An Integrated Transmission and Distribution Grid Model for the Cybersecurity Analysis of an EV Ecosystem

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***Abstract*—This paper presents a virtualization environment that is composed of a transmission network simulator, a distribution network simulator, and an Electric Vehicles (EV) ecosystem emulator. The coupling and synchronization of these three components are ensured so that the environment can simulate different applications in a context of an energy transition of the grid characterized by transportation electrification. The performance of this environment will be evaluated through some tests that highlight its advantages and show its importance in improving the grid modeling. Potential applications of our virtualisation tools include the simulation and study of cyberattacks that impact the transmission and/or the distribution systems through compromising, for instance, the operations of the EV charging infrastructure, third party systems in the EV ecosystem, or other power grid components.**

Keywords— cosimulation, cyberattack, distribution grid, electric vehicle charging station, emulation, transmission system, virtualization.

I. INTRODUCTION

The electric power system is undergoing a transformation with the increasing integration of Electric Vehicles (EVs) as a form of Distributed Energy Resources (DERs) [1]. This shift is driven by technological advancements and policy initiatives that aim to decentralize and decarbonize the electricity infrastructure. The security of the grid in its current and future form must be guaranteed, even during and after extreme events, such as cyberattacks [2, 3]. Critical loads in the Transmission System (TS) tend to be located at specific substations, while individual critical loads, such as EVs, are more prevalent in the Distribution System (DS). Given the increasing role of EVs in the energy transition, it is essential to study the impact of their massive integration or compromise on both the Transmission and Distribution (T&D) systems [4]. Simulation and analysis are essential tools for understanding the options available to grid operators, making informed decisions, and determining the technical requirements for integrating EVs into the grid [5, 6]. Furthermore, sophisticated studies on cybersecurity and resilience assessment require the use of simulated models of T&D systems along with their supporting communications and information infrastructure, thus, yielding the need to develop advanced tools that integrate different co-simulators and emulators in the same virtual environment.

Studies on electrical grids traditionally consider the modelling of one component only, either the TS or the DS, while treating the other component as a boundary condition [7]. This approach is efficient for traditional grid models including unidirectional power flow and predominantly passive loads in the DS, however, with the increasing deployment of EVs and DERs and the development of advanced control systems, bidirectional power flows are increasingly expected across the power grid. Cosimulation of T&D systems allows for testing of newly developed control and automation algorithms in a safe and controlled environment with detailed models of both systems [4, 5, 8, 9]. This approach is an intermediate step between theoretical validation and practical field implementation. Previous T&D cosimulation studies focused primarily on steady-state power flow simulations excluding the supporting communication and information systems (i.e., the cyber layer), which is insufficient for studying the impacts of potential cyber-physical events. According to [10], incorporating a cyber-physical event emulation module in T&D cosimulation is necessary to examine the effects of cyber-physical events on T&D system operation. Although there were previous academic and research tools for cosimulation of T&D, not all of them were practical for full-scale analysis [10, 11]. While some early efforts combined existing tools, others reformulated the simulation problem into a single environment [12]. Currently, a limited number of existing commercial tools can simulate a highly detailed T&D model in a single environment due to scalability challenges. Standalone T&D system models also fail to exploit legacy simulation tools that separately simulate detailed models of TS and DS. This is mainly due to the distinct structural and operational variations in TS and DS, which can create convergence issues when resolving a large integrated T&D system model using a standalone approach. Recently, the authors of [4] presented a dynamic cosimulation framework for studying the effect of EVs on frequency response. The backbone of this framework is based on the HELICS platform and the open-source power system simulators ANDES and OpenDSS. However, the built-in and existing external tools for cyber simulation in HELICS are not yet capable of supporting the advanced models and simulators required. That's why the Department of Energy (DOE) R&D program currently focuses on enhancing the existing HELICS cosimulation platform to provide individual simulation tools and corresponding interfaces [6].

This paper considers the development of an offline T&D cosimulation platform along with cyber layer components that

can be used to study the power grid impact of cyberattacks (and more general resilience problems) under high EV load penetration. Our virtualization environment integrates cosimulation and emulation tools, and it is leveraged to model an EV ecosystem that includes charging stations and a central management system that communicate using the Open Charge Point Protocol (OCPP). This ecosystem is used to analyze the penetration of EVs on the DS and study their impact on the TS's behavior. The paper is organized as follows. Section II introduces different coupling methods and tackles the development of the T&D cosimulation platform and the EV ecosystem model. Section III describes the studied use cases and models. The results using multiple test cases to validate the operation of the T&D cosimulation are presented in Section IV. Concluding remarks are drawn in Section V.

