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Microgrid R&D Program White Papers

Topic Area #2: T&D Co-simulation of Microgrid Impacts and Benefits

March 2021

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Summary

The future electricity infrastructure of the United States is projected to have the majority of generation being low to no emissions, and 30%-50% of the generation resources interconnected at the distribution level. Additionally, the future power system will have large numbers of distributed energy resources (DERs), in addition to generation, such as stationary batteries, electric vehicles, responsive loads, and distributed power electronic devices. In this future, microgrids will be a fundamental building block in addressing the challenges of interoperability and scalability. They will operate in various control architectures to support bulk power system operations, achieve local economic and operational objectives, and support the critical end-use loads where the bulk power system is not available.

To this end, the DOE Microgrid R&D Program vision is to facilitate the nation's transition to (1) a more resilient and reliable, (2) more decarbonized electricity infrastructure, in which (3) microgrids have a reduced cost and implementation times, while ensuring that microgrids support an equitable energy transition through prioritized provision of at least 40% of microgrid benefits going to disadvantaged communities in a secure manner. These three enumerated strategic goals are developed in the context that the United States' electricity system is becoming more distributed in nature, and that disruptions to the electricity delivery system (EDS) are occurring more frequently and with greater severity. The vision statement follows.

> *By 2035, microgrids are envisioned to be essential building blocks of the future electricity delivery system to support resilience, decarbonization, and affordability. Microgrids will be increasingly important for integration and aggregation of high penetration distributed energy resources. Microgrids will accelerate the transformation toward a more distributed and flexible architecture in a socially equitable and secure manner.*

The vision assumes a significant increase of DER penetration during the next decade, reaching 30-50% of the total generation capacity. In that context, the Microgrid R&D program seeks to accomplish these three goals:

> Goal 1: Promote microgrids as a core solution for increasing the **resilience and reliability** of the EDS, supporting critical infrastructure, and reducing social burdens during blue and black sky events

> Goal 2: Ensure that microgrids serve as a driver of **decarbonization** for the US EDS by acting as a point of aggregation for larger number of DERs, with 50% of new installed DER capacity within microgrids coming from carbon-free energy sources by 2030.

> Goal 3: **Decrease microgrid capital costs** by 15% by 2031, while reducing **project development, construction, and commissioning** times by 20%.

These goals additionally have cross-cutting topics of focus on equity and security in both R&D and partnered demonstrations. In regulatory R&D and demonstrations, focus will be on supporting an **equitable energy transition** through prioritized provision of at least 40% of microgrid benefits going to disadvantaged communities. In security, consideration for physical and cybersecurity research, and leveraging or teaming with appropriate entities advancing security through R&D will be considered.

This white paper is one of seven being prepared for the DOE Microgrid R&D program as part of the strategy development. The seven white papers focus on the following areas:

1. Program vision, objectives, and R&D targets in 5 and 10 years
2. **T&D co-simulation of microgrid impacts and benefits**
3. Building blocks for microgrids
4. Microgrids as a building block for the future grid
5. Advanced microgrid control and protection
6. Integrated models and tools for microgrid planning, designs, and operations
7. Enabling regulatory and business models for broad microgrid deployment

This white paper covers Topic Area #2 and presents concepts for how co-simulation of transmission and distribution systems, as well as relevant supporting infrastructure like communications systems, can be used to support the DOE Microgrid R&D program vision, as outlined in the white paper for Topic Area #1. Specifically, how microgrids, and networks of microgrids, will be fundamental building blocks for a future electrical infrastructure that is resilient, decarbonized, and is cost-effective/accessible for all stakeholders. The work proposed for the Microgrid R&D Program will leverage previous DOE investments in the form of existing tools such as the Hierarchical Engine for Large-scale Infrastructure Co-Simulation (HELICS) and the North American Energy Resilience Model (NAERM) extensively. Additionally, existing academic and industrial capabilities will be leveraged, and public/private partnerships formed as necessary. The material presented in this white paper focuses on the development of co-simulation capabilities using existing platforms, including extensions to them, and does not recommend the development of new co-simulation platforms.

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1.0 Introduction

In the United States and its territories, electric generation is increasingly supplied from distributed energy resources (DERs), and technology and policy trends are continuing to drive towards a more decarbonized and distributed electricity energy infrastructure [1]. These trends are leading to a future power system with 30%-50% of the generation assets connected at the distribution level, resulting in complex architectures, operations, and regulatory structures. Additionally, the majority of these new generation resources are renewables which are interconnected via power electronics which presents new control challenges, and opportunities. As the penetration levels of DERs continue to increase, it will become increasingly difficult to integrate them using existing centralized control architectures. Microgrid technologies will be a key enabler for a future with high penetrations of DER by enabling aggregation of DERs at the distribution level to better coordinate with the transmission system. Additionally, the increasing occurrence of extreme weather events is placing greater operational pressures on transmission systems under conditions for which they were not designed. This is another opportunity for microgrids to support critical end-use loads by enabling portions of the distribution system to operate independently when the bulk power system (BPS) is not available.

These capabilities offer bottom-up flexibility and scalability to help transition to a future grid that is higher in resiliency, lower in emissions, lower in cost, and equitable. To navigate the path to the future, simulation and analysis will be a key tool to understanding options, supporting decisions, and determining technical requirements. In particular, the co-simulation of transmission and distribution systems, as well as relevant supporting infrastructure like communications systems, will play an essential role in determining how microgrids can provide the fundamental controls and capabilities to support not only the critical end-use loads, but to also interact on a routine basis with the BPS.

Traditionally, the modeling of electric power systems has been divided along the lines of transmission systems and distribution systems [2], [3]. In each of the simulation types, the other is treated as a boundary condition. Transmission-level simulations treat the individual distribution systems as aggregated load models, typically as simple constant power loads for steady state analysis and simplified static and/or dynamic models for transient stability analysis, and distribution-level simulations treat the bulk power system as an ideal stiff voltage source [4]. While this approach was effective when distribution systems were passive actors, the increasing deployment of DERs and advanced control systems is increasing the interactions across the transmission and distribution (T&D) boundary. Nowhere is this seen more clearly than in the deployment of microgrids where aggregated DERs can participate in BPS markets during normal operating conditions and support the bulk system during abnormal events.

