Overview of HIL Co-simulation for Very Large Distribution Systems and Power Electronic Converters with a DC Fast Charging EV Benchmark Study on an IEEE Test Feeder

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***Abstract*—Current development towards implementation of the future smart grid includes advanced controller and power hardware-in-the-loop (CHIL/PHIL) testing of new technology. The impact of new loads, distributed energy resources (DER) equipment, and controls spans two fields, both electric distribution power systems modeling, typically completed in the phasor domain, and electromagnetic transient (EMT) analysis across the frequency domain. The co-simulation of distribution power systems and power electronic converter controls is a growing field of research for improved design using real-time HIL capability. Within this paper, over fifty references are reviewed to summarize the current state of HIL technology, specifically with co-simulation in laboratory facilities and testing. Additionally, a methodology for "weakly" coupling very large distribution systems with power electronic models through co-simulation is proposed and applied for DC fast charging of electric vehicles (EVs) in a benchmark case study on the IEEE 8500-node test feeder.**

***Index Terms*—Hardware-in-the-loop (HIL), Software-in-the-loop (SIL), Electric Vehicles (EV), Electromagnetic transient (EMT), Quasi-static time series (QSTS), Smart grid**

I. Introduction

Wide-spread research is being conducted to design and test new smart grid configurations including behind-the-meter (BTM) controls, battery energy storage systems (BESS), and distributed energy resources (DERs) [1]. It is a growing field of research to quantify and analyze the effects and benefits of these technologies using advanced real-time and hardware-in-the-loop (HIL) co-simulation of power electronic converters and electric distribution systems for improved integration and effectiveness. To ensure reliability, emulation of controls, impact on power quality, and Information and Communications Technology (ICT) is important before construction of public smart grid infrastructure [2]. A main challenge identified for electric power systems HIL is construction of realistic laboratory settings with large distribution systems and typical loads.

Additionally, previously existing large-scale open-source or utility electric power distribution system models and state-of-the art real-time electronics software may face significant compatibility issues including node size and phasor domain solvers that do not account for harmonics. Main contributions of this paper include a review of real-time HIL electric power system laboratory studies, a proposed "weak" coupling of power electronics to large distribution systems of 2k+ nodes using co-simulation, and a transient power electronics case study with electric vehicle (EV) fast charging coupled simulation using an IEEE benchmark test feeder.

II. Hardware-in-the-loop (HIL) Types and Specific Applications

National laboratories and universities are continuing their development, spanning the past decade, of testing facilities for DERs, microgrid, EV charging, and controls of grid equipment through power and controller hardware-in-the-loop (PHIL/CHIL) studies. They combine power electronics and electric grid distribution system simulation for DER, transient, power quality, and equipment behavior analysis. Example facilities and studies are visualized in Fig. 1 and a detailed technology and literature review is provided in Section III.

An early study conducted by Pacific Northwest National Laboratory (PNNL) in 2015 established a co-simulation framework for open-source power system software, GridLAB-D, and PHIL real-time studies with a novel JSON communication protocol [3]. It was limited by the quasi-steady-state time-step of 1 second as the minimum resolution of the software, and thus, was used for simulating the impact of solar photovoltaic (PV) inverter transients from cloud cover on system voltage. Similarly, in 2017 a distribution system partitioning method for HIL applications requiring different time-step resolutions for faster and slower transients was proposed [4]. The utilization of the subsystem partitioning mathematical method by Shu *et al.* with utility adopted or open-source power flow software still requires development.

An IoT, micro-grid CHIL study on a medium voltage benchmark distribution system was published in 2019 to address planned and unplanned islanding of micro-grids [5]. In this study, the Opal-RT real-time simulator is paired with Raspberry Pi controllers at a 60 micro-second time-step to implement demand response (DR) load shedding controls based on voltage and frequency deviations. Another CHIL case study was performed for micro-grid islanding and controls with co-simulation of PV and BESS emulators to assess the advantages of dynamic boundaries for controls [6]. In 2021, a CHIL setup was proposed to assess autonomous reconfigurable solar power plant power electronics including capacitor voltage levels modeled in FPGA at the sub-millisecond resolution with a 400kV, 8GVA grid connection [7].

