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PNNL-37021

Scalability of Real-time Distribution Models

December 2024

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U.S. DEPARTMENT OF ENERGY
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Abstract

This work will focus on developing the capabilities and validating the models for a sub transmission network with multiple feeders and microgrids. To achieve this scale of Hardware-in-the-loop (HitL) simulation, it is necessary to federate and collaborate. The work aims to design the large-scale feeder models to allow federation with complementary testbeds in the future. The feeder would be designed to be reconfigurable to put the system into a variety of modes. Aggregators models will be included in each distribution network's federate to take control actions and interact with the management systems. Lastly, the feeder model will support large scale resilience studies involving complex Distributed Energy Resources (DER) controls, microgrid studies and emulation of complex data flows in future grid architectures.

Acknowledgments

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1.0 Introduction

Transmission and distribution systems are evolving and reaching new levels of complexity with an unprecedented penetration of DERs, complex information flows, new communication architectures and ever evolving control schemes. DERs found on today’s systems operate across a range of defined standards and possess a variety of different control characteristics. Furthermore, communication architectures have to transport a larger number of control and operation signals between system operators and field devices. Control and operation architectures in today’s networks are further complicated owing to the presence of third-party DER aggregators, distribution system operators (DSOs) and market coordination schemes at the distribution and microgrid level. To ensure safe, reliable, and resilient operations under this paradigm it becomes essential to analyze the systems modes, performance during adverse events and understand the ability to the system and its components to ride through adverse conditions. Moreover, with more sensors and the associated information flows governing the operation and control of future grids, it becomes necessary to analyze the vulnerability of these cyber-physical systems to attacks and identify relevant strategies to mitigate them.

To enable these studies, it becomes necessary to develop a sufficiently complex testbed and embed all the complexities and disruptive technologies discussed above to study cyber-physical resiliency. Previous implementations under the RD2C initiative have succeeded in creating smaller distribution networks along with the associated controls, protection and cyber interactions. While this testbed was utilized to generate a variety of scenarios and to prototype novel controls, computational burdens associated with larger complex power networks and the lack of sufficient real-world controllers, diversity of mixed standard power electronics devices and insufficient resources to model interactions between DER aggregators, utility operators and microgrid operators. It is also essential to model typical human interactions with various facets of operation and control to analyze human factors and operator responses to specific adverse events. To achieve this scale of hardware-in-the-loop (HitL) and operator-in-the-loop (OitL) simulation it becomes necessary to automate model building activities for large scale models and incorporate a range of modern DER controls to generate meaningful scenarios.

2.0 Methodology

In order to accurately understand resilience and control challenges in these multi-party energy systems, meaningful experiments with the correct level of fidelity need to be conducted on realistic models while incorporating all of these emerging entities (aggregators/DSOs). Moreover, by embedding different objective functions for each of these control and operation entities and conducting experiments under normal and adverse scenarios resilience improvement and coordination schemes can be developed. With mixed standard DERs present in the system, understanding unique control challenges requires these components to be defined in a high-level of fidelity. Existing testbeds lack resources to scale in terms of managing computation burdens and modelling these unique architectures with varying objectives.

The work proposed here attempts to detail the building efforts associated with creating a large-scale distribution model that is highly reconfigurable and can support a range of experimentation. A large-scale testbed capable of simulating complex transmission and distribution networks along with the necessary protection, control and operating schemes is realized. By embedding different objective functions for aggregators/DSOs in either federate the effects at the sub transmission level can be analyzed and possible failure modes could be identified. Moreover, the coordination and information flows between these energy entities can be studied. A range of varying inverter control strategies are modelled to represent a range of commercially available inverters with multiple standards (IEEE 1547) to analyze transient behaviors in a mixed standard environment. The developed networks are highly flexible and reconfigurable to allow studies that can analyze microgrid islanding, reconnection as well as networked microgrid operation. By islanding these feeders, smart inverter functionalities like anti-islanding, intentional islanding and ride-through could be analyzed in high DER penetration environments. The behavior observed through these experiments will be used to structure protection schemes in DER-heavy environments.

System management platforms representing all energy system parties are embedded into the testbed environment. Telemetry data between hardware devices, and control entities (DSOs, aggregators, utility operators and transmission operators) can be explored to identify vulnerability. This could be used to identify attack surfaces, attack vulnerability and to design test cases that can show system collapse due to cyber-physical attacks. OitL studies could be conducted to understand human factors during adverse events. By conducting extensive experiments using such a setup, mitigation strategies for common control challenges could be developed using the cyber-physical models.