In the 2010s, with the increasing deployment of smart grid technologies, evolving operational capabilities, and changing regulatory policies, there was an increasing awareness of the need to model T&D systems in a single simulation environment. By examining both transmission and distribution in a “co-simulation” environment, it is possible to examine the interdependencies of transmission and distribution systems while still capturing key features only seen with each at full resolution. Although transmission and distribution systems are both power systems, there were many barriers that posed challenges to combining the models and running co-simulations. These include:

1) For most applications, transmission systems are assumed to be electrically balanced and modeled using a single-phase representation. In contrast, most distribution modeling

captures the inherent imbalance of North American systems using full three-phase representations. This also allows accurate modeling of single and double phase portions of the distribution system, such as laterals [3].

2) While the bulk power system of North America has three electrical interconnects, there are 36 balancing authorities (BAs) in the eastern interconnection, 34 in the western interconnect, and the Electric Reliability Council of Texas (ERCOT). Each of the BAs maintains its own power system models, with assumptions and representations for overlapping areas of connection.
3) According to the US Energy Information Administration (EIA), as of August 2019, there are 168 Investor Owned, 812 cooperative, and 1,958 public utility distribution companies [5]. Each of these companies maintain their own independent models, and in many cases may have missing or incomplete data or may include only asset management data rather than full electric models.
4) Different organizations conduct different levels of simulation and analysis.
5) Different organization use different software, each with its own modeling structure which are often not natively compatible.

While there were a number of early academic and research tools for conducting co-simulation of T&D, not all of these were practical for full scale analysis. Some of these early efforts combined, or "federated", existing tools [6]-[8], while others reformulated the entire simulation problem into a single environment [9], [10]. While the approaches that reformulated the entire simulation approach were mathematically innovative, they failed to leverage decades of research, development, and investment that existed in current tools; and also, often failed to address the data handling challenges of the different tools. Additionally, those co-simulation approaches that did use off-the-shelf simulation components were typically developed using custom connections that hampered utility and extensibility [11]-[13].

While there are large number of tools that have been developed in the last decade to examine various aspects of co-simulation, the most advanced tool to date that leverages existing commercial investments is the DOE's Hierarchical Engine for Large-scale Infrastructure Co-Simulation (HELICS), and the extended HELICS+ [14]. Consistent with DOE's effort to support, and not reproduce, industry capabilities, HELICS+ is designed to federate the capabilities of existing tools, both research and commercial. HELICS+ acts as the central coordinator to enable simulations to be run in parallel and for information to be exchanged during the simulation run time. Specifically, time management and message passing between the simulators is handled by HELICS+. This allows different simulators to be run at different time resolution, if needed. These functionalities allow models that already exist at utilities to be used by HELICS+, and combined with other simulations, including those that cross the T&D boundary [15].

While HELICS+ has been used for a wide range of studies on the power system as part of the North American Energy Resilience Model (NAERM), including T&D power flow studies [16], faster dynamics [17], hardware-in-the-loop [18], and integrating multiple infrastructures [19], [20], it has not been used widely for microgrid applications. To be able to effectively incorporate microgrid and networked microgrid operations, additional development of tools and interfaces are required to support the range of use-cases introduced by collections of individual microgrids, and networks of microgrids. This includes operating to support the bulk power system, distribution system, and critical end-use loads. Additionally, as an industry it is still not clear what operations may exist in the future that require co-simulation. The purpose of this white paper is to examine what T&D co-simulation capabilities will be necessary in the next 5-10 years to support the design and operation of microgrids and networked microgrids.

Based on the current capabilities of the HELICS+ platform, the DOE Microgrid R&D program will not need to develop generalized co-simulation capabilities but will instead focus on how existing co-simulation capabilities can be used to identify/validate the utility and value of microgrids across the T&D boundary, including enhancements to individual simulation tools and corresponding interfaces for use in established co-simulation frameworks. Additionally, relevant supporting infrastructure like communications systems will be included as necessary to properly represent the range of architectures, controls, and operations necessary in a future power system where microgrids are a fundamental building block [20], [21].

2.0 Vision for the Future

In the United States and its territories, electric generation increasingly comes from distributed energy resources (DER) [22]. Technology and policy trends are driving towards a more distributed electricity energy infrastructure. These trends are leading to a future power system with 30%-50% of the generation assets connected at the distribution level, resulting in complex architectures, operations, and regulatory structures. Additionally, the distributed assets will include a high percentage of inverter-connected sources, presenting both operational challenges and opportunities.

The increasing number of DERs include, but are not limited to, distributed solar, stationary battery energy storage systems (BESS), electric vehicles (EVs), and responsive end-use loads. The increasingly large number of distributed assets cannot readily be integrated into existing centralized operational system architectures. One option to effectively integrate the increasing number of distributed assets, while simultaneously increasing reliability and resilience, is to use microgrids as a fundamental building block of system planning and operations. DERs may be implemented in a microgrid, which can operate in support of the BPS, or independently from the BPS as necessary. In remote applications, microgrids may not be connected to any bulk power system, but there may still be multiple small microgrids that can interconnect. The degree to which such generation is coupled among distributed assets and aggregated into microgrids, and networks of microgrids, depends on the needs and constraints of the end-users and access to technical capabilities, available resources, mid and long-term planning considerations, as well as regulatory and policy issues.

In addition to addressing technical issues, microgrids have the potential to address some equity challenges while introducing others. Microgrids can provide mechanisms for local communities to have autonomy over energy resilience that can address equity and environmental justice that are specific to their community needs. Place based research and development activities support consistency with Justice40 Initiative objectives.[1]

Within the next 5 to 10 years, the operations of microgrids will begin to transition from independent one-off deployments to coordinated systems that can interact with one another and support the BPS. As microgrids move to these more complicated operational scenarios, the control systems will evolve from traditional centralized systems to architectures with more distributed features to support the increasing number of distributed devices and mixed ownership modes. Enabling such future operations, including evaluating new control architectures, will require significant advancement of existing simulation capabilities and analysis processes.

