Co-Simulation Architectures and Communication Interfaces for HIL-based Large-scale Power System Simulations

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***Abstract*—Co-simulation is a powerful technique for managing the computational demands of large-scale power system simulations. This paper introduces a robust co-simulation architecture and a set of communication interfaces designed specifically for hardware-in-the-loop (HIL) based large power system applications, addressing key challenges in data exchange and synchronization across diverse co-simulation scenarios. The framework categorizes co-simulation into *local* and *remote* scenarios based on whether sub-systems are connected within a single local area network (LAN). In the local scenario, characterized by low-latency communication, co-simulation integrates electromagnetic transient (EMT) and phasor domain modeling within a single power network and enables interaction with local control centers. In contrast, remote co-simulation scenarios—where long geographic distances create data exchange challenges—utilize sharing file and VPN-based TCP/IP communication to manage various latency requirements. Using OPAL-RT as an example of the real-time power network simulator, extensive testing validates the co-simulation and communication interface performance, demonstrating reliable functionality across diverse applications.**

Index Terms -- Co-simulation architecture, power system simulation, HIL, data exchange, communication latency, local and remote co-simulation, synchronization.

I. Introduction

Due to the large-scale integration of distributed energy resources (DERs) and inverter-based resources (IBRs), power systems continue to grow in scale and complexity. The need for accurate and efficient large-scale simulations has become essential to ensure grid stability, reliability, and optimal performance. Modern power system simulations encompass both static and dynamic analyses across transmission and distribution networks. To study the impact of DERs and IBRs on system transients and stability, dynamic simulations are usually needed. However, these dynamic simulations with power electronic devices demand substantial computational resources, especially the real-time hardware-in-the-loop (HIL) system-based simulations, which can strain conventional modeling approaches.

Co-simulation has emerged as a promising solution to address these challenges by integrating multiple sub-systems within a unified simulation environment. This approach allows for diverse modeling domains to operate concurrently, offering a comprehensive perspective on complex system interactions. Key advantages of co-simulation include streamlined integration of varied subsystems and facilitation of system development through modular, scalable simulation capabilities. Despite these benefits, co-simulation introduces challenges related to data exchange, synchronization, and communication among different resolution and timescale sub-systems, all of which are crucial to ensure simulation accuracy and reliability.

Depending on the application scenario, different co-simulation can be applied to the simulation of power system modeling. In [], the device level co-simulation of different domain models, such as the Electromagnetic (EMT) and phasor models, are discussed, where . In [], the co-simulation of network level (T&D) are investigated to study the interaction caused by the integration of IBRs. Besides, co-simulation between the power network and its energy management system is also needed to mimic a practical system. Communication latencies are inevitable for co-simulation. The requirement on the date exchange among subsystems varies. Different methods can be applied for. The co-simulation and communication modeling is also important for cybersecurity analysis.

To address these challenges, we investigated different co-simulation scenarios for smart power systems and developed a comprehensive co-simulation architecture and a set of communication interfaces based on the HIL platform OPAL-RT. Our research categorizes co-simulation into two primary scenarios: local and remote. Local co-simulation is designed for scenarios where subsystems operate within a shared environment, typically connected via a local area network (LAN), enabling low-latency communication. This setup is ideal for applications such as device-level of different domain simulations within a transmission or distribution network or co-simulating power networks with local control systems.

Conversely, remote co-simulation enables simulations across geographically dispersed locations, facilitating collaboration between teams and systems located at different institutions. In these scenarios, high latency and network constraints become significant challenges, necessitating robust communication interfaces. For instance, our work explores remote T&D co-simulation use cases between North Carolina State University (NCSU) and Clemson University, employing solutions such as VPN-based TCP/IP and file-sharing methods to enable data exchange despite the physical separation of systems.

This paper presents a comprehensive co-simulation architecture and communication interface solution tailored to both local and remote scenarios, with rigorous testing conducted using OPAL-RT as the real-time power network simulator. Our results highlight the architecture's capability to manage data exchange, synchronization, and varying communication latencies, validating its performance for a range of applications in large-scale power system simulations.

II. Local and Remote Co-simulation Testded

In this section, we introduce the local and remote co-simulation testbed setup for power network modeling.

