An Asynchronous Real-time Co-simulation Platform for Modeling Interaction between Microgrids and Power Distribution Systems

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***Abstract* — This paper presents the modeling framework of an asynchronous, real-time co-simulation platform for modeling the interactions between microgrids and power distribution systems. Components of each microgrid are simulated on the OPAL-RT eMEGASIM platform so that electromagnetic transients of the inverter units are modeled at a time step of 100 microseconds. The 3-phase unbalanced distribution feeder that microgrids are connected to is simulated by using the OPAL-RT ePHASORSIM so that load transients, capacitor switching, and tap-changing events can be modeled. A MATLAB-based microgrid controller will interface controllable microgrid components through the Modbus communication. This co-simulation framework allows different microgrid controller logic to be developed and tested on a hardware-in-the-loop testbed considering both the inverter-level transient and the dynamic response of loads and utility equipment. Because the controller communicates with controllable devices via actual communication links, the impact of communication errors, delays, or denial-of-service can also be properly quantified.**

***Index Terms* — asynchronous, co-simulation, distributed energy resources, OPAL-RT, hardware-in-the-loop, SIMULINK.**

I. INTRODUCTION

The integration of microgrids (MGs) significantly increases the flexibility, reliability, and resiliency of power system operation. Microgrids are usually powered by distributed generations (DGs), such as diesel generators, cogeneration through combined heat and power (CHP), photovoltaics (PV) systems. Other distributed energy resources (DERs), such as battery energy storage systems and controllable loads, are often used to assist DGs to maintain the power balance in normal operating conditions and achieve frequency and voltage stability during outages. Thus, the reliable operation of a microgrid depends on how different DERs control systems interact with each other under different operation modes.

On the other hand, when the penetration of microgrids increases, the interaction between microgrids and the main grids are becoming critical to the reliable operation of the main grid. This is because the switching transient of many small DERs and microgrid control systems may start to affect the main grid operation, causing stability and reliability issues.

Since different communication links may be used between microgrids and the main grid or inside a microgrid, it is increasingly important to account for the modeling of the communication network so that communication network failures, errors, and delays can be accounted for in such a complexed mix of control systems.

An approach known as the multi-rate simulation [1] offers significant advantages in the computer-based simulation of such large-scale dynamic electric power systems. Each sub-system can be simulated with the most appropriate time step and numerical integration method. This technique is developed based on system partitioning in which different subsystems can be distributed among the simulator agents and each subsystem can communicate through an efficient interface asynchronously or synchronously. Multi-rate simulation provides a particular advantage in real-time applications, where it is essential to complete each set of calculations in the allotted interval. Another simulation technique proposed for smart grid system is co-simulation. By combining distribution system simulation software such as OpenDSS [2] or GridLAB-D [3] with a real-time hardware-in-the-loop (HIL) simulation platform together, one can build a co-simulation platform that not only simulates the electromagnetic transient response of each DER within the microgrid but also address the aggregated impact of microgrids on voltage stability along a distribution feeder. Communication between microgrids or between different microgrid components and the distribution control center can also be modeled.

There are several co-simulation platforms presented in the literature. A power hardware-in-the-loop (PHIL) platform is developed where the JSON-link based communication protocol is utilized to interact with a remote physical device [3]. A real-time co-simulation platform is built based on OPAL-RT and OPENT that varied communication issues can be evaluated [4]. A testbed using HELICS framework to coordinate different simulator agents is demonstrated in [5].

The primary contribution of our paper is the introduction of a novel asynchronous co-simulation framework that co-simulates transmission, distribution, microgrid, and all the way down to each DER. Due to the page limit, we will only introduce our benchmark co-simulation platform, which is built using IEEE test systems. The IEEE 118-bus system is used for modeling the transmission grid and the IEEE 123-node feeder is used to model the distribution grid. Both are modeled on the OPAL-RT ePHASORSIM platform. Our microgrid models are developed and validated using field data collected from a testbed operated by Total Inc. in Lyon, France.

II. System Modeling

In this section, we outline the system modeling and coupling for transmission, distribution and a detailed microgrid system.

A. Transmission and Distribution System Modeling

The ePHASORSIM, a model-based time-series simulation tool that capable of solving unbalanced three-phase power flow and dynamic simulation, is used to simulate the transmission and distribution system. The core of ePHASORSIM solver is that it can link different models which are developed in other professional software, such as PSS/E or CYME, and execute the models in the SIMULINK environment with a real-time fashion. The advantages of this particular co-simulation setup over other existing circuit-based simulators are twofold. First, it takes advantage of the robustness of professional software packages (e.g. PSS/E and CYME) and can import utility network models directly. Second, once connected those network models to an HIL platform, one can connect to it with external controllers, protection relays, or microgrid hardware components for testing the interaction among those devices.