3.0 Large-scale Real-time Distribution Testbed

A large feeder model was developed in this effort to serve as the backbone for experimentation. The IEEE 9500 node test feeder [1] was identified as a viable candidate to enable experimentation at scale. As part of this effort one of the three feeder sections in the 9500-node test case was modelled. The realized distribution model (Fig. 1) is in the 3000-node range making it large enough to explore interesting use cases. Single phase loads at the triplex level were aggregated up to the medium voltage nodes on this system to enable ease of modeling. A novel tool to explore automated model building was developed as part of this work and will be detailed in the following subsection. To incorporate a variety of inverter control strategies, a few candidate control frameworks were modelled and benchmarked as part of this work and will be detailed in subsection 3.2. Since, third party energy entities are a focus of this work; an open-source implementation of a publish-subscribe agent is developed in python to allow a range of third-party agents with carrying objective functions to be modelled on the network layer. Subsection 3.3 will detail the same.

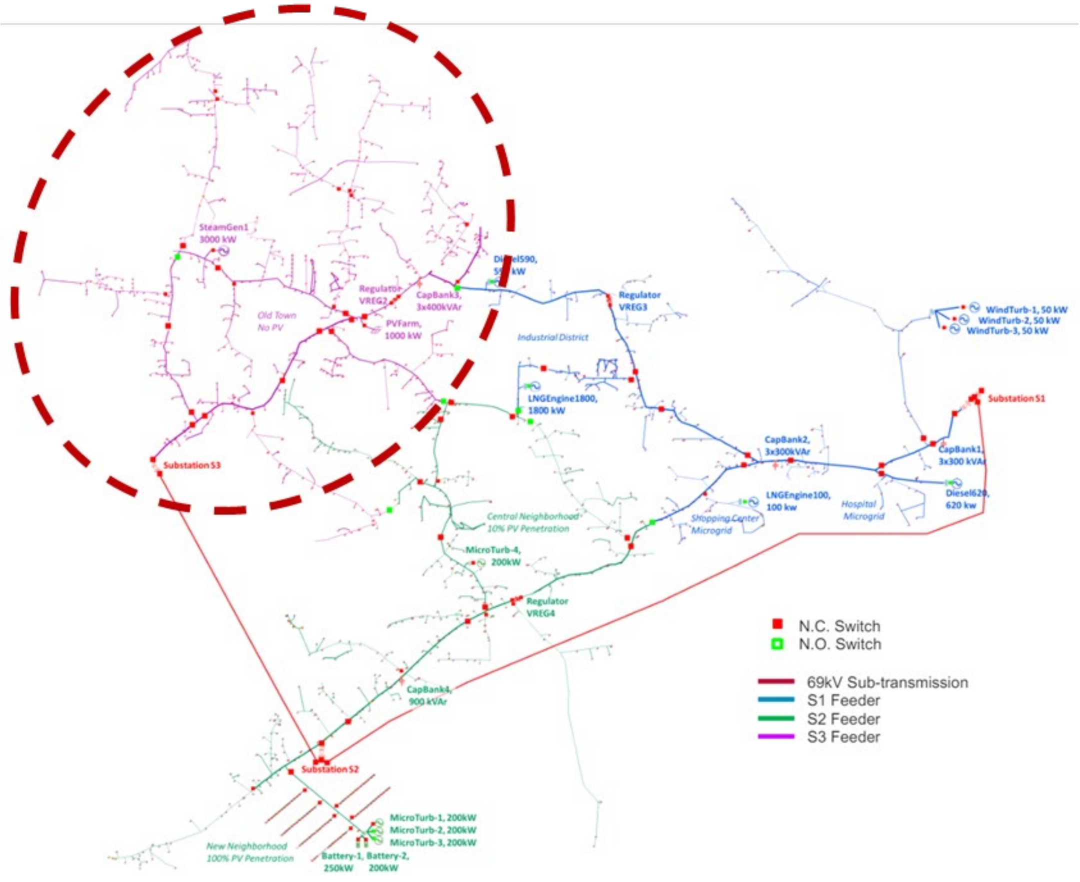

Figure 1. Feeder subsection of interest in the IEEE 9500 node test feeder [1]

3.1 Feeder conversion and automation

There is an extensive library of large-scale benchmarked feeder models developed in a range of low-fidelity platforms like GridlLAB-D [2], OpenDSS [3] and CYME [4]. While these models are adequate for slower Quasi-static Analysis, they are inadequate for capturing cyber-physical phenomenon or for studying system transients with large number of DERs. To enable this analysis a model conversion pipeline was developed to enable low-fidelity benchmarked models to be converted to high-fidelity real-time simulation platforms. The pipeline was developed to convert existing GridLAB-D models to Hypersim – a real-time simulation platform [5]. Fig. 2 shows a flowchart detailing the methodology.