II. METHODOLOGY

In this section we provide a comprehensive description of the T&D coupling methods and cosimulation architectures, and their respective advantages and disadvantages. We explain the necessary steps for creating the simulation model, integrating the various simulation tools, and exchanging data between them. Moreover, we discuss the importance of accurately modeling the cyber-physical interactions for a typical EV ecosystem and the data exchanges within T&D systems.

A. T&D Cosimulation Coupling Method

Two coupling methods, namely loosely-coupled (LC) and tightly-coupled (TC), are commonly employed in the cosimulation of T&D systems. In the LC method, the TS and DS simulators exchange relevant values at each time step assuming that changes in the system states occur gradually compared to the solution time-steps, which allows the boundary variables for LC T&D systems to converge over multiple time-steps [13]. On the other hand, in the TC method, the boundary variables are exchanged multiple times within a given time-step until they converge with a pre-specified convergence criterion. An iterative procedure is employed, and it terminates when the boundary variables obtained by separately solving the TS and DS models are within a pre-specified tolerance limit [13].

While the TC coupling method is used to study specific transient behavior of the grid, it requires extensive studies of the coupled systems and is highly dependent of the models in each simulator, which makes it unsuitable to be generalized. However, the LC coupling method can be easily generalized as it is based on the exchange of specific signals. Our objective in this paper is to create a T&D virtualization environment that is appropriate to conduct cybersecurity studies for the power grid and more general studies on its resilience under other disrupting conditions such as extreme weather events, hence, we chose to implement the LC coupling method.

We consider an LC-based cosimulation platform that utilizes the TS simulator Hypersim developed by OPAL-RT [14], and the DS simulator CYMDIST developed by Eaton [15], along with the EV ecosystem emulators. The TS simulator exchanges the transmission bus voltage value with the DS simulator at each time-step. The DS model is then solved using the updated bus voltage value, and the solutions from the DS load flow simulator are exchanged with the TS model. Subsequently, the time-step is advanced to (t + 1) without considering the convergence of the boundary variables, and the TS simulator solves the model for (t + 1) time-step using the load demand obtained from the DS simulator at time step t.

B. T&D Cosimulation Architecture

The primary aim of this paper is to develop a T&D cosimulation architecture that employs the InSystemLab (ISL) middleware which is developed by E-Sim Solutions [16] for the integration of the DS simulator CYMDIST and the TS simulator Hypersim. Studies for steady-state analysis and transient stability analysis on the TS level are traditionally conducted using an independent TS model in Hypersim, while assuming that the DS model can be simplified by constant power loads or dynamic loads depending on the objectives of the studies. Conversely, the DS model considers the point of interconnection to the TS as an ideal stiff voltage source in CYMDIST. For more comprehensive modeling of the overall power system, a synchronous integration of the TS and the DS models is required using our Hypersim and CYMDIST cosimulator.

To the best of our knowledge, there are three methods for designing an integration tool for the T&D cosimulation. The most convenient integration solution is to exchange the CYMDIST and Hypersim data using the message queues telemetry transport (MQTT) messaging protocol such as the implementation of T&D cosimulation in [8]. In this reference, Hypersim acts as the master and sends the updated voltage values to CYMDIST. Then, in the next step, CYMDIST updates the source node voltages and returns the active/reactive power of the distribution feeders after completing the load flow analysis to Hypersim. This method of integration is not appropriate for large DS models because of the lack of synchronization between CYMDIST and Hypersim.

The second method is based on the HELICS cosimulation framework which is designed to integrate separate transmission, distribution, and communication network simulators to simulate regional and interconnection-scale power system behaviors [4, 9]. This requires the use of the “cymepy” and “cympy” packages in Python to link the CYMDIST interface to the HELICS broker. However, at the time of this writing, there isn’t any Hypersim interface that can be used for the integration with the HELICS broker. In addition, this method is not cost effective since the integration of multiple CYMDIST instances to the HELICS broker cannot be achieved without acquiring the complete set of CYMDIST licenses for each instance.

In this paper, we provide a third method for T&D cosimulation in our lab that relies on the use of the ISL middleware which provides an interface to HYPERSIM for an offline cosimulation. In order to integrate ISL with CYMDIST, we developed Python interfaces based on the “cympy” package [17] and Functional Mock-Up Interface Exchange (FMX)-based module. This allows us to connect multiple CYMDIST instances to the core of ISL. The “cympy” Site Package has all the modules and functions required to access DS properties, manipulate equipment and devices, perform various analyses including the load flow. We execute CYMDIST scripts for interfacing in a “stand-alone” mode outside of the CYMDIST application environment using PyCharm. The FMX-based module specifies the details regarding the input/output ports and the simulation time of each CYMDIST instance and Hypersim.

C. Data Exchange and Time Synchronization

The data exchange between CYMDIST and Hypersim based on the LC method is shown in Figure 1.