For microgrids to become active elements that support both distribution and transmission system operations, it is necessary to enhance the fundamental understating of the T&D boundary. This Topic Area #2 whitepaper envisions a future where evolved simulation and analysis capabilities will be able to support examining the planning and operational issues of microgrids for both distribution and transmission systems. This includes a range of simulation capabilities from static power flow solutions to the more complex dynamic and transient simulations.

This white paper outlines the required fundamental and applied capabilities so that planners and system operators will be able use advanced tools to answer the more complex questions related to microgrids. An example capability would be to examine the economic optimization of microgrids using locational marginal pricing (LMP) at both the transmission and distribution level while

[1] White House Justice40 Initiative https://www.whitehouse.gov/environmentaljustice/justice40/

ensuring dynamic stability of the BPS. To do this, a number of individual technological developments are necessary.

Co-simulation capabilities will be essential to support the microgrid operations necessary to enable the transition to the future power system. To fully evaluate the technical and regulatory impacts of microgrid operations that span the T&D boundary, it will be necessary to move beyond static power system flow simulations. Specifically, it is expected that T&D co-simulations will need to support:

1) Power flow (steady-state)
2) Time-series, also referred to as Quasi-Static Time-Series (QSTS)
3) Electromechanical Dynamics (time-steps of approximately 1 millisecond)
4) Electromagnetic Dynamics (time-steps of approximately 1 microsecond)
5) Control and Protection
6) Techno-economic Optimization (production cost model type studies)

Future co-simulation environments and workflows that can support all six of these areas will be necessary to fully evaluate how microgrids will be most effective in supporting the nations electrical infrastructure. Accelerating towards these capabilities will be a focus of the Microgrid R&D Program.

3.0 Technology Developments

The central challenge of co-simulation lies in providing the ability to simultaneously simulate multiple systems while managing the data structures and timing between the individual federates. With the federates being collections of software environments, scripts, and/or hardware. In many cases, there are existing simulation tools that allow simulation of each system or subsystem individually, but these tools tend not to be compatible with one another, both in terms of data structures as well as simulation methodologies. If it were possible for these tools to be federated into a single simulation environment, a wide range of co-simulation scenarios could be examined, this is the goal of the DOE funded HELICS+ program [14]. HELICS+ is a powerful tool that has been effective in a wide variety of co-simulation applications. More detail on the HELICS+ platform can be found online [23]. The DOE is investing in the HELICS+ co-simulation platform and, as such, the microgrid program will not develop parallel capabilities. Where necessary, additional capabilities will be developed and committed into the open-source HELICS+ code so that the work has the greatest value. Because of the wide range of potential planning and operational scenarios that can be examined, this white paper will focus on the capabilities that should be developed, and how they can be used to address larger classes of problems.

It will be necessary to have the capability to fully model and understand the T&D boundary at the full range of time scales. This will require the use of existing co-simulation capabilities to build the use-cases and knowledge to examine co-simulation for a range of analyses, that include, but are not limited to:

- **Resource optimization**: to conduct optimizations that span from the transmission system to the end-use load.
- **Static power flow conditions**: to conduct power flow simulation that include large transmission systems with many individual distribution system models.
- **Dynamic simulations**: to conduct dynamic simulations that allow for dynamics at the distribution level to impact the transmission solutions, and vice versa.
- **Control and Protection**: to examine control schemes for resilient operations and to determine if new protection schemes that span across T&D are necessary.
- **Market interactions**: to explore and refine the bid, price, and control interactions between ISOs and microgrids for energy and service provision.
- **Islanded and Integrated Simulations**: to enable a single co-simulation setup to seamlessly model the system as one large system or—without restarting—as multiple smaller islands, potentially up to thousands of individual microgrids.
- **Transitions among multiple timescales**: Transitions to/from islanded and integrated states during a longer duration simulation might also require heterogeneous timescales such as using quasi-static power flow for timeseries simulation and then shifting to use faster dynamic or transient simulation during these transitions.

Similar to how the power flow solution is used as the building block for more complex applications, the capabilities listed above will form the foundations necessary to evaluate microgrid planning and operations in an integrated T&D environment. Large BPS are studied using a variety of tools depending on the time scale of the phenomenon being studied. For powerflow studies positive sequence simulators such as PSS/E, PSLF, or PowerWorld are widely used and are sufficiently accurate [24]-[26]. These tools also include dynamic simulators capable of accurately representing electromechanical dynamics typical of power systems supplied by large rotating machines during events such as load switching, system faults, and/or a loss of a generator. For large BPS, these dynamics typically have time constants on the order of seconds to tens of seconds, and the simulation tools used have optimized solvers that allow them to efficiently simulate systems with tens of thousands of nodes or more [27]. When electromagnetic phenomena such as capacitor switching are studied, electromagnetic transient (EMT) simulators such as PSCAD, EMTP-RV, or MATLAB/Simulink are used to study only a small portion of the affected system (tens to hundreds nodes), with the rest of the system being reduced, with methods such as a Thevenin equivalent comprised of a voltage source behind an impedance [27]-[29]. The voltage source may have some dynamic behaviors represented, but it is typically assumed that these dynamics are far slower than the electromagnetic phenomena being studied [30].

It is also true that a variety of tools are used to simulate and study microgrids, depending on the planning problem being addressed. At the planning stage, tools like HOMER are often used to perform adequacy planning ("sizing") and preliminary economic optimization and feasibility studies [31]. When a microgrid is connected to the larger grid, typical distribution analysis tools can be used to study power flow, perform protection studies, and examine the impacts of microgrid on the circuits they are connected to [32]. These tools include CYME, Synergi, WindMil, ETAP, and SKM, among several others [33]-[37]. When the microgrid is operating autonomously, it is often necessary to use an EMT simulator like PSCAD or MATLAB/Simulink because: a) there is no "infinite bus", so the frequency is no longer constant at 60.0 Hz and the power, energy and current limitations of the microgrid sources must be explicitly represented; and b) the time constants of microgrid responses to various phenomena tend to be on the order of milliseconds to seconds.

Modern power systems have an increasing number of assets that are interfaced to the system via a power electronics converter. As a result, there are some microgrids in which the majority of generation is inverter connected [38]. Power electronic sources can be modeled, averaged, and aggregated at a variety of different time scales depending on the phenomena or mechanisms being studied, but it is becoming increasingly true that proper modeling of power system dynamic and transient behavior requires that the detailed inner workings of the hardware and software of inverters be represented in the model. The modeling of these higher speed inner-control loops requires the use of EMT type solvers.