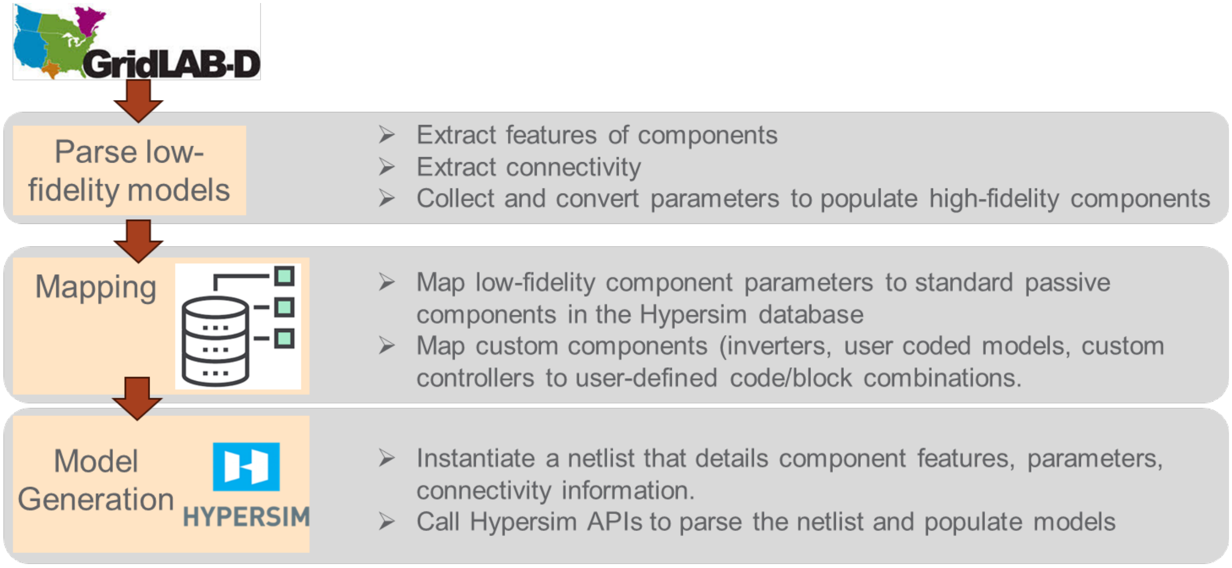

Figure 2. GridLAB-D to Hypersim Conversion Tool

The process begins by parsing through text-based models in GridLAB-D to collect component definitions and their connectivity to build a rudimentary graph of the power system model. Next, the component parameters are extracted and converted to definitions conducive to a electromagnetic transient simulation platform. Lastly, a netlist of component definitions is generated, and a python API interface is called to use Hypersim's inbuilt population tool to correctly populate a large-scale feeder in Hypersim. Commercialization and licensing processes for this tool are currently being explored. Fig. 3 shows the realized Hypersim model for the feeder of interest using this conversion processes. The developed model was tested to benchmark and match steady state power flows as compared to its GridLAB-D counterpart.