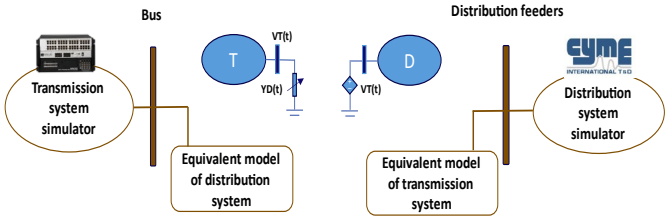

Figure 1 - The overview of T&D cosimulation data exchange

One of the main challenges to integrate the DS simulator and the TS simulator is the synchronization of data exchanges. In fact, the load flow calculation in the DS simulator takes some seconds to run, while the TS simulator is much faster. To address this issue, we introduced functionalities to the ISL core so that it will be able to handle the data exchanges and assure the synchronization between the simulators by handling the global execution time and the waiting time based on the maximum execution time of the load flow for the instances.

Another challenge is the size of the DS model in CYMDIST which takes more execution time compared to the Hypersim to be executed at each iteration. This can impact the total execution time of the cosimulation and the synchronization with Hypersim. The solution is to install CYMDIST on a 16-core server and divide the distribution feeders to several instances that are running in parallel, as can be seen in Figure 2. As the distribution feeders can be separated based on their characteristics, we use one CYMDIST instance for each distribution feeder. This solution can reduce the total load flow execution time by nearly 85% (from 14 seconds to 2 seconds). It is also cost-effective in the sense that it uses three Python scripting tool licenses and only one license of the other CYMDIST modules.

Other advantages of the developed cosimulation platform shown in Figure 2 are the possibility of integrating large models in both Hypersim and CYMDIST, and its capability to connect to the emulation environment of the EV ecosystem.

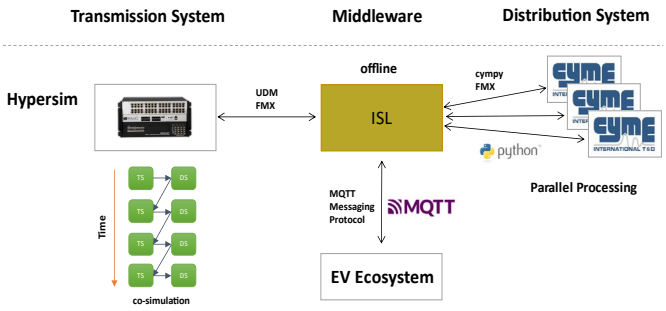

Figure 2 - LC-based cosimulation platform architecture

D. EV ecosystem infrastructure

To simulate the behavior of the EV ecosystem, different components should be modeled. The main component of this ecosystem is the EV which is considered as a DS load. The EVs are connected to the power grid using the EV Charging Stations (EVCSs). These charging stations communicate with the manufacturer Charging Station Management System (CSMS) using an open communication protocol (OCPP). The management system can control the operation, the status, and the transactions of each EVCS. Since the aim of this work is to develop a virtual environment for the study of large-scale impact on T&D system following events such as cyberattacks, modeling individual EVCSs is not useful. Hence, for the simplicity of the EV emulations, we consider aggregating the behaviour of the charging stations located at each distribution feeder in one charging station emulator. Using Node-Red, we implement an associated Human Interface Machine (HMI) panel for the user interactions with the EVCS. Such HMI allow the users to check their charging profile, and the status of charging. Another HMI panel is developed in Node-Red to emulate the user mobile app. In this paper, we emulate the aggregated EVCSs and other EV ecosystem components in different Virtual Machines (VMs), as illustrated in Figure 3.

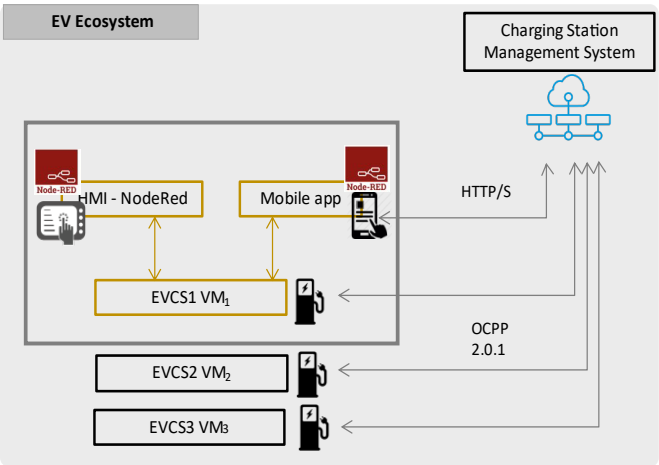

Figure 3 - EV ecosystem components

We present three VMs in Figure 3 that emulate in an ESXi environment three aggregated EVCSs that are connected to three distribution feeders. An additional VM is dedicated for the CSMS emulation, and it communicates with the three EVCSs via OCPP. The operation of the EVCSs can be controlled using the CSMS's commands. During normal operation, we initialize and integrate the CSMS and the three aggregated EVCSs emulators. The initial boot notifications, vendor name, message interval, and the connection status for three EVCSs are exchanged with the CSMS through the OCPP protocol. When the connection is established, the EVCSs return heart-beat messages every 10 seconds to signal their connections to the CSMS.