The future power grid will be comprised of a backbone BPS with central generation in the form of traditional thermal plants, hydro, natural gas, wind farms, and solar plants, which needs to interact with networks of microgrids at the distribution level which must work together to maintain system security, stability, and reliability. This interconnected system may have the ability to spontaneously self-disassemble during major events into adaptive intentional islands, and then self-assemble after the event [38]. Microgrids embedded within the larger system may have the ability to black-start other portions of the interconnected system after an outage, in coordination with the centralized restoration efforts. Each microgrid can have power electronic sources and one or more levels of microgrid controllers, and the entire system will likely have an assortment of communications channels. The behaviors of microgrid sources can also be dependent on meteorological factors such as available sunlight and wind, the states of charge of various energy storage elements, and even factors such as the ambient temperature which may impact the ability to call on controllable loads. The fundamental challenge of modeling such a system lies in the need to accurately represent both the long-term and short-term dynamics, at extremely large scale, with the ability to run the simulations fast enough to enable a range of studies to evaluate operational options.

4.0 Enabling Technologies

Effective co-simulation of microgrid planning and operations across the T&D boundary will require leveraging existing DOE investments in co-simulation tools, leveraging existing industrial tools, coordinating with other DOE analysis efforts, and coordination with the other six topic area white papers in this series. While there are multiple co-simulation environments that have been developed, the Microgrid R&D Program will primarily use the HELICS+ framework. Additionally, the program will extensively leverage the existing capabilities of NAERM, which conducts much of its work using HELICS+. Finally, because co-simulation is simply the tool for analysis, it will rely heavily on the work of the other program white papers to provide new capabilities. Two specific white paper areas are Area 5 “Advanced Microgrid Controls and Protection” and Area 6 “Integrated Models and Tools for Microgrid Planning, Design, and Operations.”

The focus of the Microgrid R&D program is not on developing new co-simulation tools. Instead, the focus is on developing new capabilities for existing tools and/or extending their current capabilities. This could include, but not be limited to, the development of new co-simulation workflows and analysis, development of new device and controllers for existing federates, and the development of new federates.

While co-simulation environments have existed in other domains for years, it is only in the past decade that power systems have begun to examine the issue. Existing commercial simulation packages have historically focused on either the transmission or distribution system, with the other treated as a boundary condition. Early work on co-simulation took an ad-hoc approach where existing simulation environments were extended into either transmission or distribution in a very limited scope. Following the early ad-hoc approaches, there were disparate efforts at various national laboratories that were eventually unified into the GMLC-funded Hierarchical Engine for Large-scale Infrastructure Co-Simulation [14]. The current work on HELICS+ focuses on building a platform that allows for the “glue” of co-simulation, focusing on issues such as time synchronization, memory management, data structures, and managing the various federates. As used by HELICS+, a federate can be an instance of software environment, a script or program that emulates a controller and/or function, hardware emulator, or any other federate that could be included in the co-simulation environment. One of the greatest advantages of HELICS is that it is being developed as a “federate agnostic” environment. This means that instead of being optimized for one commercial product family, it is being designed to support the entire range of industry tools. While there is a performance cost for such broad support, the benefits of being accessible to all software platforms far outweigh them. Not only is HELICS designed to support a wide range of power system tools, but it has also federated tools for communications and natural gas co-simulation as part of NAERM.

Past and on-going work with HELICS+ has focused on power flow and time-series work for traditional power systems and their interconnected infrastructures such as natural gas, transportation, and communication. There has been limited initial work on electromechanical dynamic simulations [39], with faster electromagnetic co-simulation only captured when HELICS+ is used to bridge QSTS simulations to real-time EMT simulations, but without exchanging the microsecond-scale EMT data among multiple federates.

Currently the simulation of operations optimization, such as market clearing or direct control are conducted with a single federate, with the exception of work with distributed controls where the simulated communication system connects multiple federates as would occur in practice. The HELICS+ team is currently exploring adding solver-level support to enable co-optimization where a centralized optimization is split between multiple federates. This capability is still one or more years away from being ready for significant analysis work.

Finally, the existing work of both HELICS+ and NAERM have focused on bulk power system operations. Where the distribution system has been included, it has typically been treated as a passive actor, and therefore microgrid operations have not been examined. To this end, the efforts of both HELICS+ and NAERM will be central to the Microgrid R&D Program, but their capabilities will need to be extended. For example, building new controller models for microgrids to extend the analysis and workflows developed as part of NAERM to include high-DER scenarios where microgrids serve a fundamental role for aggregating large numbers of devices. This example would build on the foundational work of NAERM that has co-simulated power flow studies and passive distribution system dynamics, using HELICS+, to an example where microgrids are active control participants that interact with the bulk power system. Collections of individual microgrids as well as networks of microgrids would be included in this example.

5.0 Use-case/Scenario Examples

These use-cases highlight how co-simulation of microgrid operations could be used in the next 5-10 years as part of a larger analysis strategy to support the transition to more a resilient, lower carbon, and lower cost electricity infrastructure. It is anticipated this would be through extending the current work of HELICS+ and NAERM so that microgrids are modeled as active control elements that interact with the bulk power system, distribution systems, and critical end-use loads. This will include individual microgrids, networks of microgrids, and a heterogenous collection of individual and networks of microgrids. This section is divided into four high level use-cases, each with individual scenarios providing specific examples of how co-simulation could be used to examine new microgrid architectures, planning considerations, and operational strategies. The presented use-cases are qualitative in nature and are intended to show how T&D could be used to evaluate future microgrid operations. They represent the types of analysis that will need to be done in the future to provide context for how co-simulation needs to evolve to support microgrid operations. These use-cases do not specify the complete details of how co-simulation should be used; that is the role for future research projects.

For the various scenario descriptions below, the details are provided in two paragraphs. The first provides a qualitative description of the use-case, why co-simulation is needed, and how existing capabilities could be leveraged. The second describes the capabilities that are currently missing and what the benefits of filling these gaps might be.