A. Local Co-simulation

1) Power Network and Control Center Co-simulation

Fig. 1 illustrates a hierarchical local co-simulation framework for power system simulations, integrating a microgrid control system, an application interface, and real-time simulation. We adopt OPAL-RT here for the real-time simulation of power networks. The Real-time Simulation involves device models, device-level controllers, network models, communication, and protection systems, operating at a fast simulation rate (from microsecond (µs) to millisecond (ms)). This layer replicates the physical power system components, including DERs such as PV and battery energy storage system (BESS) units. The real-time simulation enables detailed and dynamic analysis of network behavior under various operating conditions, supporting high-fidelity simulation of events at the power distribution level and facilitating precise system response testing.

The Microgrid Control System performs high-level functions such as energy management, Volt/VAR control, and frequency regulation, with control actions executed at intervals ranging from 5 to 30 minutes. This system monitors the overall performance and stability of the grid, adjusting parameters based on real-time data and optimizing the grid's operation.

The Application Interface serves as the communication bridge between the control system and real-time simulation, utilizing Modbus and TCP/IP communication for data exchange. This layer manages data processing and database management, facilitating measurements and control signals between the OPAL-RT simulator and the control center. The interface agent processes control signals from the control center and relays them to the real-time simulation environment, enabling accurate control and monitoring. Depending on the specific application, the Application Interface process data from second to minute level.

2) Electromagnetic(EMT) and Phaosr Dodomain Co-simulation for Power Networks

For the electrical device modeling in power networks, there are usually two options: electromagnetic transient (EMT) domain and phasor domain models. EMT models are usually at µs level, which includes magnitude and frequency information. Phasor models are at ms level, which doesnot have frequency information. In comparison, EMT models provide higher modeling accuracies, especially fit for the

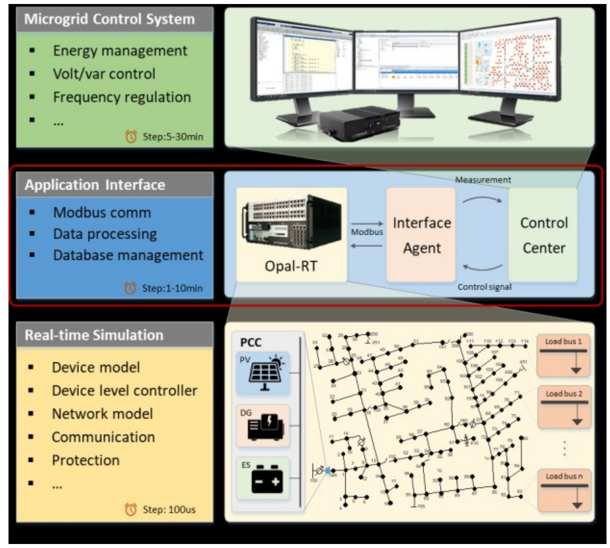


Fig. 1. Layout of the local distribution co-simulation testbed.

detailed dynamic behavior of power electronics, protection devices, and rapid switching events. Phasor models are suitable for capturing the steady-state behavior and slower dynamics of power systems. However, EMT models also require higher computational cost.

To evaluate the integration impact of IBRs and considering computation cost, we adopt the co-simulation of EMT and phasor models. Fig. 2 presents a hybrid co-simulation framework integrating simulations for the power system with different IBRs. The framework is divided into two main sections: eMEGASIM and ePHASORSIM, which are two simulation tools for EMT and phasor time-series models.

In the eMEGASIM domain, a high-fidelity EMT model simulates the detailed dynamic behavior of individual components within a microgrid. This includes high-power PV plant, BESS, diesel generator, and grounding transformer, all connected at the point of common coupling (PCC). The EMT simulation operates at a fast timestep of 100 microseconds to capture rapid transient effects. EMT-TS coupling enables the interaction between EMT and phasor models through a "Phasor to Waveform" and "Waveform to Phasor" interface, allowing current and voltage signals to be exchanged and synchronized across domains, facilitating real-time data transitions.

In the ePHASORSIM domain, a phasor model of the IEEE 123-node test feeder represents the broader power distribution network. This model includes rooftop PVs and dynamic ZIP loads, capturing slower dynamics and steady-state interactions within the network. The phasor simulation operates at a timestep of 10 ms, providing a computationally efficient way to simulate the larger-scale system. Feeder currents and PCC voltages are exchanged between the EMT and phasor domains, ensuring coordinated operation across the hybrid simulation.