III. System Model

This section provides an overview of the various components that make up the T&D cosimulation model. These components include the TS, DS, and the interface with the EV ecosystem. During the cosimulation study, both the TS and DS are modeled and solved separately using their respective simulation platforms. This allows for a more detailed and accurate analysis of the T&D system, as each subsystem can be studied in greater depth and then combined to obtain a complete picture of the system's behavior.

A. Large-Scale T&D model

Hypersim is used to model a past state of the TS of Hydro-Québec, as can be seen in the left side of Figure 4. Reference [18] details the main characteristics of the Hydro-Québec TS. This model details the James-Bay West portion of the grid

while providing simplified models for the rest of the grid. The Hypersim model contains a 300-bus grid and includes the whole generation capability of Hydro-Québec that's connected to the 735-kV transmission lines and several substations. This electrical grid model is limited to the TS and models the DS as PQ dynamic loads, which is not sufficient to visualize the impact of EV penetration on both the DS and the TS. Therefore, we modify the TS model in Hypersim for the integration of an appropriate DS model.

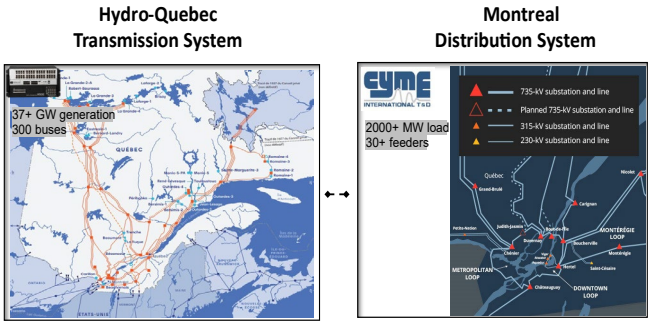

Figure 4 - TS and DS model [19]

To model the DS, we use CYMDIST software. The CYMDIST software is a focused and powerful tool to model and analyze the whole DS and can be used also for the planning, design, and operation of any electrical power system. The steady-state performance of the power system under various operating conditions can be simulated using the load flow analysis of CYMDIST. In this paper, we use Unbalanced Newton-Raphson load flow which considers underground secondary networks (urban grid systems or spot networks), low voltage installations, and sub-transmission systems tied to the DS.

We consider a detailed model of the distribution grid for the Montreal region. The model in CYMDIST includes the source node, overhead lines, shunt capacitors, circuit breakers (CBs), spot loads and the transformers. This model uses the "Enhanced Substation Modeling" module to accurately represent all the major components of a distribution feeder. In this paper, we use approximately 1000 MW DS loads for three distribution feeders. Each distribution feeder consists of a source node which represents the equivalent model of the TS model in Hypersim and the circuit breakers for each sub-feeder. The DS loads are modeled as spot loads in CYMDIST by considering the customer type, the power characteristics, and the phase connections. The iterations are computed with a tolerance of 0.1% and a maximum number of iterations of 60. The voltage sensitivity for the load model is 90%. These parameters are needed for the optimal load flow calculation of this specific DS model in CYMDIST.

To capture and communicate the exact behaviour of the DS simulator, we assign the input/output signals for each dynamic load in the TS simulator. We get the active and reactive power values from the DS model counterpart of each dynamic load as the input signals, and we send back the voltage magnitude of dynamic loads as the output signals to update the DS model. The voltage angle is not needed to be exchanged with the DS model as we have balanced distribution feeders in the DS simulator. We create a User-Coded Model (UCM) file in Hypersim to exchange the input/output signals of all the loads with the external DS simulator.

B. EV Ecosystem Model

The OCPP is the industry-supported de facto standard for communication between a EVCS and a CSMS and is designed to accommodate any type of charging technique. Within the EV charging infrastructure, the OCPP is a key enabler for bidirectional power flows, real time information exchange, demand control and eMobility services. We use a Python package implementing the JSON versions 1.6, 2.0 and 2.0.1 of OCPP [20]. We also use the open-source OCPP version 2.0.1 to implement the functionalities related to Availability (Heartbeat), Firmware Management, Display Message, Charging Profile, Meter Values, and Monitoring Report. As can be seen in Figure 5, the three aggregated charging stations are connected to the CSMS and sending the boot notification command. After a while they start sending the heartbeat message every 10 seconds to the CSMS.