5.1 Use-case #1: Networks of Microgrids Providing Bulk Grid Services During Normal Operations

A key characteristic of microgrids is their ability to integrate a range of devices and to coordinate them to provide operational flexibility. This operational flexibility will be essential for large numbers of DERs to support routine operations of the bulk power system. As an example, historically distributed resources have been part of the passive demand, perhaps with some of the larger industrial loads participating in infrequently used demand response or curtailment programs. Microgrids (and recent regulations) have the potential to enable demand-side resources to instead become key contributors to transmission-scale grid support services. As the nation's electrical infrastructure transitions to the vision described in Section 2, the increased amount of DER at the distribution level will transition from the current structure of a limited number of distribution devices participating in a transmission market into structures where there will either be a large number of devices collaborating through various control systems and/or market structures. Co-simulation will allow researchers to examine various options for architectures, controls, and regulatory structures. The following use-cases provide examples where co-simulation could be used to characterize the capabilities and value of microgrids, and networks of microgrids. These scenarios are only examples, and do not represent an exhaustive list.

5.1.1 Use-case #1, Scenario #1: Microgrids to Support Bulk System Operations

In a future power system where 30%-50% of the generation capacity is located at the distribution system, it may not be practical to continue to require the central generating plants to supply all of the basic operating functions, such as frequency control and ancillary services. Specifically, at 30%-50% penetration levels, DERs will need to do more than supply kW-hr to ensure a reliable, resilient, and equitable system. The recent FERC order 2222 sets the foundation for DERs and microgrids to participate in support basic system operations [40]. In this scenario, microgrids and networks of microgrids use their existing connections to the bulk power system to ensure a stable frequency and voltage during normal system operations. This is primary done through their participation in system-wide ancillary services. To evaluate operations under these conditions, it is necessary to conduct co-simulations to evaluate the effectiveness of the services provided by microgrids and to evaluate the impact, if any, to the distribution system. Existing co-simulation frameworks such as HELICS+ enable conducting full co-simulations of both power flow and dynamics [41], but microgrids have not been examined in any detail. However, the simulation tools and interactions required for full-scale dynamic simulations that span both the transmission and distribution systems continue to face challenges related to scale and numerical issues. Numerical challenges within this context are primarily associated with the limitations posed by the simulator APIs which ultimately dictates the type of coupling protocol that can be employed at the T&D interface. Additionally, most optimization packages face challenges with the size of models appropriate for a complete T&D model, which can easily be in the range of millions of nodes, when examined over extended timeframes [42].

Current co-simulation capabilities would be able to evaluate steady state operations, but not operations that would require a dynamic simulation spanning transmission and distribution. Additionally, this could include evaluating the certainty that DERs will respond as necessary when requested by the bulk power system, including an evaluation of the impact when there are shortfalls in anticipated response. The inability to conduct full scale dynamic co-simulations is a challenge of integrating pre-complied vendor tools; it is technically possible, but it just has not been fully done. Additionally, for co-optimization there are computational challenges that have not been overcome. And for all of these simulations, there is a need to resolve modeling differences between transmission and distribution elements. If support operations of all types could be fully modeled, then the ability of microgrids to provide them could be fully evaluated. This would increase the benefit of microgrids, and networked microgrids, under existing regulatory structures, and provide a basis for their support of future high DER scenarios.

5.1.2 Use-case #1, Scenario #2: Protection Coordination

As the penetration of generation resources at the distribution level continues to increase, it will become increasingly necessary to examine the coordination of protection schemes between transmission and distribution, including any microgrids at the distribution level. Independent protection mechanisms are present at the transmission level, in distribution, and also in the individual generation sources, particularly power electronics-based sources with fast overcurrent and other internal protection. The ability to simulate all of these, over the same time and system-size scales, is key to ensuring coordination between the various protection schemes.

In order to properly coordinate protection of this combination of microgrid and bulk grid assets, it will be necessary to co-simulate the fault performance of both traditional resources and power electronic-based devices. This includes their local controls, the decision-making software of the microgrids, the electromechanical dynamics of segments of the bulk grid, and the communications systems they may use, and to do so over large areas of the grid containing hundreds of thousands of nodes. This co-simulation capability would facilitate a wide range of use-cases. One near-term example would be to allow power electronics manufacturers to ensure that their internal self-protection functions are properly coordinated with system-level needs in a range of different grid topology conditions to the greatest extent possible.

5.1.3 Use-case #1, Scenario #3: Load Transfer to Support Transmission Overloads

Traditionally, distribution systems are viewed as points of aggregated load from the transmission systems perspective. As the penetration of DERs continues to increase, and are aggregated by microgrids, there is need for a correspondingly higher level of observability and controllability for monitoring and control to allow distribution systems to be a resource to support transmission operations. This includes building a fundamental understanding for what level of observability and controllability are necessary for various planning and operational objectives. In this use-case, distribution systems contribute to the remedial control of the transmission system through load management. A line overload condition on the transmission system is alleviated by load transfer in the distribution systems that shifts loading from a substation to other substation(s) and/or by a microgrid operating to pick-up additional load. By doing so, the loading of the overloaded transmission line is reduced.

Co-simulation of transmission and distribution systems with microgrids is needed for this use-case [43]. The transmission system portion of the co-simulation determines the amount of load that needs to be moved from substations on the two sides of the overloaded line and allows computing sensitivity and boundary constraints. Distribution systems determine the load transfer on the distribution feeders to implement the new loading of substations. Reconfiguration of the distribution system is performed to identify the switching sequence for the feeders. Microgrids contribute to load transfer, reconfiguration, and control in coordination with the distribution grid, removing the transmission system operating constraint.

5.2 Use-case #2: Networks of Microgrids Providing Bulk Grid Services During Abnormal Operations

In the first use-case, scenarios were examined where networks of microgrids could support the BPS during normal operations. Similar to normal operations, there is a parallel in abnormal operations. Specifically, with 30%-50% of the generation assets located at the distribution level, it would not be practical to expect the remaining central units alone to address abnormal system conditions, e.g. system level frequency or voltage instability. To that end, co-simulation will be essential in evaluating the architecture and controls for networks of microgrids to effectively support abnormal operations. The following three scenarios provide examples of scenarios where co-simulation could be used to advance the utility and value of microgrids and networks of microgrids. These scenarios are only examples, and do not represent an exhaustive list.