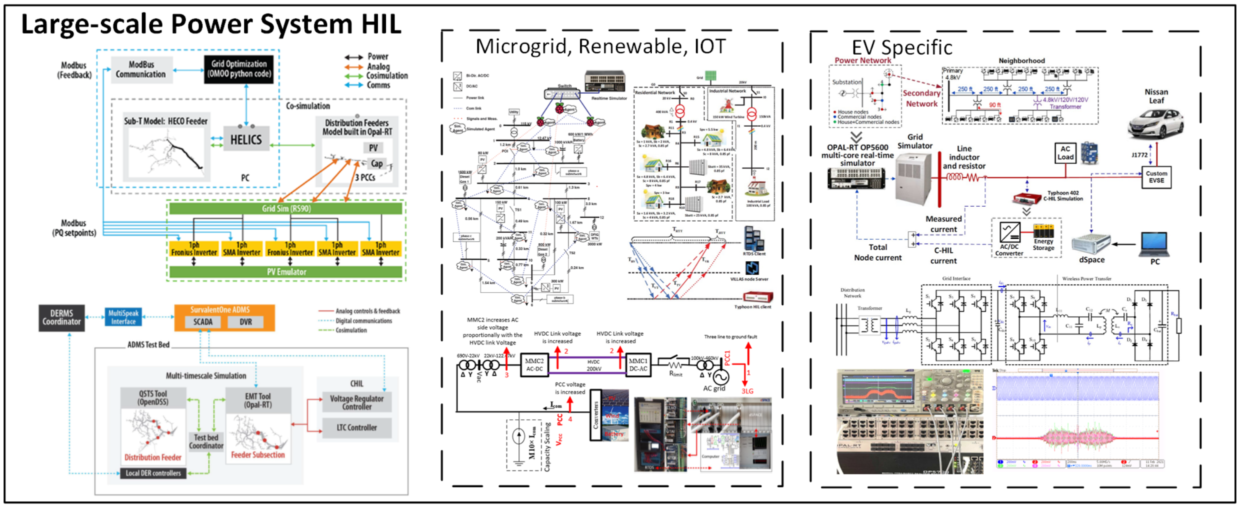

Fig. 1. Power system HIL configurations for co-simulation of large-scale distribution systems with specific groupings of micro-grid, renewable integration, IOT, and EV specific studies. Example graphics included from top to bottom, left to right are from: Padullaparti *et al.* (2021), Wang *et al.* (2021), Al Jajeh *et al.* (2019), Meghwani *et al.* (2020), Hossain *et al.* (2023), Ucer *et al.* (2022), Zeng *et al.* (2021).

Also recently, an electric grid hardware testbed (HTB) for both CHIL and PHIL was built with representative emulators and commercial products for synchronous generators, induction motor and power electronic loads, solar PV, ZIP loads, transmission lines, high-voltage direct current (HVDC) overlay, grid protection devices, PMU collecting data and SCADA equipment etc. [8]. This advanced test facility operated by CURRENT at the University of TN was developed to function across a range of time scales from sub-microsecond to days and be scalable to emulate the entire WECC and ERCOT transmission systems with high penetrations of DERS. Another advanced testing facility was built by NREL in 2022 for power electronic and electric power system coupled PHIL/CHIL simulation using commercial products, a Nissan Leaf EV, to develop EV charging controls [9].

To ensure cohesive simulation effectiveness and future smart grid deployment, it is important for HIL test benches to be compatible with large-scale utility circuits. For example, Padullaparti *et al.* from NREL coupled a 11MW utility distribution system modeled in open-source OpenDSS software with electromagnetic transient (EMT) CHIL analysis of load tap changers (LTCs) and voltage regulators (VRs) [10] through use of a testbed coordinator in Python. The co-simulation allows for peak demand reduction using dynamic voltage regulation to be evaluated for its effect on the physical equipment as would be deployed in the smart grid. A similar study utilized an NREL tool, HELICS, to co-simulate a transmission feeder and distribution feeders modeled for PHIL in OpenDSS and ePHASORSIM with phyiscal DER inverters and grid simulators [11]. In this configuration, the authors optimized the DERMS controllers for reduced solar PV curtailment while considering voltage transients from variable generation.