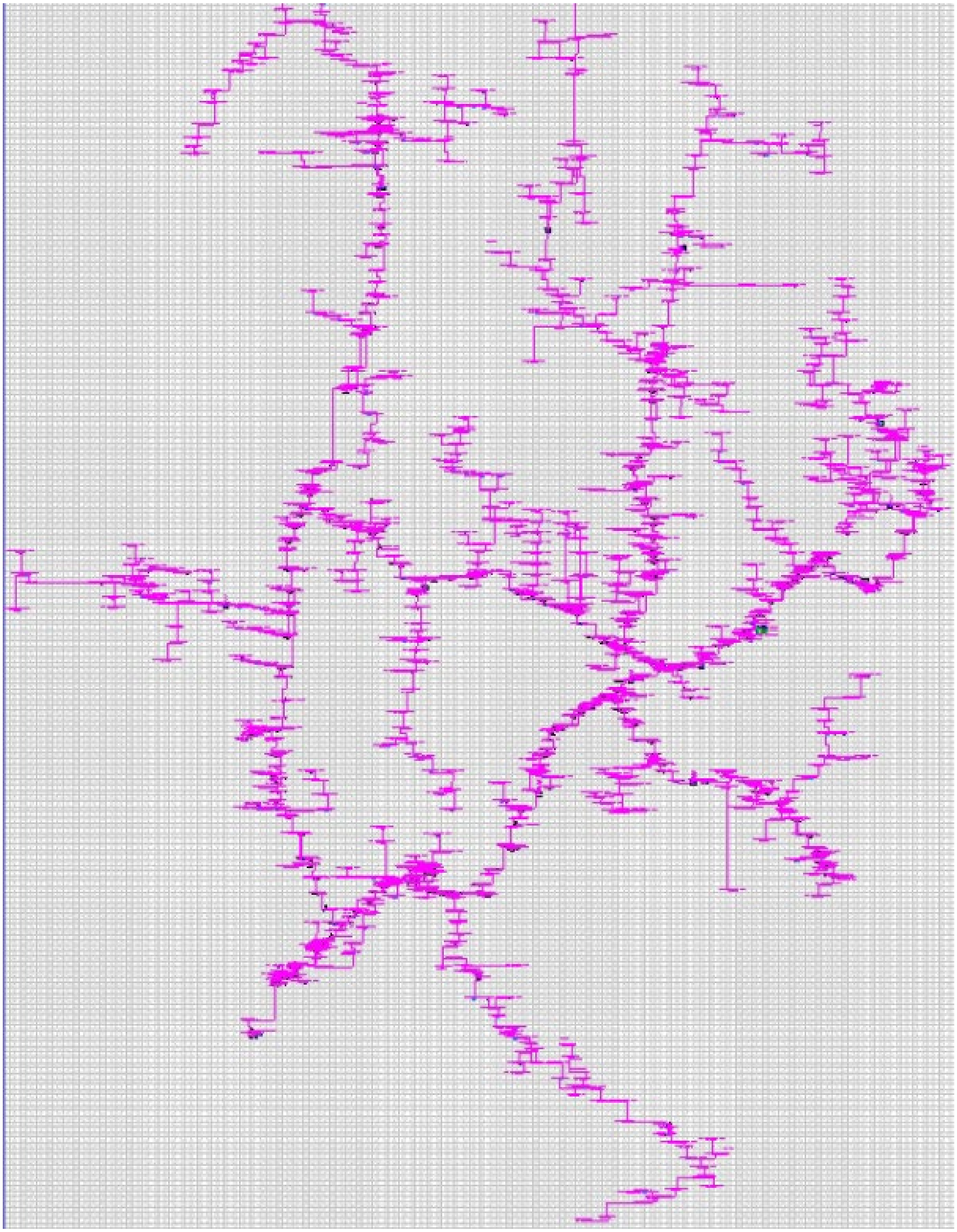

Figure 3. Real-time Hypersim Model of Feeder 3 from the 9500 node test feeder

3.2 High-fidelity Models for DERs with Varied Control Strategies

To understand the impact of varied inverter control strategies benchmarked models were developed as part of this effort to model legacy as well as modern control approaches seen in distribution systems. Three main control strategies were modelled in Hypersim to enable real-time experimentation.

- Single-phase grid-following inverters with Proportional resonant (PR) control [6]
- Single-phase grid-forming inverters [7]
- Three-phase inverters with advanced IEEE 1547 based controls [8]

Fig.4 shows the implemented model for a grid-following inverter with PR controls. The performance of this model has been benchmarked against typical behavior seen in literature.