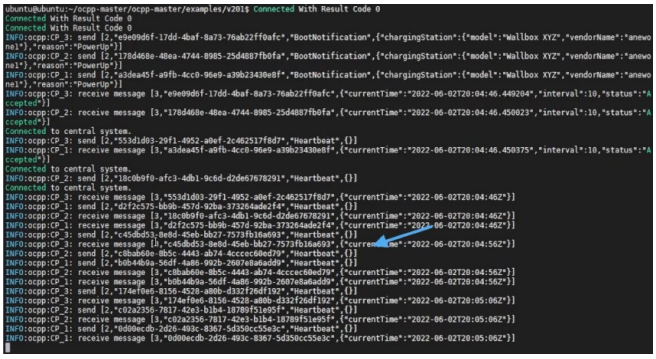

Figure 5 - OCPP message exchanges between CSMS and EVCS

IV. Simulation

Figure 6 illustrates the complete virtualization environment including the TS simulator (Hypersim), the DS simulator (CYMDIST) and the emulated EV ecosystem. This advanced environment can be used to simulate, and study cyberattacks that impact the transmission and/or the distribution systems through compromising, for instance, the operations of the EV charging infrastructure, third party systems in the EV ecosystem, or other power grid components. The three distribution feeders in CYMDIST (in total 1000 MW) and their connection with the TS model in Hypersim are shown in Figure 6. The FMX files are used in each simulator to define the input/output ports, the total execution time, and the step size for each simulator. The configurations in the FMX files will be used by the ISL core to perform the cosimulation, manage the synchronization of the CYMDIST instances and ensure their integration with Hypersim.

To run the simulation, we open the CYMDIST model in the main function of each instance and call the load flow function. Then, we start the interaction of instances and iterate for the whole duration of the simulation. To connect the EV ecosystem emulator to the DS simulator (CYMDIST), we use the MQTT messaging protocol as can be seen in Figure 6. To this aim, each aggregated EVCS communicates its connectivity status via the MQTT messaging protocol to the correspondent's distribution feeder running in one of the CYMDIST instances. In normal operation, the virtualization environment can be initialized by running ISL and its interfaces with CYMDIST and Hypersim. When the connection between the CYMDIST instances and Hypersim through the ISL is established, ISL lets Hypersim run in a