This coupling between detailed EMT models and phasor-domain representations allows for an accurate and scalable analysis of interactions between local microgrid dynamics and the broader power distribution network, balancing high fidelity with computational efficiency.

The detailed data conversion between EMT and Phasor can refer to the paper that we published before.

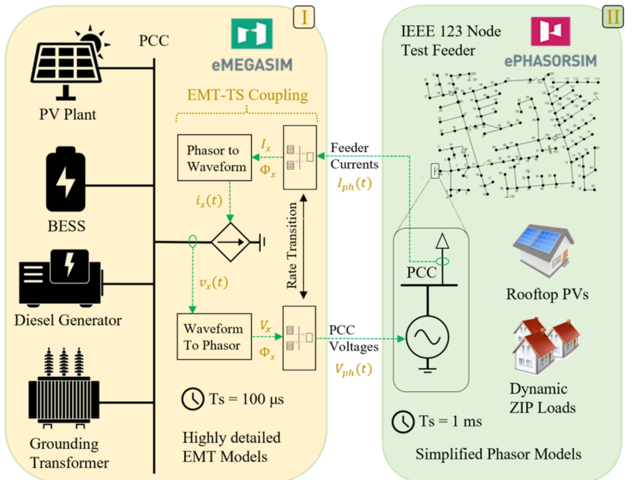


Fig. 2. Co-simulation of EMT and phasor models for power network modeling on OPAL-RT

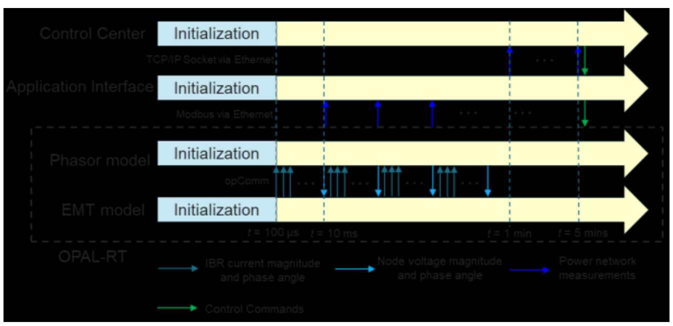


Fig. 3. Time sequence of the local co-simulation testbed

B. Remote Co-simulation

In large-scale power system simulations, sub-systems like control centers, generation sites, and distribution networks are often geographically separated, creating challenges for real-time or near-real-time data exchange. Effective remote communication with suitable latency is essential to synchronize these distributed components for accurate simulation. Communication channels must provide sufficient bandwidth, speed, and reliability, with different latency requirements based on data type—low latency for critical control signals, and tolerable latency for less time-sensitive data. Careful configuration of this infrastructure helps maintain accuracy by minimizing delays and data loss. To address the communication challenges in remote co-simulation, Sharing-file based and VPN-based approach are implemented.

1) Sharing-file based Approach

The file-sharing-based approach involves creating a shared file accessible by all subsystems for coordinated data exchange. In our setup, we use Google Drive as the shared medium, as illustrated in Fig. 4. The interface agent in the local system gathers measurements from the local OPAL-RT simulator and writes the new data to the shared file. Simultaneously, the agent reads any incoming data updates and transmits them back to OPAL-RT. The updated file is then uploaded to the Google Drive server, where it syncs across all remote subsystems. This allows each remote subsystem to access the shared file, retrieve the latest measurements, and incorporate the newly available local data into their respective simulations. All reading and writing process can be automated with Python scripts.

The latency in this file-sharing method includes time for data processing tasks such as loading, reading, writing, and saving, as well as the time required for Google Drive to sync the file across servers. Based on our tests, it usually needs 500 ms to read and write 15000 16-bits number data. It usually takes about more than 5 seconds for the Google Drive to synchronize data.

Additionally, simultaneous access by multiple subsystems may lead to conflicts, such as overwriting or data loss, if multiple systems attempt to access and modify the shared file at once. To mitigate this, coordinated access scheduling is required to ensure that different subsystems access and process the file sequentially, reducing the risk of data conflicts and ensuring reliable data updates. This introduces more latency for data exchange.