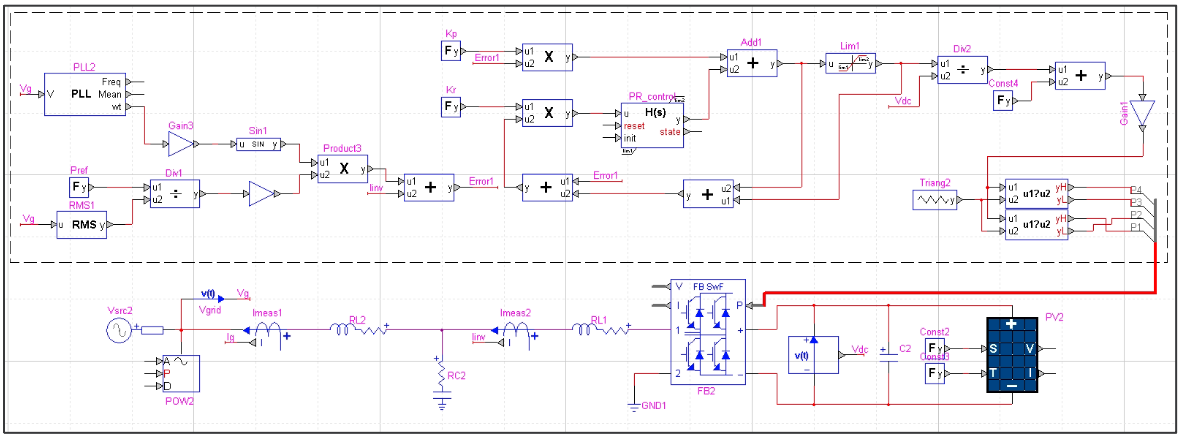

Figure 4. Real-time model of a single-phase grid-following inverter with PR controls

Fig. 5 illustrates an implemented model in Hypersim for a grid-forming inverter based on d-q parameters. This model captures typical legacy inverters seen in the field.

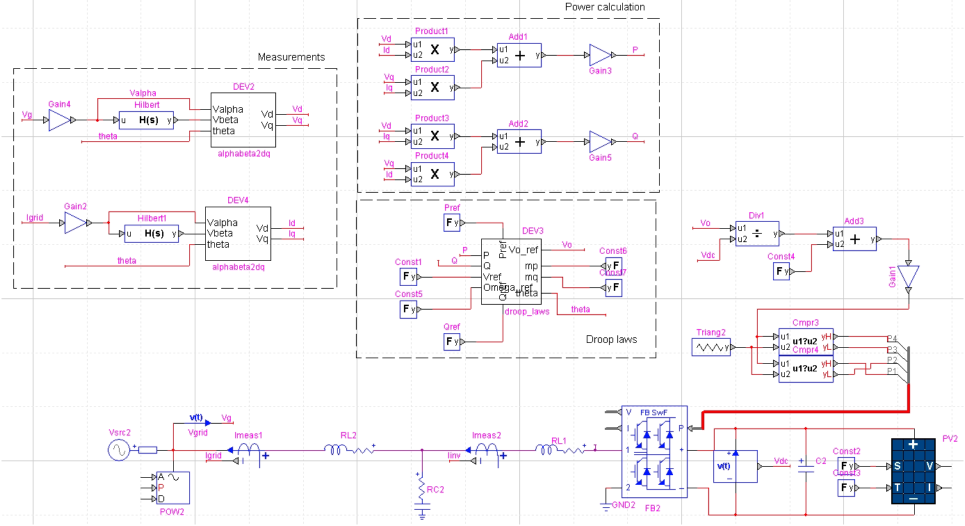

Figure 5. Real-time model of a single-phase grid-forming inverter

3.2.1 Modern DER control standards

Newer control frameworks focus on the ability of inverters to rife-through disturbances. By incorporating discrete behavioral characteristics IEEE 1547 based controls allow inverters to maintain predetermined responses to voltage and frequency events [8]. Fig.6 and 7 detail the voltage ride-through requirements detailed for existing DERs and future DER technologies respectively, that are part of this standard.

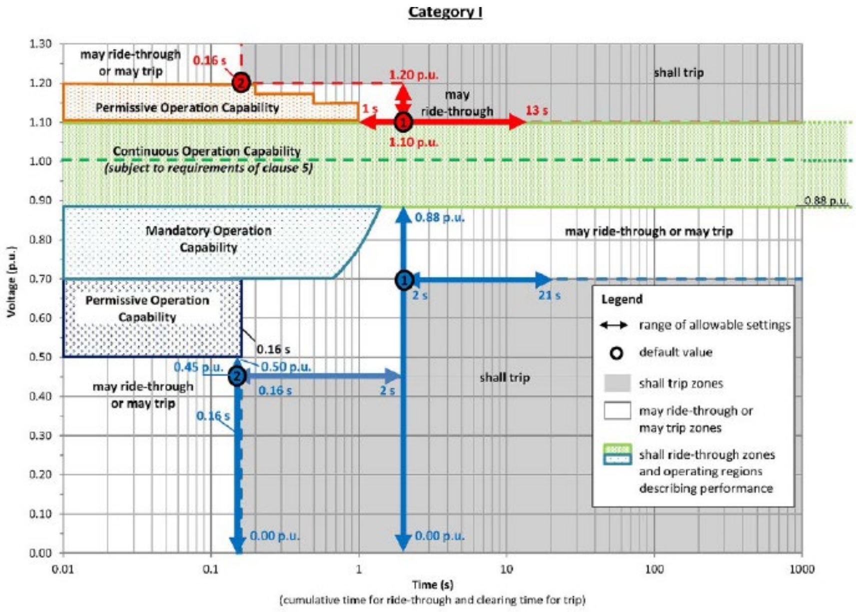

Figure 6. Abnormal Voltage Ride-Through Requirement for existing DERs [8]