5.2.1 Use-case #2, Scenario #1: Support of Bulk System During Dynamic/voltage Event

In a future where a large portion of the generation capacity is connected at the distribution level, it will be necessary for them to actively support the bulk transmission system during abnormal events. Two examples being frequency instabilities and voltage collapses. Simulating the ability for the DERs to support transmission system during these abnormal operations can best be accomplished with co-simulation. Tools used within existing co-simulations have the fundamental capabilities to examine the time-series events of a voltage collapse, but they may not have the necessary device models. For dynamic stability events, a dynamic simulation would be required, which lacks some of the simulation capabilities and necessary equipment models [44]. Additionally, electromagnetic simulation capabilities may be needed for events with higher frequency components.

Currently, the ability to model the advanced control functions of DERs only resides in distribution level simulation tools. And for functions such as grid-following operations, these only exist in research packages such as OpenDSS and GridLAB-D [45], [46]. To properly model the ability of microgrids to support the bulk power system during abnormal events, it will be necessary for co-simulation capabilities that allow for advanced controls operating in a range of architectures. When accomplished, co-simulation will allow for the evaluation of the various control systems and architectures that would enable this level of interaction. This would increase the benefit of microgrids, and networked microgrids, under existing regulatory structures, and provide a basis for their support of future high DER scenarios.

5.2.2 Use-case #2, Scenario #2: Restoration with Black Start Supported by Distribution

Severe disruption events to the BPS, whether due to extreme weather events, such as hurricanes or wildfires, or intentional bad-actor attacks, can cause cascading outages throughout the transmission system. However, with the higher penetration of DERs in distribution systems it might be possible to not only maintain services to local distribution customers but to also restore transmission services to some degree during the restoration process. While there are many open questions that need to be answered about this type of operation, the core question is "can a specific set of distribution system assets, e.g. microgrids, support black start in a particular transmission corridor?" Co-simulation offers the ability to answer this question while leveraging existing capabilities, such as high-fidelity power flow simulators for either transmission or distribution, and HELICS+ to combine them.

The ability to analyze the potential for a distribution system to support black start activities on the BPS requires more detailed research into topics such as optimal restoration ordering, voltage stability during restoration actions (switching and load-pickup), system protection in the case of power flow reversal (most protection schemes in distribution systems are designed based on unidirectional power flow). Some of these actions, such as analyzing fast transients during load pickup, would benefit from research into quasi-steady approximations to increase computation speed, and more analysis of the required modeling fidelity to adequately capture the physics of a combined transmission and distribution system is essential. Furthermore, restoration ordering problems are non-trivial, but with fast co-simulation tools, a multitude of scenarios could be tested in parallel. With improvements in these areas, capabilities could be developed which can accurately and quickly simulate the ability to black start the BPS from DERs and microgrids.

5.2.3 Use-case #2, Scenario #3: Dynamically Reconfiguring Microgrids

In this scenario a number of microgrids are able to dynamically reconfigure as necessary to achieve global objectives. During normal operations, this could be via a direct control signal or resources sharing in a virtual power plant type arrangement, and during abnormal conditions it could include topological reconfigurations. The specific control architectures for how the microgrids are engaged will vary depending on the ownership model, operational objective(s), and asset composition, and for this reason it will be essential to use co-simulation capabilities to evaluate performance. While current co-simulation capabilities allow for some analysis, for full-scale applications this is primarily at the steady-state level, e.g., power flow, and there are limited capabilities to examine large-scale dynamics or the ability to perform system wide optimizations.

What is lacking is the ability to conduct system-wide dynamic simulations, possibly electromechanical and/or electromagnetic, to evaluate system stability for new operating modes, and to evaluate switching operations. Additionally, there is a need to be able to conduct optimizations that involve multiple microgrids, and/or networks of microgrids, which are interacting with each other and with the bulk power system. These capabilities will allow for new control schemes and operational strategies where microgrids are a fundamental building block of the future power systems.

5.3 Use-case #3: Evaluation of Control Structures for Networked Microgrid Architectures

As the penetration of DERs and microgrids increase, there will be a variety of potential architectures for how they will interact with the bulk power system. In particular, it will be necessary to examine various potential control architectures from the perspective of both planning and operations. The following three scenarios provide examples of scenarios where co-simulation could be used to advance the utility and value of microgrids and networks of microgrids. These scenarios are only examples, and do not represent an exhaustive list.

5.3.1 Use-case #3, Scenario #1: Fully Distributed

In a fully distributed control system, there is no supervisory function; all distributed elements are equal. This type of architecture has the advantage that there is no single point of failure, but there can be complexities with the lack of supervision and the distribution of information. The open Field Message Bus (OpenFMB) is one such reference architecture, which uses a publish and subscribe (pub/sub) approach for the exchange of information and commands [47]. In order to evaluate the utility of distributed control systems to support high penetrations of microgrids, co-simulation would be necessary to evaluate if information, computations, and commands can reliably be exchanged within the necessary time frames. Because the evaluation of control structures requires power and communications system models, co-simulation is essential.

The evaluation of distribution control architectures requires the examination of the interactions of control signals with communications systems, which occur at the timeframe of power system electromechanical dynamics, i.e. milliseconds. While this has been accomplished with tools such as GridLAB-D and OpenDSS, it has not been done with commercials tools. This can be attributed to the fact that commercial software currently does not perceive an immediate need with their current customers, therefore the tools have not been extended to provide an APR to facilitate co-simulation. Additionally, since they are commercial products, the code is pre-compiled so there are challenges with federating without a provided Application Program Interface (API); it can be done, but it is typically time intensive and a “one-off” solution. If distributed control architectures could be evaluated in co-simulation, it would enable the examination of how networks of microgrids could coordinate their operations. Initial work of this type is being conducted in the GMLC-funded Citadels Project, but this is a preliminary effort and much more work is required.