III. Technology Review for HIL

State-of-the art PHIL/CHIL technology has been developed in recent years to experimentally design and test new configurations and controls for smart grid and power electronic technologies before large capital investment and application in the field. An effort to review available software and hardware products was published by an IEEE PES taskforce in 2015, including hardware architecture diagrams and detailed descriptions of the OS and Application; Communication Protocols, Interfacing I/O; and software used by the leading HIL companies [12]. The companies listed included RTDS, eMEGASIM and HYPERSIM from Opal-RT; dSPACE; VTB; xPC Target; rtX from ADI; and Typhoon HIL.

Since this early HIL review paper, the applications and capabilities have expanded. Facilities for CHIL testing and the HTB for PHIL have advanced, and the methods across the world were summarized as power systems protection and control, smart grid/microgrid controllers, energy management systems, power electronic converter operation, co-simulation and real-time simulation, alongside industry development and standardized testing [13]. A very recent summary, published in 2023 by Baylor University and NREL, serves as a resource for the requirements of the real-time, open-loop, and closed-loop classifications and discussed hardware interfacing, communication protocols and I/Os, stability, and accuracy across PHIL specifically for inverter-based grid-edge solutions [14].

Investigations into the effects of inverter-based generation when grid balancing without thermal inertia is a growing area of HIL research. Numerous studies have explored and evaluated the effectiveness of volt/var controls for solar PV integration in low-voltage distribution systems and micro-grids [3], [15], [16]. Additionally, solar PV and BESS micro-grid PHIL and CHIL studies including planned and unplanned islanding have been proposed to assess the capability of real-time evaluation of controllers to maintain the power, voltage, and frequency [5], [6], [17], [18]. Grid protection and coordination including device-level fault response testing and PHIL relay coordination is another prominent HIL application [19].

Studies integrating EVs into simulated power systems is

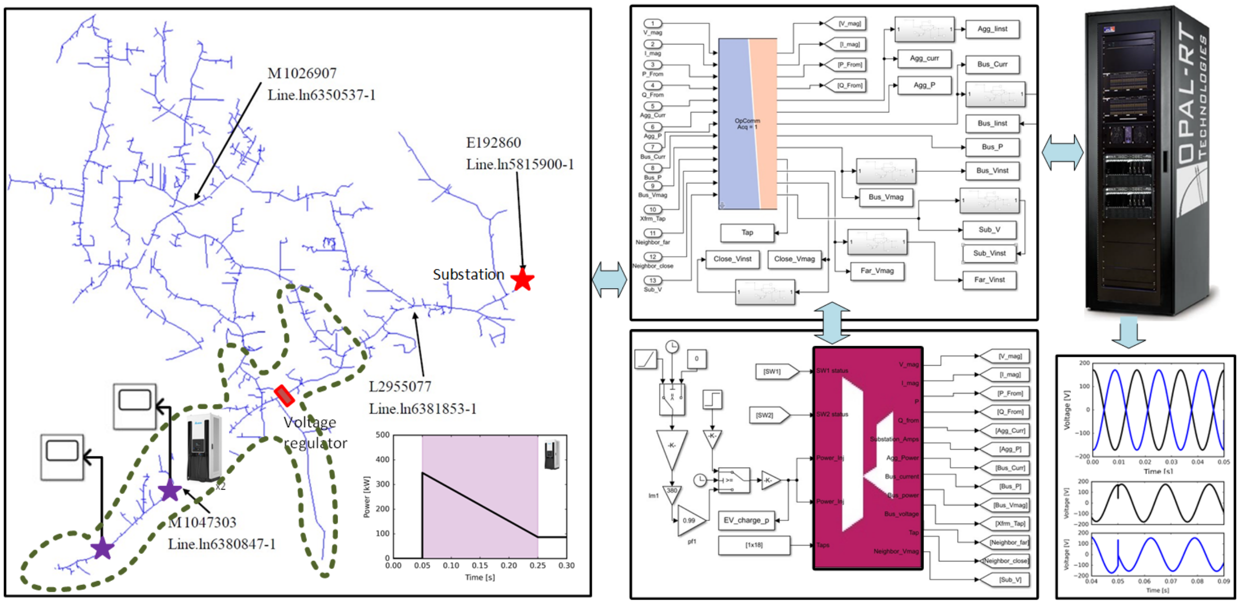

Fig. 2. Large-scale distribution system HIL modeling for compatibility of power flow and power electronic transient analysis. Included is an example coupling segmentation shown by dotted green line for proposed coupling methodology. Exemplified as is implemented with an Opal-RT system and with time variable load for the EV DC fast charger.