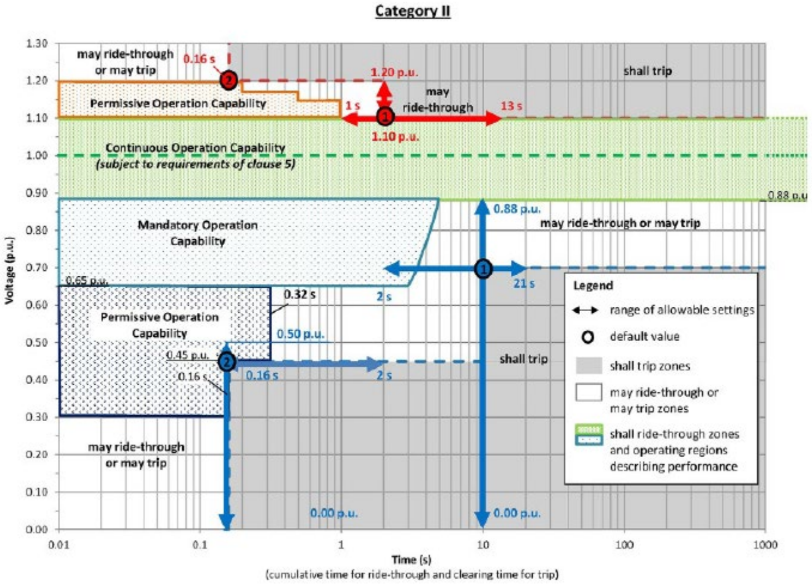

Figure 7. Voltage Ride-Through Requirements to meet NERC reliability requirements.

In order to capture this, an equivalent of the WECC REEC(A) model [9] that captures IEEE 1547 characteristics like momentary cessation, voltage ride-through and frequency ride-through was developed. The WECC REEC(A) model is a benchmarked model that has been replicated in numerous power system platforms. The control structure modelled is detailed below in Fig. 8. The highlighted sections represent the momentary cessation functionality and the ride-through controls that are a feature of this control framework.

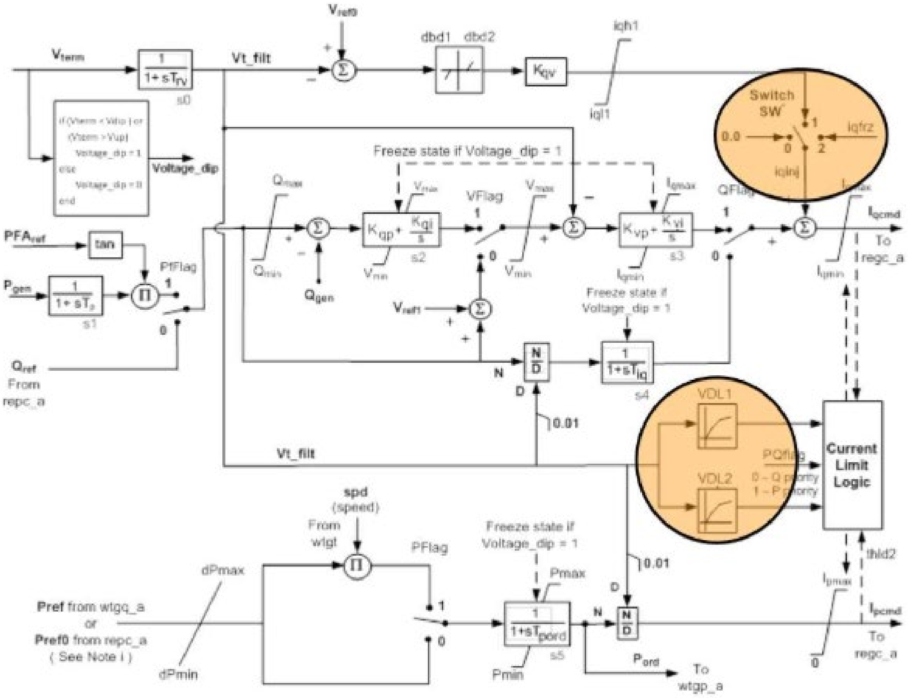

Figure 8. WECC REEC model incorporating smart inverter features.