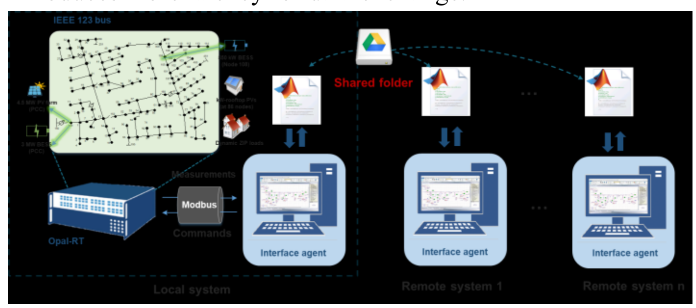


Fig. 4. Google drive sharing-file based remote co-simulation

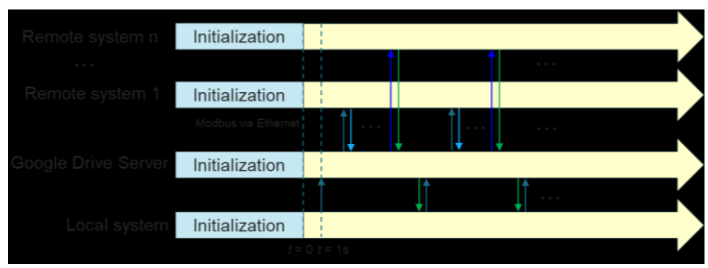


Fig. 3. Time sequence of the local co-simulation testbed

2) VPN-based Approach

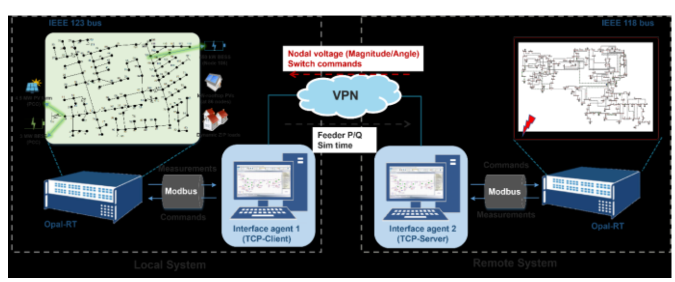


Fig. 5. VPN-based remote co-simulation

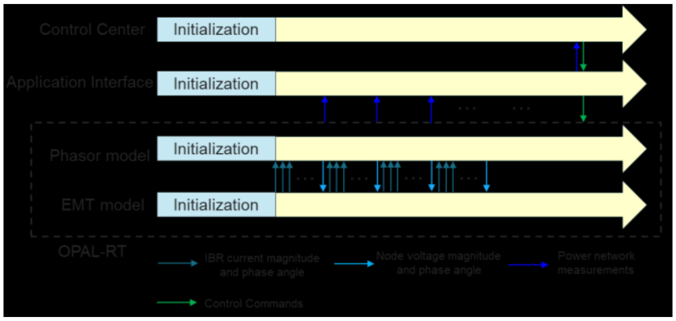


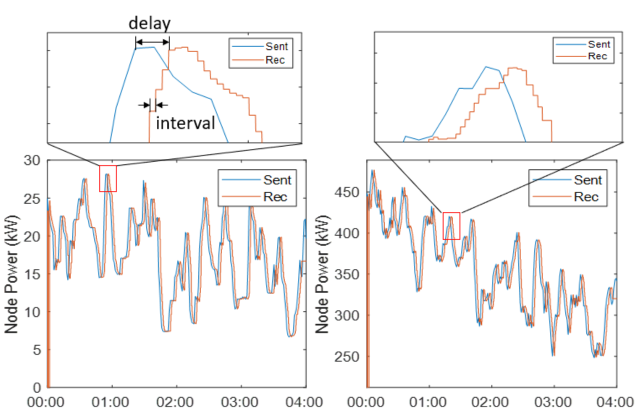
Fig. 3. Time sequence of the local co-simulation testbed

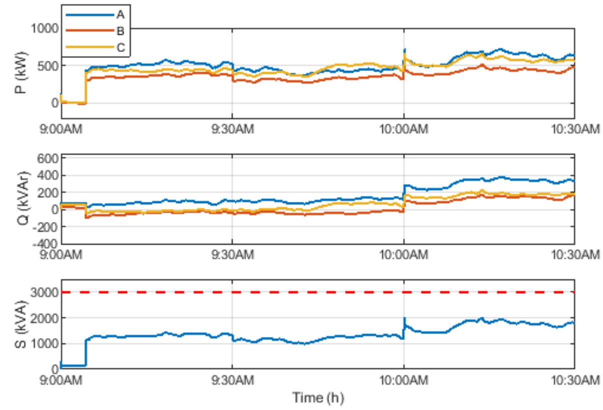
In this setup, a Virtual Private Network (VPN) establishes a secure, encrypted connection between remote and local systems. By creating a private communication channel over the internet, VPNs enable geographically distant systems to interact as if they were on the same local network. This connectivity allows seamless data exchange and control between co-simulated components, facilitating real-time interactions necessary for large-scale power system simulations.