5.3.2 Use-case #3, Scenario #2: Hierarchical

Hierarchical control systems decompose the complex control of large-scale systems at multiple levels of functionality including monitoring, control, and optimization. Control partitioning can include a primary-level fast local monitoring and control at the device (e.g., DER), secondary-level controls that manage stability (e.g., feeder-level voltage), and tertiary-level controls that perform supervisory system-level optimization (e.g., optimal power flow). These levels of monitoring and control interact over, often heterogeneous, communication systems with system state information communicated from primary to higher level and optimal decisions communicated from tertiary to primary-levels. Supervisory Control and Data Acquisition (SCADA) Systems and Energy

Management Systems (EMS) are examples of such systems as are emerging control paradigms [48], [49].

To evaluate the performance of hierarchical control system, it is necessary to model not only the response of the system physics but also controller behavior, communications, and system-level decision-making. This requires heterogenous models from different domains and co-simulation is essential to design and evaluate the performance before deployment. This evaluation requires investigating control interactions with continuous systems (physical systems) and discrete systems (communication systems) at varying time scales. Additionally, networked microgrid systems are software-intensive and require modeling the software and computational optimization for evaluating the end-to-end performance. While individual tools for modeling the system behavior exist, there is a lack of methods and APIs to integrate diverse set of simulators for trustworthy system-scale modeling with multi-scale dynamics.

5.4 Use-case #4: Interaction Between Microgrids and Transmission Level Market Operations

Another major area where co-simulations will be necessary is in the evaluation of market structures, and how microgrids and networks of microgrids will interact with them. The following three scenarios provide examples of cases where co-simulation could be used to advance the utility and value of microgrids and networks of microgrids. These scenarios are only examples, and do not represent an exhaustive list.

5.4.1 Use-case #4, Scenario #1: Calculation of LMP with Active Microgrids

In places where organized wholesale markets exist, LMPs represent a key signal to generators and demand-side entities about the time and locational value of electricity. Traditionally, the demand-side has effectively been a near vertical demand curve representing a fixed quantity of electricity at nearly any marginal price [50]. Microgrids represent one option to enable demand-side participation in markets by representing the aggregated potential to adjust demand as a function of price in a time-varying way, while also considering the distribution-level technical constraints as coordinated by the microgrid controller. The recent FERC order 2222 further facilitates this type of interaction by eliminating barriers to DER participation in such markets [40]. To simulate and evaluate such a paradigm requires simultaneously capturing the behavior, interactions, and technical and network limits of the hundreds to tens of thousands of entities connected to each microgrid while also capturing a full nodal optimal power flow (OPF) optimization at the transmission-scale [42]. Co-simulation is well suited for capturing these interactions by allowing the full techno-economic simulation of each of multiple microgrids to be modeled in separate software instances, while also connecting and exchanging data for bids and price formation at every market timestep (e.g., day ahead, intra-daily, real-time up to five minutes). Such analysis could build on existing models of market operations including the production cost tools, such as Plexos, Prescient, and SIIP [51], [52], which are currently used. These could then be federated using existing co-simulation frameworks, such as HELICS+, to connect to representations of microgrids.

A key missing capability for fully realizing this scenario is the lack of equivalent techno-economic software tools for microgrids. Most traditional microgrid simulations have focused on the technical aspects without consideration of the economic components, and the limited past work that includes both has historically been custom developed for individual studies and/or imposes a single pre-defined and often simplified market paradigm [53]. Moreover, past work on the technoeconomics of microgrid operations traditionally focuses on coordination within the microgrid itself, while treating corresponding wholesale markets and their LMPs as fixed exogenous boundary conditions. Hence, to support the development of microgrid-transmission-market analysis, a key need is tools for capturing the techno-economic simulation of the microgrids themselves, including both bid formation and microgrid response to various price signals. This capability also needs to support the various microgrid modes and transitions, such as conversion to and from islanded operations and corresponding changes from being removed from and re-included in the transmission-scale market [54]. Additionally, since LMP formation is inherently an optimization problem, additional development is needed to support the integration of external information from microgrids into OPF optimization at each timepoint [55]. Incorporating these new developments into existing frameworks will allow T&D co-simulation to support the exploration and comparison of different paradigms for transmission-level LMP formation with varying quantities and configurations of microgrids. This capability can then help guide both transmission-scale market design and microgrid techno-economic control design for a microgrid-enabled grid modernization future.

5.4.2 Use-case #4, Scenario #2: Bilateral Market Structures

Microgrids at the distribution level can aggregate the increasing penetration of DERs and facilitate their large-scale participation in various market structures. Although recent FERC Order 2222 helps to reduce barriers for DERs to trade in the wholesale market, issues associated with trading of DERs in the retail level still remain [40]. A retail trading mechanism in the distribution system environment provides incentives to further increase the development of microgrids and DERs. Since the number of trading agents in the retail level can be large, a bilateral market that allows generation and load agents to trade with one another and represents and alternative approach to a centralized market. Such a bilateral market would need to be supported by an organization such as a reliability coordinator, e.g., a distribution utility system with the control capability to maintain power system security, e.g. N-1 or N-2, in the market environment [56].

Co-simulation between transmission and distribution (including microgrids) is required to support the functions of the reliability coordinator in the distribution system level. This could include examining the role/requirement of microgrids to provide aggregated ancillary services similar to their central generating counterparts. Bilateral markets do not necessarily balance the supply and demand based on the pool of resources in the retail level. Hence, the distribution system needs to import from or export to the transmission system (or other distribution systems).

5.4.3 Use-case #4, Scenario #3: Market Interactions in the Presence of Microgrids

As the nation’s electricity infrastructure modernizes and becomes more decarbonize and distributed, distribution markets will begin to emerge. As potentially prominent actors in these markets, microgrids will have an important role as they can facilitate large penetrations of responsive loads, increasing the elasticity on the demand-side [57]. Techno-economic co-simulation is key to properly understand the role of microgrids in potential distribution market structures (both as participants and enablers) and to capture the impacts on bulk power system wholesale markets, particularly as interdependence between distribution and bulk power system markets arise. For example, if the wholesale market price is obtained while ignoring the elasticity and flexibility added by microgrids at the distribution level, significant uncertainty in load can be introduced at the TSO-DSO boundary, consequently increasing the need for ancillary services [58]. This effect might be seen as microgrids take advantage of lower prices to buy energy and on the high prices to sell energy, particularly if these prices are presented to customers as fixed values, rather than depend on the distribution market clearing process. Thus, enhanced co-simulation solutions to capture the interactions between wholesale prices, consumers' response, and utility microgrid operations, are necessary for increasing the overall economic efficiency of various market structures. Among the existing available capabilities, some options that could provide a starting point are the Flexible Energy Scheduling Tool for Integrating Variable Generation (FESTIV) tool [59], and the price-based dispatch models from the Distributed Resources Customer Adoption Model (DER-CAM) [60].