As shown in Fig. 1, the IEEE 118-bus system imported from PSS/E is used as the transmission system; the IEEE 123-node system is created in CYME and used as the distribution system. Since the bus voltage and phase angle are transferred from the positive-sequence equivalent transmission model to a three-phase distribution feeder head, we assume the feeder head has identical voltage for each phase. The phase angle of Phase *a* is set as the angle value received from the transmission simulation and, therefore, other phases then can be calculated. Because transmission spot loads are modeled as the constant impedance load, the equivalent admittance at the distribution feeder head is then fed back to the transmission system synchronously.

B. Microgrid Modeling

Since the simulation step (100μs) for the downstream system is relatively large compared to the general FPGA-based power electronics device model, an AC-bus MG system using the average models based on SIMULINK and eMEGASIM is developed for the proposed platform [6]. This microgrid is a part of the distribution system and operates at 120V/60Hz. It is connected to the distribution grid using a 2.4kV/120 V step-up transformer. There are three DGs in the microgrid: a lead-acid battery system and inverter, a PV array and inverter, and a diesel generator, as presented in Fig. 2.

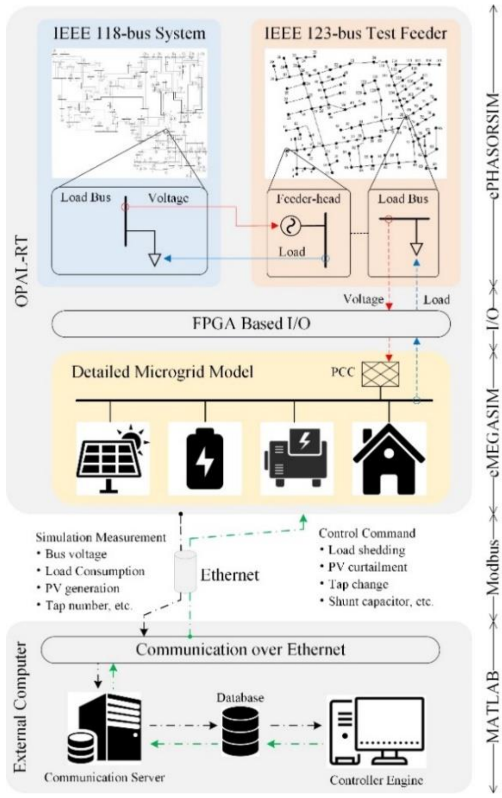


Fig. 1. Co-simulation platform architecture

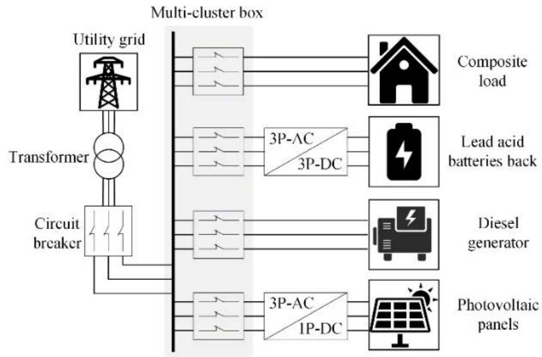


Fig. 2. The configuration of the microgrid model

The PV array is connected to the microgrid through a three-phase inverter employing the maximum power point tracking (MPPT) control scheme. The lead-acid battery is modeled using the equivalent circuit model [7] and connected to three inverters which operates as a controlled current inverter for each phase when grid connected or generator operated, but its control strategy is switched to controlled frequency voltage source when the microgrid operates as an islanded grid and the generator also is disconnected. The diesel generator is modeled as a synchronous machine with a governor for frequency control. The microgrid load is modeled as a 3-phase unbalanced composite load peaking at 30kW.