a newer application of HIL technology. In 2022, an effort was made to summarize the state of HIL and real-time simulations applied to EV integration in electric power distribution systems, including battery modeling and control, voltage and frequency regulation, management strategies, and power quality analysis [20]. A potential challenge to the development of wide-spread HIL identified in the research is the significant expense to build a HTB with equipment for PHIL and CHIL. A recent paper in 2021 includes a comparison of the existing emulators and testbeds for PHIL of EV charging [21]. Complete charge cycles, pulse and discharge tests, and error assessments were used to compare and validate EV battery emulators against EV batteries. Testing of PHIL HTB against real systems is an important step towards large-scale application, such as employing the validated PHIL testbed with a weak distribution system and a commercial EV charger.

Notable EV integration HTBs include PHIL with Nissan Leafs by NREL and University of Texas for smart charging and V2G discharging with electric power distribution system feedback and impact assessment [9], [22]. Other completed EV HIL testing include voltage stability with controllers for variable power charging, V2G testing with real-world distribution systems for peer-to-peer (P2P) trading and fault restoration, as well as optimal charging station placement and dynamic wireless power charging [23]–[26]. Examples of similar real-time studies for level 3 DC fast charging include PHIL and CHIL with power ratings from 50kW to 360kW [27]–[29]. These studies had small distribution systems with a low number of nodes modeled in RSCAD, and more significant voltage impacts due to the higher power demand were identified through high resolution transient simulation.

The real-time HIL assessment of intermittent DERs has also been considered for fault studies and grid impact through EMT co-simulation with distribution power systems modeled as quasi-static time-series (QSTS) in the phasor domain, specifically with high voltage DC (HVDC) transmission lines and BESS solutions [30]–[33]. The co-simulation methods for EMT and phasor solvers have also been applied to coupled transmission and distribution systems [34], [35] to enable large-scale CHIL and PHIL. Software used across literature to facilitate this co-simulation include Modelica, Python, MATLAB, C++, Windows COM, and SQL [36], [37].

The coupling of EMT and QSTS models allows for electric power distribution systems, some at large-scale with hundreds+ or thousands+ of nodes, co-simulated with DERs such as solar PV, wind, and BESS like EVs in micro-grids as initially introduced in Section II. Large-scale distribution system models are important for smart grid research to evaluate wide-area interactions of rapidly increasing DERs, advanced control schemes, and network resilience assessment. Open-source very large synthetic models are being developed for this purpose [38], [39]. Conversion of existing QSTS large-scale models between phasor-domain power system software that is compatible with commercial HIL technologies may be necessary to save substantial work in rebuilding [40], [41].

For multi-rate EMT analysis with HIL of small distribution systems co-simulation of solvers types may [42]–[44] or may not be necessary [45], [46], depending on if the systems are modeled in the same or HIL compatible power system software. Examples of HIL studies including large-scale distribution systems with 11,000, 4,000, and 1,100 nodes for EMT and phasor domain co-simulation respectively [47]–[49]. Within these large-scale simulations, portions of the larger systems have been modeled in EMT solvers such as

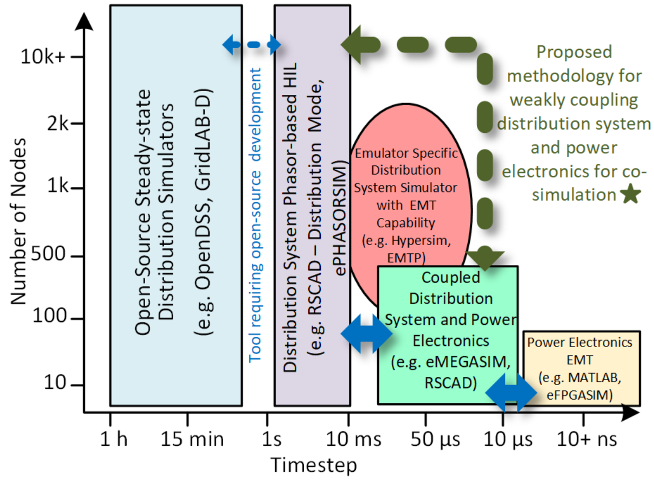

Fig. 3. Typical approaches and example technologies for power electronics and distribution simulation. A methodology for coupling two largely different systems is proposed in this paper.