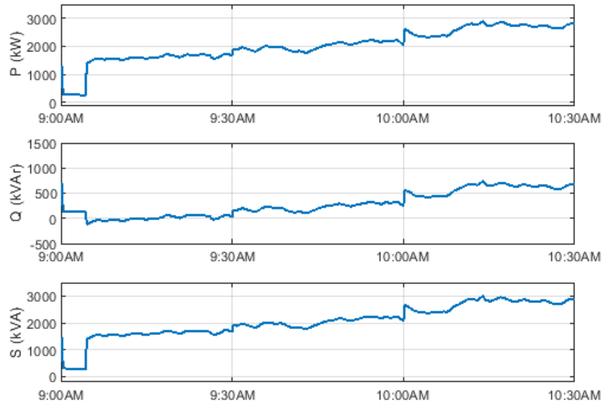
The VPN-based approach provides relatively fast communication, with an average delay of approximately 20 milliseconds. This speed is sufficient to support remote co-simulation applications where low-latency data exchange is essential, allowing the remote and local systems to synchronize effectively. This is especially important for applications where timely response to control signals or data updates is critical to the stability and accuracy of the simulation.

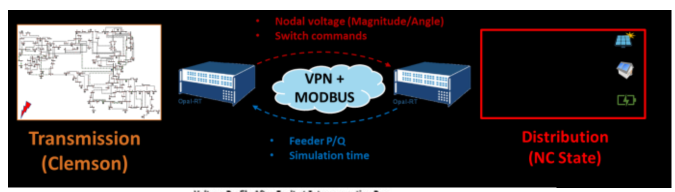
To establish the VPN connection, remote systems must have authorized access, requiring VPN credentials and necessary permissions from the network administrator. In addition, firewall configurations must allow VPN traffic, ensuring secure data transmission across organizational or public networks. These requirements may necessitate additional administrative setup, such as configuring firewall rules and user permissions, but they help maintain network security and protect against unauthorized access.

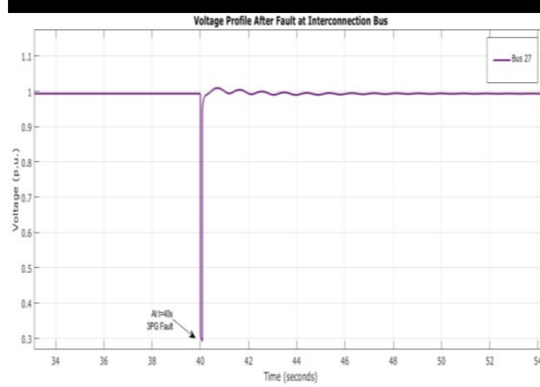
III. Simulation Results

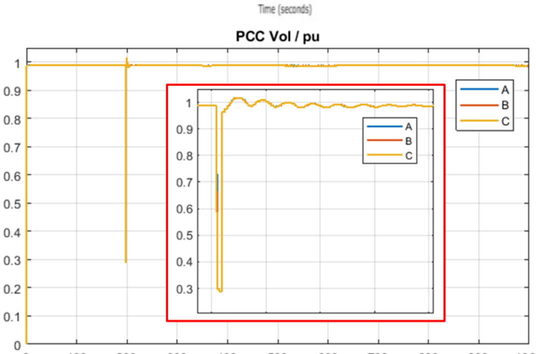












IV. CONCLUSIONS

In this study, we conducted a comprehensive analysis of the influence of different types of transmission faults on a distribution feeder with high IBR penetration. We modeled different transmission fault locations and types, distributed IBR locations and types, and various IBR PLRs. The integrated T&D model is co-simulated on the OPAL-RT real-time simulation platform, where 3-phase IBRs are modeled in the EMT domain and 1-phase IBRs are modeled in the phasor domain.

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