By capturing these legacy and modern controls commonly seen within inverters and benchmarking real-time models for them, the effect of mixed standards seen across DERs in today’s distribution system can be captured. These strategies were randomly distributed and populated at 24 key points on the high-fidelity feeder model from section 3.1.

3.3 Third-Party Energy Entity Emulation

With a rise in third-party energy agents like aggregators, distribution system operators (DSOs) and microgrid operators, the control decisions are often more distributed than a centralized control approach. These agents collect data over telemetry, add in upstream system objectives conveyed from a SCADA system, execute control algorithms, and send command signals back to DERs that are aggregated. Thus, a middle ware agent that relies on inputs from both upstream and downstream telemetry signals needs to be realized.

The work proposed in this section details the development of an open-source python agent that can subscribe and publish decisions to an upstream (SCADA) entity as well as a downstream group of devices (DERs). Fig. 9 is a schematic of the developed agent. The agent is developed by leveraging the openDNP3 code set that allows processing of packets over the DNP3 protocol

[11]. The agent also heavily leverages prior work that encompasses the VOLTRON platform [12]. The current implementation of this agent can publish and subscribe on all channels. However, the message bus between the upstream and downstream channels is still under development.

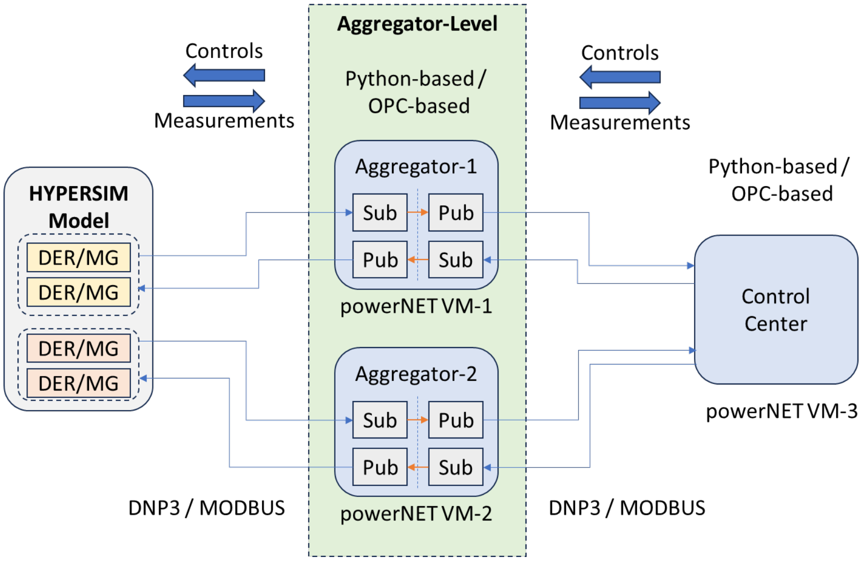

Figure 9. Open-source third party energy agent model

4.0 Outcomes

The developed tools will allow use case generation to analyze complex cyber-physical phenomenon on a large-scale distribution system with mixed DER standards and multiple third-party energy agents. The testbed is built with federation in mind to allow even more scaling through interfaces with other complex real-time testbeds. The developed model generation pipeline will allow conversion of a large set of usable models from low-fidelity to high-fidelity platforms.

4.1 Future work

The work highlighted in this report is being leveraged in a capstone project that capture numerous other thrusts within this initiative. A range of datasets will be generated using the large-scale testbed to analyze system modes in a variety of configurations, DER responses, test varying control architectures at both the device and system level and capture information flows and coordination metrics between varying information flows. These datasets can support the design and validation of a variety of proactive and adaptive tuning measures that can improve resilience in cyber-physical systems. One such solution is an online optimization based adaptive learning-enabled resilient tuning (ALERT) tool developed at PNNL [13]. The tool has demonstrated the ability learn from adversarial scenarios and generate robust predictive dispatch measures as well as modify DER setpoints in response to events to maintain a margin of resilience. This tool could serve as a viable basis and be extended towards an environment with multiple energy parties to account for the coordination between these entities and issue hierarchical setpoint changes to improve resilience.