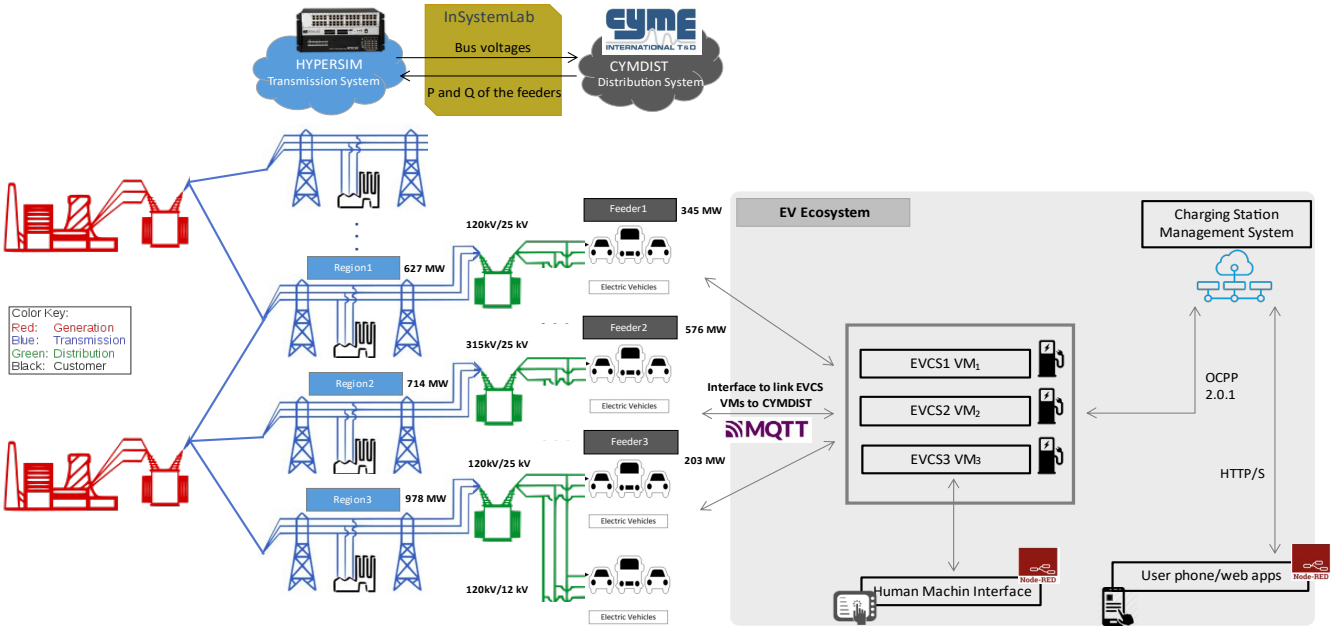

Figure 6 - The proposed cosimulation architecture interfacing with EV ecosystem

stand-alone mode for the first 40 seconds. This prevents the initial transient behaviour of the Hypersim model impacting the load flow calculation in CYMDIST. The data exchange between Hypersim and CYMDIST starts after 40 seconds. To this end, Hypersim sends the updated voltage value of the buses to CYMDIST. Then, CYMDIST updates the source node voltages of each distribution feeder and executes the load flow analysis. By running this analysis, the value of the active power (P) and reactive power (Q) for each distribution feeder is being updated and then sent back to Hypersim. At the same time, the emulated EVCSs communicate to CYMDIST the status of their connections. The operation of the EVCSs is managed by the emulated CSMS via the OCPP protocol. Next, we discuss the performance of our T&D coupling method compared to other simulation method in the context of a given cyberattack scenario targeting the EVCSs' operation. To compare the performance of the developed platform we use the evaluation matrices of closed-loop delay and the dynamic time-difference propagation. Using these two matrices we can evaluate the performance of the LC T&D coupling and compare it with the stand-alone simulation.

A. Closed-loop delay in the presence of malicious EV dynamic behavior

To evaluate the performance of the LC-based cosimulation platform, an initial test was conducted assuming a cyberattack scenario where the attackers infiltrate the EVCS manufacturer cloud, take control of the CSMS and start injecting malicious commands to a significant number of EVCSs. The consumption power of the EV loads at the distribution feeder 3 illustrated in Figure 6 is configured to undergo a step change from 203 MW to 406 MW following the malicious commands that are issued from the compromised CSMS to the EVCSs connected to this feeder. These commands are being sent at the same time interval as the cosimulation data exchange timestep. Such malicious commands leverage the smart charging capability of the OCPP protocol, which is primarily used for load balancing or peak reduction purposes. The transmission bus nominal voltage is 120 kV L-L, and the total load seen from the transmission bus (region 3) is 978 MW. We monitor the voltage reference of the transmission bus (region 3) connected to the distribution feeder 3. The impact of the cyberattack can be seen as a disturbance in the frequency and voltage of the transmission bus, as can be seen in Figure 7 and Figure 8. The frequency value obtained from both the cosimulation setup and Hypersim showed a perfect match, as depicted in Figure 7. Additionally, as shown in Figure 8, the voltage at the Point of Common Coupling (V-PCC) between CYMDIST and Hypersim precisely matched at each time step, confirming the absence of closed-loop delay in the cosimulation.