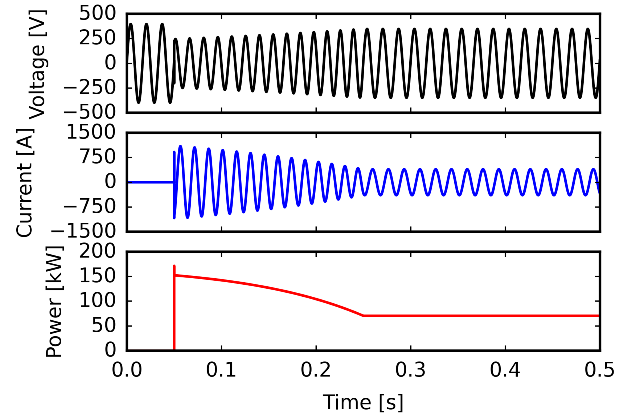

Fig. 4. Transient voltage, current, and power at the connection bus for a community DC fast charging station without soft starting power electronics. Following a start at t= 0.05s, the voltage drops significantly from 395V to 245V, i.e. 0.62p.u.

Opal-RT's eMEGASIM and coupled to the rest of the system in the phasor domain to avoid the computational challenges described in Section IV and Fig. 3. A gap in the literature is filled by this paper through a proposed general methodology to select how much of the larger system should be coupled with EMT modeling and co-simulation.

IV. Multi-step Method for Coupling and Co-simulation

Large complex systems with higher computational demands, like the modeling of frequency based transient problems such as EMT for power electronics (Fig. 3), are challenging to conduct in real-time. For this reason, multi-timescale co-simulation is proposed by "weakly" coupling large scale distribution systems (500+ nodes) with sub-regions necessitating higher resolution time-scales, e.g. power electronic simulation and/or HIL. This approach, for example, was used to co-simulate a large utility distribution system with a subsystem of 65 nodes in EMT compatible real-time software at the 100 micro-second timescale for CHIL evaluation of dynamic voltage regulation [10].

To establish a representative and sufficiently large sub-region per case study, a **methodology for evaluating the points of common coupling (PCCs)** is proposed in the following steps:

1) **Simulate variable load** on the very large distribution system at lower resolution (1s to 10ms) while monitoring the voltage and loads in surrounding buses and at the main substations
2) **Identify affected buses**, such as those with voltage violations or power quality issues
3) **Establish PCCs** to encompass a region of all significantly affected buses
4) **Solve the sub-region** at a finer time-step (100-10µs)
5) **Compare new PCC voltages** to the slower simulation with a tolerance
6) **Expand the region as needed** and repeat from step 4) until tolerance is passed

Using this approach, the distribution system modeling and power electronic converter EMT studies can be co-simulated using state-of-the-art real-time emulators with improved granularity across a larger distribution system. An example sub-region is visualized in Fig. 2. This method can be applied for testing additions of controls, new irregular loads, DERS, EV smart charging etc. Future use cases over a longer time period, for example, a day with multiple EV charging events and configurations requires realistic residential house models that are computationally efficient, such as developed in [50]. Time of day and seasonal load peaking are influential on the system impact and should be considered in assessments of strain and overloading.

V. High Power DC Fast Charging Case Study on a Large IEEE Test Feeder

A case study is designed and performed for "weak" coupling between distribution system modeling and power electronic converter simulation on the IEEE 8500-node test feeder with ePHASORSIM on a Opal-RT real-time emulator as a benchmark. To represent the potential smart grid scenario that a wealthy neighborhood installs a DC fast charging station for the community, two high power 200kW DC fast charging modules have been attached to an upgraded transformer on the very large 12MW peak residential distribution system as visualized in Fig. 2. The rated voltage and current have been used from the UFC 200 Ultra Fast Charger at 400Vrms and 380Arms, respectively. An in-rush current of four times rated is assumed as the worst case scenario without specially developed power electronic converters, following [51], as an initial simulation of the case study.