Further, by analyzing information flows and packets on the network in such complex architectures, proactive and reactive defense strategies can be developed against cyber-attacks. The approach would involve creating situational awareness based on control strategies commonly implemented in an environment with multiple energy parties and analyzing the system’s vulnerability against state-of-the-art attack models such as denial of service, data integrity attacks or command injection scenarios. A physical aware cyber platform (PACP) developed at PNNL will be extended towards developing a detect, protect, and respond layer to help mitigate cyber-attacks on the developed testbed [14].

Lastly, local control options like enhanced DER control strategies that are part of evolving standards will be tested and validated to evaluate system resilience. Standards such as IEEE 1547 and their associated DER controls structures will be evaluated on the testbed to validate microgrid resilience under islanded and grid connected modes. By evaluating resilience measures at the local control, system control and on the cyber layer a holistic view of resilience and mitigation strategies can be evaluated on a realistic scalable and federated testbed.

5.0 References

[1] Anderson, Alexander A., Vadari, Subramanian V., Barr, Jonathan L., Poudel, Shiva, Dubey, Anamika, McDermott, Thomas E., and Podmore, Robin. Introducing the 9500 Node Distribution Test System to Support Advanced Power Applications: An Operations-Focused Approach. United States: N. p., 2022. Web. doi:10.2172/1922914.

[2] D. P. Chassin, K. Schneider and C. Gerkensmeyer, "GridLAB-D: An open-source power systems modeling and simulation environment," 2008 IEEE/PES Transmission and Distribution Conference and Exposition, Chicago, IL, USA, 2008, pp. 1-5, doi: 10.1109/TDC.2008.4517260.

[3] OpenDSS- An electric power distribution system simulator. EPRI Home. (n.d.). https://www.epri.com/pages/sa/opendss

[4] Cyme Power Engineering Software Solutions| Eaton. https://www.eaton.com/us/en-us/digital/brightlayer/brightlayer-utilities-suite/cyme-power-engineering-software-solutions.html

[5] Barry, A. O., et al. "Digital real-time simulation for distribution systems." 2000 IEEE ESMO-2000 IEEE 9th International Conference on Transmission and Distribution Construction, Operation and Live-Line Maintenance Proceedings. ESMO 2000 Proceedings. Global ESMO 2000. The Pow. IEEE, 2000.

[6] Y. Liu, R. Bai, D. Wang, W. Ma and L. Wang, "Proportional-resonant control method of three-phase grid-connected inverter," The 26th Chinese Control and Decision Conference (2014 CCDC), Changsha, China, 2014, pp. 4797-4800, doi: 10.1109/CCDC.2014.6853032.

[7] H. Rezazadeh, M. Monfared, M. Fazeli and S. Golestan, "Single-phase Grid-forming Inverters: A Review," 2023 International Conference on Computing, Electronics & Communications Engineering (iCCECE), Swansea, United Kingdom, 2023, pp. 7-10, doi: 10.1109/iCCECE59400.2023.10238661.

[8] "IEEE Application Guide for IEEE Std 1547™-2018, IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces," in IEEE Std 1547.2-2023 (Revision of IEEE Std 1547.2-2008) , vol., no., pp.1-291, 20 May 2024, doi: 10.1109/IEEESTD.2024.10534228.

[9] Pourbeik, Pouyan, and Jeffrey K. Petter. "Modeling and validation of battery energy storage systems using simple generic models for power system stability studies." Cigre Sci. Eng 9 (2017): 63-72.

[10] R. T. Elliott, A. Ellis, P. Pourbeik, J. J. Sanchez-Gasca, J. Senthil and J. Weber, "Generic photovoltaic system models for WECC - A status report," 2015 IEEE Power & Energy Society General Meeting, Denver, CO, USA, 2015, pp. 1-5, doi: 10.1109/PESGM.2015.7285992.

[11] OpenDNP3| https://dnp3.github.io/

[12] J. Haack, B. Akyol, N. Tenney, B. Carpenter, R. Pratt and T. Carroll, "VOLTTRON™: An agent platform for integrating electric vehicles and Smart Grid," 2013 International Conference on Connected Vehicles and Expo (ICCVE), Las Vegas, NV, USA, 2013, pp. 81-86, doi: 10.1109/ICCVE.2013.6799774.

[13] Upton S.A., G.L. Kidd, S. Kundu, S. Bhattacharya, Y. Lin, V.A. Adetola, and T. Ramachandran, et al. 2023. “Introduction to ALERT: A User-Interface Tool for Resilient Optimization: Technical Report” Richland, WA: Pacific Northwest National Laboratory

[14] S. Niddodi, ”Physical Aware Cyber Platform” | https://www.pnnl.gov/physical-aware-cyber-platform

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