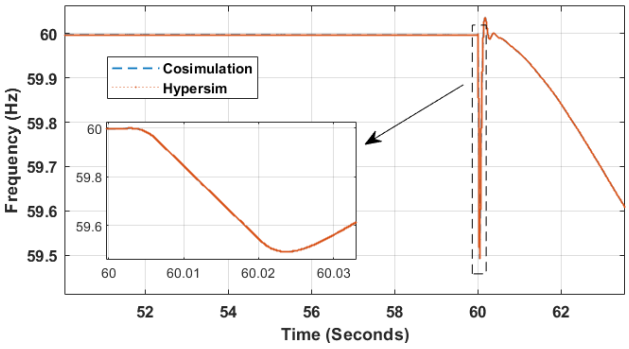

Figure 7 - Frequency changes for the validation of cosimulation performance

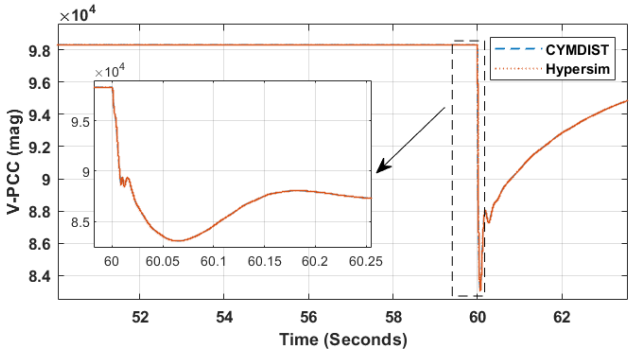

Figure 8 - V-PCC changes for the validation of cosimulation performance

B. *Dynamic time-difference propagation*

To assess the dynamic time-difference propagation of the cosimulation platform, assuming the same cyberattack scenario introduced in the previous subsection. A stand-alone T&D system model was created in Hypersim, utilizing the same TS model, while the DS was designed as simple PQ dynamic loads to ensure an equitable comparison. Assuming the injection of malicious commands by the CSMS as in the previous subsection to induce a step change in the voltage reference of the transmission bus connected to the distribution feeder. The voltage (V-PCC) and frequency (F-PCC) results at the transmission-distribution point of common coupling are illustrated in Figure 9 and Figure 10, respectively, for comparison. The injection of malicious commands by the CSMS and the change of consumption power of the EV loads at the distribution feeder, cause a disturbance in the voltage (V-PCC) and frequency (F-PCC). The graphs indicate a disparity between the Hypersim-CYMDIST cosimulation and the stand-alone Hypersim simulation, with mean differences of 0.001% and 0.065% for frequencies and voltages, respectively. These differences were expected since in the Hypersim-CYMDIST cosimulation, both the TS and DS are modeled and solved independently using their respective simulation platforms, providing a more comprehensive and precise analysis of the T&D system compared to the stand-alone Hypersim simulation.

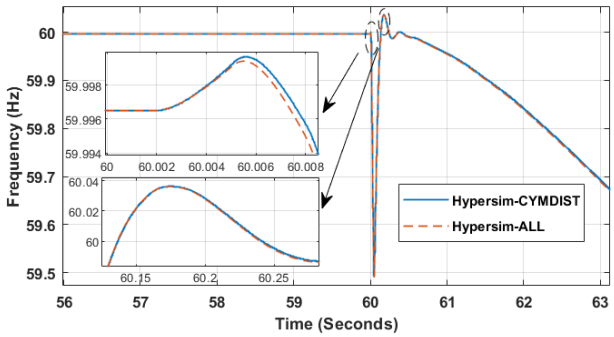

Figure 9 - Dynamic time-difference propagation for the frequency

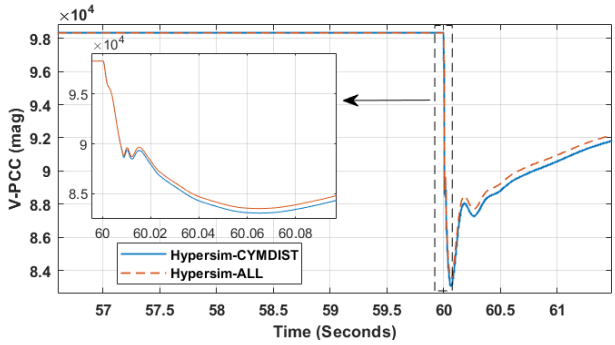

Figure 10 - Dynamic time-difference propagation for the V-PCC

The results of this study confirm the effectiveness of the developed co-simulation platform in facilitating the integration of LC T&D coupling and EV ecosystem operations. This platform is deemed appropriate for conducting further research and enhancing the power grid's resilience against cyber attacks. However, the proposed virtualization environment has a main limitation of offline operation, which poses a challenge in integrating real equipment into the simulation. In future studies, we aim to address this limitation by enhancing the parallel processing features of the platform, which will not only reduce the load flow time but also enable real-time operation.

CONCLUSION

This paper presented a virtualization environment that allows the development of an integrated transmission and distribution grid model through cosimulation and its integration with emulation tools. Our virtualization environment has been leveraged to model an EV ecosystem and analyze the potential impact of cyberattacks. The coupling and synchronisation of the employed simulators in one cosimulation platform were ensured using the InSystemLab middleware and the OCPP protocol for data exchanges. We used a loosely-coupled method to couple the TS simulator (Hypersim) and the DS simulator (CYMDIST), thus, providing a generic virtualisation environment that can be used not only for the study of cyberattack scenarios but also of more general power grid resilience issues such as extreme weather events and poorly planned integration of massive numbers of EVs and DERs.

Assuming a cyberattack scenario where attackers compromise the CSMS, we test the performance of our virtualisation environment using an integrated T&D model along with emulated EVCSs. In addition to illustrating the attack impact, our results highlighted the advantages of our cosimulation-based platform compared to other platforms that rely on the use of a single simulator. In fact, each simulator in our platforms operates in its native environment, thus, allowing elaborated models for each power grid component using the functionalities of the appropriate simulator. Another advantage lies in the scalability aspect of our environment since it allows the integration of detailed models of the transmission and distribution systems while keeping the computing time at a minimum, which is particularly essential for the analysis of large-scale power grid events such as cyberattacks with multiple grid targets.