The load on the distribution system was assumed constant for the duration of the initial simulation time of 0.5 seconds because typical high resolution for steady-state load measurements is minute level. The start-up of charging causes a

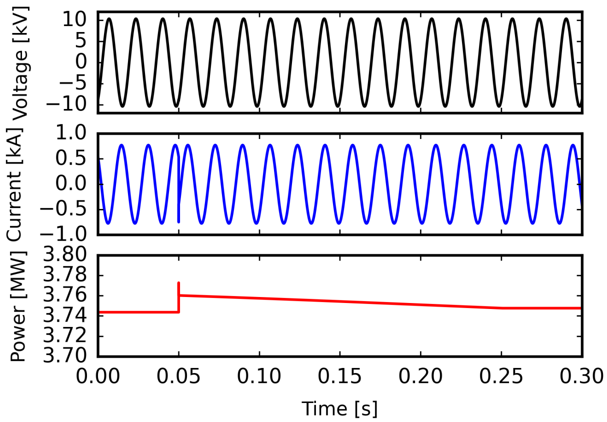

Fig. 5. Substation power and voltage are not significantly affected by example DC fast charging load, indicating the large system may be decoupled to smaller sub-regions through proposed methodology.

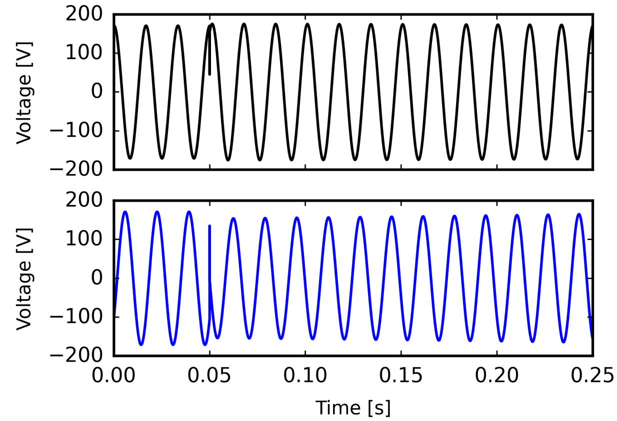

Fig. 6. Voltage from example buses neighboring the DC fast charging station, as indicated by the purple stars in Fig. 2. The farther bus (bottom) remained at a p.u. value below 0.95 for the entire duration of nine cycles.

violation as voltage drops to 0.62 p.u. on the node with the community EV DC fast charging station (Fig. 4). The voltage stabilizes at a 0.87 p.u. after the in-rush current, indicating that the load is too large for the current transformer LTC tap setting and that further controls, voltage regulation, or upgrades to the distribution system are necessary.

The substation voltage was unaffected by the additional load (Fig. 5), indicating the effects are localized and may be isolated in a sub-region of the circuit as proposed. At two neighboring buses, the voltage was monitored to assess the range of system disturbances (Fig. 6). The closer bus (top) to the station and voltage regulator experienced a voltage drop that recovered in that same cycle, while the farther bus (bottom) remained at a p.u. value below 0.95 for nine cycles. For illustrating extreme conditions, in the case study, the uncontrolled charger start-up transients cause unacceptable voltage violations at the connection node and at nodes toward the end of the feeder.

VI. Conclusion

Laboratory testing is conducted internationally for CHIL and PHIL analysis to determine grid impact and ICT requirements with new technologies such as DERs, EVs, and highly variable loads. Over 50 references have been summarized and organized to describe current state-of-the-art HIL distribution system and power electronic converter co-simulation for EMT and QSTS analysis. A general methodology is proposed to "weakly" couple large distribution systems with EMT transient simulation of power electronic converters and distribution systems by identifying sub-regions within the large system. A benchmark case study on the large IEEE 8500-node test feeder with DC fast charging of EVs showcases the necessity of co-simulation to design and implement smart grid technology.

Acknowledgment

This work was supported by the NSF Graduate Research Fellowship under Award No. #1839289. Any findings and conclusions expressed herein are those of the authors and do not necessarily reflect the views of the NSF. The support of the University of Kentucky L. Stanley Pigman Chair in Power endowment is also gratefully acknowledged.

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