C. System Spatial Coupling

The proposed co-simulation platform enables a closed-loop simulation for the electric power system from transmission and distribution grids all the down to individual DER devices. Each control system has its own control and modeling time steps. We implemented a multi-rate technique so that different parts of the system are modeled separately and connected via equivalent links. As shown in Fig. 1, the distribution feeders are connected to the transmission network as transmission load buses; MG systems are attached to distribution system as load nodes. At each point of common coupling, we place a 60-Hz AC sources to represent the upper system such that the voltage magnitude and phase angles captured from the upstream transmission or distribution system are passed on to the lower part of the system. The load consumptions of the lower systems are passed back to the upper systems as shown by the blue arrows in Fig. 1. Because this platform is developed for dynamic simulation, the load measurements is acquired based on the load type in the upstream system. For example, when a distribution load node is modeled as a constant impedance load, the load measurement is the equivalent admittance of downstream MG system.

The co-simulation platform conducted for this research utilized the Modbus protocol over Ethernet to implement the closed-loop connection between the software models and external physical equipment. This method offers the advantage of being one of the easiest and straightforward ways to implement and can exhibit the stable communication. As the dash dot lines shown in Fig. 1, a communication server is built to record the simulation results, and then an external controller can use these data to perform control strategies and send the control command back through the server.

D. System Temporal Coupling

A successful co-simulation platform consisting of multi-rate subsystems that require time synchronization between different simulation packages during the entire runtime. Existing co-simulation platforms usually connect different software or systems using an external Application Programming Interface (API) as a coordinator, such as HELICS [5].

In the proposed co-simulation platform, different systems are first imported or created in RT-LAB and SIMULINK. Then, they are executed as real-time discrete simulation. Fig. 3 illustrates how to coordinate the simulation among three modeling systems: transmission, distribution and microgrid. As shown in the Fig. 3, both the transmission and distribution systems are modeled in a module using ePHASORSIM with a simulation time step 10ms. Since the transmission system is driven by the distribution system, there are no calculation delays when passing data from the distribution system to the transmission system. However, the microgrid model is built in another module using the eMEGASIM with a simulation time step 100µs. Thus, a communication buffer is inserted between the distribution model and the microgrid models, and there will be a calculation delay before the results of the distribution model or microgrid model can be received by the other. As shown in Fig. 4, we defined "A*i*" for the Arrow *i* and we model the impact of a fault happened in the transmission system on distribution and microgrid operation as an example to illustrate how the co-simulation platform couples the modeling of three different systems together.

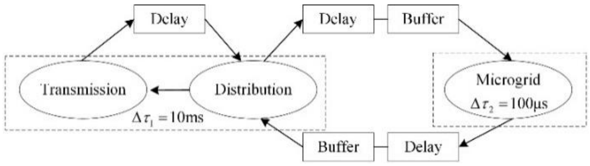


Fig. 3. State transition flow chart

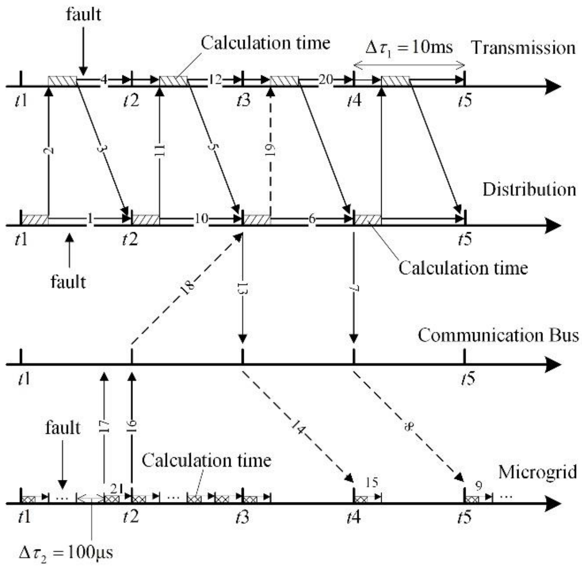


Fig. 4. Temporal coupling between transmission, distribution, and microgrid.

At the beginning of time t_1, which is the time step right before the fault happens, the distribution system and microgrid system simulation start with their initial conditions. The distribution simulation results (A2) are immediately sent to the transmission system as its initial condition. Note that there is no calculation delay. After transmission simulation is completed, the results (A3) will be sent back to the distribution system right before the next simulation time step t_2 starts.

Between time t_1 and time t_2, if a fault happens at the transmission system. The distribution system model still use the transmission model results (A3) as inputs to complete its pre-fault simulation and pass the results (A11) to the transmission system. The transmission system will now calculate the after-fault conditions based on the fault and the results (A11) sent by the distribution model. At the beginning of time t_3, the distribution system will receive this after-fault transmission simulation result (A5) and calculate the associated impact. The after-fault results (A6) of the distribution system will be passed to the communication link (A7) and wait to be sent to the microgrid systems. Due to the communication delay, which is a constant 10ms in this paper, the microgrid will receive the distribution system after-fault results (A8) at the beginning of time t_5, and microgrid will calculate it operation status (A9).

