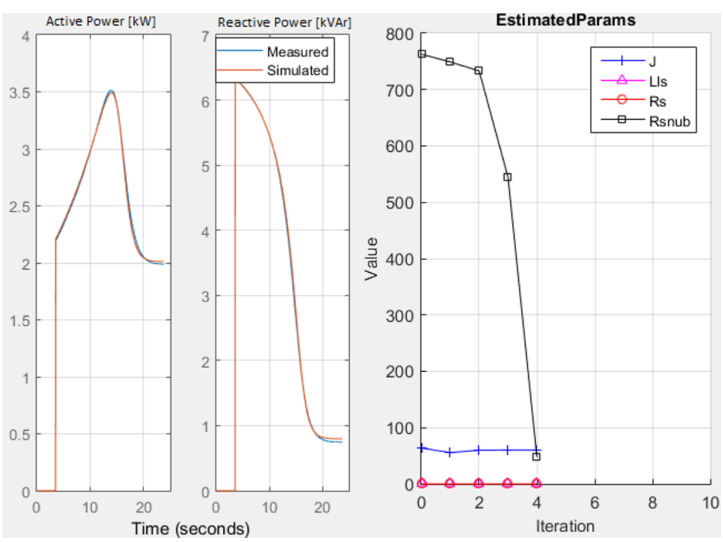

Fig. 7: PET parameter estimation results for J=Motor Intertia, L_{ls}=Stator Inductance, R_s=Stator Resistance, R_{snub}=Snubber Resistance

C. Simulation Results for the Microgrid

TABLE V: Results from Individual Buses of the Microgrid

	P(MW)	Q (MVAR)	P (MW)	Q (MVAR)
Injected Power	4.16	1.79	4.13	1.82
Bus Number	Voltage	Angle	Voltage	Angle
5	474.5	-30.42	473.87	-30.67
8	13753.13	-0.12	13753.14	-0.91
12	465.84	-61.75	466.12	-61.78
16	13793.07	-0.02	13785.16	0.02
	Opal-RT		Typhoon HIL	

Steady state analysis was carried out to investigate the differences for this system. The total active and reactive power injected from the main grid; voltages and angles at some buses are compared based on the equilibrium solution (i.e. when the simulation reaches a new steady state). These results are presented in Table V. Both platforms have to decouple the distribution network into sub circuits to be able to solve the differential equations of this system. In Typhoon HIL transformer-based decoupling (called coupling core) is used while in some cases small snubbers are used to improve numerical stability. OPAL-RT uses the state-space nodal solver (SSN) method for decoupling. The SSN method avoids numerical problems and gives more realistic results without the need of snubbers. [8] Five coupling cores and SSN blocks are used in Typhoon HIL and OPAL-RT respectively, to divide the whole system into 6 sub circuits in both platforms. To match the behavior of the Typhoon model, snubbers are added to the model in OPAL-RT based on similar analysis (PET) as explained for the induction machine earlier.

V. Discussions

Reproducibility of real time simulations across different platforms, using disparate software and hardware architectures, is a major challenge as illustrated in the experiments above. In these studies the major issues faced by the authors were:

- Modelling Coverage: It was observed that, certain Opal-RT blocks (e.g. governor) were missing in the Typhoon HIL Schematic library. Hence the user is required to create custom models in the Typhoon HIL environment which will be able to replicate the performance of those in other environments.
- Indiscriminate Simulation: Typhoon HIL provides the option to simulate using a solver called 'exact' method. On the other hand Opal-RT has multiple available methods to simulate a system, while none of them are as accurate as the 'exact' settings in Typhoon. The only option for fair comparison was to use the less accurate 'trapezoidal' methods in both platforms.
- Architecture Differences: The architecture of the Typhoon HIL uses two very different step sizes for simulation (T_s and T_{exec}). This requires to use additional rate transition blocks in Opal-RT. In practice, this makes it impossible to create two identical simulation conditions in the two different simulators.

VI. Conclusions and Future Work

This work is the first step towards 'homogeneous' modeling of power system components across different real-time platforms. The experiments reported in this work show how model portability and model exchange standards being adopted in other engineering fields, such as the Modelica language [10] and the Functional Mock-Up Interface [11], would be desirable for power systems simulation in general [9], but even more in real-time hardware-in-the-loop simulation to minimize modeling uncertainties. Currently, there are only two power system domain-specific tools that support the FMI standards, namely, Opal-RT's ePhasorSim[2] (only providing support for positive sequence models as a 'master' co-simulator solver) and EMTP-RV[3] (only as a 'master' co-simulation solver). As described in [11] model exchange faces tremendous challenges in conventional power systems tools used in off-line analysis, and thus, this paper aims to build the body of evidence documenting challenges with model portability for real time simulation where Modelica and the FMI standards can play a major role.

Because, only one type of solver was tested. with a single reasonable step size in all the experiments, it calls for a future exploration of the performance comparison with varying step size, and with different solvers. It is also needs to be noted that, in the presented experiments, none of the RT models are interacting with any physical hardware from the external world. Experiments with RT models interacting with real life external hardware are essential for further advancements in the area of cross-platform homogeneous modeling of power system components.

[2]https://www.opal-rt.com/wp-content/themes/enfold-opal/pdf/L00161_0304.pdf

[3]See: http://emtp-software.com/page/fmi-options

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