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REFERENCES

[1] P. Babu, B. Palaniswamy, A. Reddy, V. Odelu and H. Kim, "A survey on security challenges and protocols of electric vehicle dynamic charging system," *Security and Privacy,* 2022.

[2] Z. Garofalaki, D. Kosmanos, S. Moschoyiannis, D. Kallergis and C. Douligeris, "Electric Vehicle Charging: A Survey on the Security Issues and Challenges of the Open Charge Point Protocol (OCPP)," *IEEE Communications Surveys & Tutorials,* vol. 24, pp. 1504-1533, 2022.

[3] A. Vosughi, A. Tamimi, A. B. King, S. Majumder and A. K. Srivastava, "Cyberphysical vulnerability and resiliency analysis for DER integration: A review, challenges and research needs," *Renewable and Sustainable Energy Reviews,* vol. 168, 2022.

[4] Y. Liu, T. J. Overbye, W. Wang, X. Fang, J. Wang, H. Cui and F. Li, "Transmission-Distribution Dynamic Co-Simulation of Electric Vehicles Providing Grid Frequency Response," in *2022 IEEE Power & Energy Society General Meeting*, 2022.

[5] S. M. Mohseni-Bonab, A. Hajebrahimi, I. Kamwa and A. Moeini, "Transmission and distribution co-simulation: a review and

propositions," *IET Generation, Transmission & Distribution,* vol. 14, no. 21, pp. 4631-4642, 2020.

[6] K. P. Schneider, K. Balasubramaniam, D. Fobes, A. Moreira, V. Donde, B. Palmintier, T. Kuruganti, M. E. Ropp and C.-C. Liu, "T&D Co-simulation of Microgrid Impacts and Benefits," U.S. Department of Energy, 2021.

[7] A. Maitra, K. S. Kook, J. Taylor and A. Giumento, "Grid impacts of plug-in electric vehicles on Hydro Quebec's distribution system," IEEE PES T&D 2010, 2010.

[8] V. Paduani, R. Kadavil, H. Hooshyar, A. Haddadi, A. Jakaria and A. Huque, "Real-Time T&D Co-Simulation for Testing Grid Impact of High DER Participation," in *IEEE PES Grid Edge Conference*, 2023.

[9] T. Phillips, L. D. Marinovici, C. Rieger and A. Orrell, "Scalable Resilience Analysis Through Power Systems Co-Simulation," *IEEE Access,* vol. 11, pp. 18205-18214, 2023.

[10] X. Fang, M. Cai and A. Florita, "Cyber-Physical Event Emulation-Based Transmission-and-Distribution Co-simulation for Situational Awareness of Grid Anomalies (SAGA)," in *IEEE Power & Energy Society General Meeting (PESGM)*, 2021.

[11] V. Venkataramanan, P. S. Sarker, K. S. Sajan, A. Srivastava and A. Hahn, "Real-time federated cyber-transmission-distribution testbed architecture for the resiliency analysis," *IEEE Transactions on Industry Applications,* vol. 56, no. 6, pp. 7121-7131, 2020.

[12] G. Krishnamoorthy and A. Dubey, "Transmission–Distribution Cosimulation: Analytical Methods for Iterative Coupling," *IEEE Systems Journal,* vol. 14, no. 2, pp. 2633-2642, 2020.

[13] R. Sadnan, G. Krishnamoorthy and A. Dubey, "Transmission and Distribution (T&D) Quasi-Static Co-Simulation: Analysis and Comparison of T&D Coupling Strength," *IEEE Access,* vol. 8, pp. 124007-124019, 2020.

[14] "The Power System Simulator," OPAL-RT, [Online]. Available: https://www.opal-rt.com/systems-hypersim/. [Accessed 13 04 2023].

[15] "CYMDIST," Eaton, [Online]. Available: https://www.cyme.com/software/cymdist/. [Accessed 7 March 2023].

[16] "InSystemLab," e-sim solutions, [Online]. Available: https://www.esims.tech/. [Accessed 7 March 2023].

[17] Eaton, "CYME Scripting Tool with Python Module," [Online]. Available: https://www.eaton.com/us/en-us/products/utility-grid-solutions/software-modules/cyme-scripting-tool-with-python-module.html. [Accessed 04 04 2023].

[18] H. Annissa, I. Kamwa and M. Dobrescu, "Hydro-Québec's Defense Plan: Present and Future," in *IEEE Power & Energy Society General Meeting*, 2013.

[19] "Power transmission," Hydro-Quebec, [Online]. Available: https://www.hydroquebec.com/transenergie/en/. [Accessed 14 04 2023].

[20] "Python implementation of the Open Charge Point Protocol (OCPP)," [Online]. Available: https://github.com/mobilityhouse/ocpp. [Accessed 7 March 2023].