Thus, from the fault happens at transmission to the impact is considered by the microgrid model, the simulation as least advanced four different time steps (A5-A6-A8-A9). Note that the simulation time step of the transmission and distribution model is 10ms and the microgrid simulation is 100μs, while the time delay for communication is 10ms. Therefore, the total time delay for spreading a simulation result from the transmission model to the microgrid model is about 30.1ms.

If a fault happens to distribution system between time t_1 and time t_2, the distribution system and transmission system may still calculation the pre-fault simulation at time t_2 using the initial conditions (A1 and A4). At the beginning of time t_2, the distribution system now calculate the after-fault conditions (A10) based on the fault and the pre-fault results (A3) from the transmission system, and both them will get the after-fault result (A10 and A12) right before time t_3. The after-fault results (A10) of the distribution system will be passed to the link (A13) and wait to be sent to the microgrid. After the communication delay, the microgrid receive the distribution system after-fault results (A14) at the beginning of time t_4, and microgrid will calculate its associated operation status (A15). Thus, from the fault happens to distribution system to the impact is considered by the microgrid model, the simulation as least advanced three different time steps (A10-A14-A15) which is about 20.1ms.

When a fault or event happens to microgrid system between time t_1 and time t_2, the microgrid system may use the initial condition to calculate the pre-fault results first and then at the time step that right after the fault happened, the microgrid system will start to calculate the after-fault conditions based on the fault and the previous status. The after-fault results of the microgrid system will be passed to the communication link (A16 and A17) and wait to be sent to the distribution systems. At the beginning of time t_3, the distribution system start to calculate the after-fault conditions by only using the latest simulation results (A18, which is A16 before transferring by the communication link) from the microgrid, and both distribution system and transmission system will get the after-fault results (A6 and A20) right before time t_3. The time cost from the event happens to microgrid system to the impact is considered by the transmission model is at least about 20.1ms (A21-A18-A20).

We summarized the system impact propagation delay, which is defined as the time cost for spreading the event impact from the original system to another system, in Table I.

TABLE I. SYSTEM PROPAGATION DELAY

		To		
		Transmission	**Distribution**	**Microgrid**
From	**Transmission**	10ms	20ms	30.1ms
	Distribution	10ms	10ms	20.1ms
	Microgrid	20.1ms	20.1ms	0.1ms

III. CASES STUDIES

In this section, we use three cases to demonstrate the performance of the proposed co-simulation platform.

A. Case Studies 1: System Benchmarking

We first conducted a series of benchmarking tests by comparing the simulation results obtained by the OPAL-RT based HIL test system and the results obtained on an IEEE test system. The first benchmark test is conducted by using the IEEE118-bus system (serving as our transmission system model). We converted the constant power load into constant impedance loads and ran the system on the ePHASORSIM platform. The simulation results are compared with the results obtained by running the 118-bus system on PSS/E [8]. The second benchmark test is conducted using the IEEE 123-bus test feeder model (serving as our distribution system model) developed in CYME and ran on the ePHASORSIM platform. We compared the node voltages calculated with those in the IEEE standard test report [9]. As shown in Fig. 5 and Fig. 6, the OPAL-RT simulation results match the benchmark data very well and the maximum deviation is less than 0.01p.u. The error of distribution system may be relative larger since we convert the regulator to controllable transformer in our CYME model.

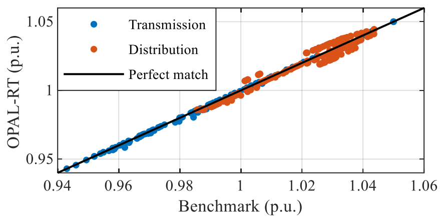


Fig. 5. Comparison between OPAL-RT model and IEEE standard model

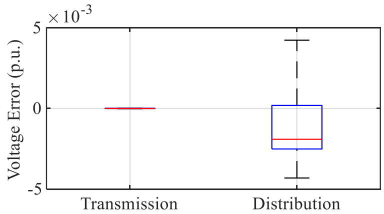


Fig. 6. Boxplot for the model deviation

B. Case Studies 2: Transmission Fault Analysis

A combined test is conducted by using the proposed co-simulation platform. It is assumed that the test feeder is connected to Bus 102 of the 118-bus transmission system, while a 30 kW microgrid is connected to Node 47 of the 123-node distribution feeder system. A three-phase-to-ground fault is placed on the line between Bus 92 and Bus 94 at 5s on the transmission system. The fault is cleared after 0.01 second.

Since the transmission is driven by distribution system and they are modeled within one single module, therefore, they are synchronously linked and there is no communication delay between them. The distribution voltage will be updated after one calculation time step, as the red line shown in Fig. 7. However, due to the computation and communication delays, the voltage at the microgrid point-of-common-coupling (PCC) will start to react the fault after 30.1ms.

When the microgrid PCC protection breaker detects the unusual grid voltage, it tries to protect microgrid components by disconnecting the microgrid from the external grid. As shown in Fig. 8, since the substation system is simulated with a higher resolution and more dynamic responses can be observed. The battery is operated at the standby mode before 5.03s because we start with a low battery state-of-charge, and the loads will be supported by the grid and photovoltaic array. The microgrid starts to respond the transmission fault at 5.031s and the grid power will drop down to zeros after 0.01 second. The battery power jumps up immediately and it picks up the load together with PV module.

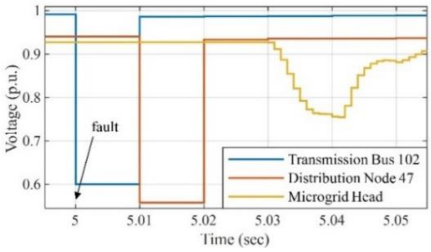


Fig. 7. The propagation delay over the voltage

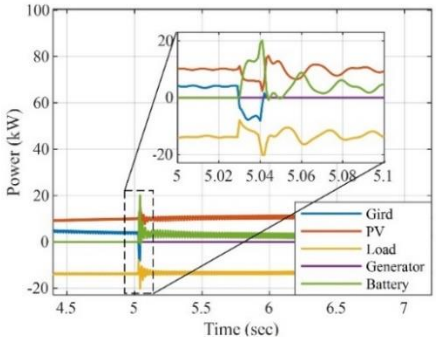


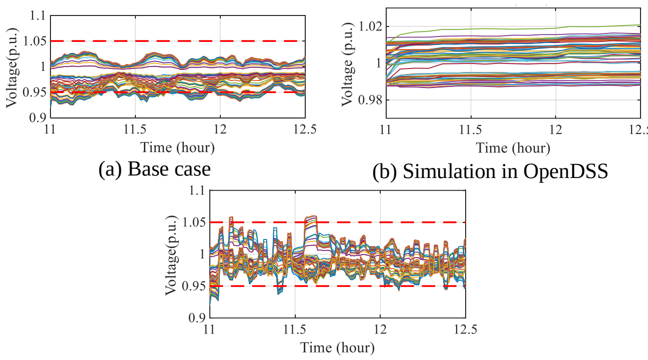
Fig. 8. The active power of different component within the microgrid

C. Case Studies 3: Distribution Volt-Var Control

The proposed co-simulation platform is utilized to test a online distribution Vol-Var controller whose control objective is to limit the distribution system voltage within the allowed range for each time step by controlling the loads, regulator tap number, capacitor status, and the active power and reactive power of the smart PV farms. Fig. 9 shows that the distribution voltage may violate the allowed boundary under the base case and we can achieve ideal control if we implement the controller in OpenDSS standalone. When we connect the controller to the proposed co-simulation platform through Modbus link, we can achieve HIL simulation and the it show the communication delay has a huge impact over the controller performance.

IV. Conclusion

In this paper, we presented the setup of an OPAL-RT based real-time co-simulation platform that couples the simulation of transmission, distribution, and microgrid systems all the way down to each DER. The computational delay and the communication delay will cause the simulation to be out-of-synchronization if two systems are modeled on different HIL platforms and communication links are modeled. In this paper, we demonstrate the existence of those delays and quantified their possible impacts. Although those out-of-sync events are predictable and are short-lived, they may cause controllers to fail if not properly handled, one need to use precaution when developing and testing controllers on the co-simulation platforms. Due to the page limit, we did not include the detailed discussion on controller design and evaluation. In our follow-up paper, we will discuss how to use the platform to design and develop the voltage regulation methods that coordinates resources at both the transmission and distribution levels.



(c) Co-simulation between OPAL-RT and OpenDSS
Fig. 9. IEEE 123-node system voltage under different cases

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