While some capabilities currently exist, additional capabilities are needed to fully explore and evaluate the participation of microgrids in market structures. For example, it should be examined how the bids and offers of microgrids can impact on the wholesale market of the BPS. In addition, how the uncertainty associated with renewable generation on the transmission side could be alleviated by the demand elasticity provided by microgrids in the day ahead market. To address these points, the advent of transmission and distribution co-simulation is critically important.

6.0 Research Targets & Goals for 5 to 10 Years

The challenge with defining program targets and goals is that co-simulation, as discussed in Section 2.0, exists for multiple simulation types, e.g., power flow/time-series, electromechanical, electromagnetic, and optimizations. To address this, this section will first examine the technical focus areas for co-simulation, and then map the gaps of these to the program targets and goals.

6.1 Microgrid Co-simulation Technical Focus Areas for

The technical focus for microgrid co-simulation over the next 5 to 10 years should focus on three specific areas:

- Development of new workflows and analytics
- Creation of new device models to support existing tools
- Creation of new federate interfaces to support existing tools

In the first area, the work should focus on how to use co-simulation platforms to conduct specific microgrid analysis. While projects such as HELICS+ are developing the underlying frameworks needed to bring together modeling tools and conduct co-simulation, this only provides the "glue" and demonstration of a limited number of use-cases, none of which target microgrids. Additionally, co-simulation-based analysis currently requires significant effort in data management and post-simulation analysis. Therefore, future work in this area should focus on the overall workflow required to effectively assemble the unique needs for microgrids. This includes identifying the most effective research and industry-oriented workflows tailored to microgrid-BPS interactions in simulation and analysis. This includes ensuring that there is consistency between data and co-simulation models across the different simulation types in Section 2.0. For example, the steady state solution of an electromagnetic solution should be consistent with a static power flow simulation.

The second area of work should focus on the need for new device and controller models for co-simulation. While a range of device models already exist, few are currently able to handle the unique needs of microgrids, notably the ability to support islanded and grid-connected operations, to transition accurately between these modes, and consistently simulate all of these operations across the multiple timescales required. For example, dynamic models may already exist for equipment for a transmission-level model, but that model may not be suitable when coupled with an unbalanced distribution system in a co-simulation. Likewise, many longer-duration simulations would be best enabled by models that can seamlessly transition between time-series analysis and dynamic or EMT simulations during transitions to/from islanded modes. In addition to individual devices controls, it will be necessary to build a range of system level control models to represent the various levels of potential hierarchical control schemes that control microgrids. This can include, but not be limited to, controls for networks of collaborative microgrids, microgrids coordinating with centralized controllers, and EMS/DMS coordination with distribution level microgrids. This area should be coordinated with Topic Area #6: "Integrated Models and Tools for Microgrid Planning, Designs, and Operations."

The third area of work should focus on building new federates for use in existing co-simulation platforms, specifically using HELICS+. As previously discussed, federates for a co-simulation platform can take various forms. These can range from a single instance of a controller in a Python script to a full-scale commercial simulation package. Although a number of tools have existing interfaces for co-simulation, the emerging standardized interfaces that enable true modularity do not cover microgrid use-cases. Identifying a common nomenclature, structure, and conventions for these interfaces to support microgrids is a key need. Also required is a library of off-the-shelf federates for common microgrid needs, such as microgrid controllers. Work in this area should develop the federates and corresponding interfaces necessary to conduct simulation and analysis that specifically supports future scenarios of high penetrations of microgrids interacting with the bulk power system.

In each of the three areas, two key consideration will be the computational and data requirements. The computational capabilities of platforms such as HELICS+ will not be a focus of the Microgrid R&D Program because that will be driven by the larger DOE co-simulation agenda. However, the work in the Microgrid R&D Program should ensure that when extending capabilities within existing platforms that it is done in a way that considers computational efficiency and does not replicate existing capabilities. Specifically, work in the program should coordinate with the platform to ensure that best practices are followed to ensure the best integration; one-off "hacks" that are quick solutions at the expense of extensibility or computational efficiency must be avoided. Similarly, the data structures developed for microgrid work should follow "best practices" of the platform, and where appropriate support efforts to standardize within industry.

6.2 Co-simulation Current Status and Gaps

Currently, the technical capabilities of co-simulation vary depending on the type of simulation being conducted. As a result, the technical needs are expressed as a matrix, Table 6.1, with the axes being the three areas from Section 6.1, and the types of co-simulation. The data in Table 6.1 is based on a HELICS+ co-simulation capabilities using full-size interconnection-level models for the transmission system (e.g., Western Electricity Coordinating Council and Eastern Interconnect models), and multiple full-size distribution circuit models (e.g., unbalanced distribution circuits with 5,000+ nodes each).

Table 6.1: Current Technical Capabilities of Co-simulation for Microgrid-Bulk Interactions

	Power flow/time-series	Electromechanical	Electromagnetic	Optimization
Workflows/Analytics	ongoing	preliminary	foundational	foundational
New Device Models	preliminary	preliminary	foundational	foundational
New Federates	ongoing	foundational	foundational	preliminary

The technical targets for co-simulation, which will support the Microgrid R&D Program Target and Goals for the next 5-10 years are:

- **3 years**: the ability to conduct time-series co-simulations to support planning and operations, with a level of detail and the necessary models, to examine various architectures for how networks of microgrids would operate during normal and abnormal conditions. Initial efforts to introduce tools and workflows to introduce electromechanical phenomena and techno-economic optimization into co-simulations.
- **5 years**: the ability to conduct electromechanical co-simulations to support planning and operations, with a level of detail and the necessary models, to examine various architectures for how networks of microgrids would operate during normal and abnormal conditions. Initial efforts to introduce tools and workflows to introduce electromagnetic phenomena into co-simulations, while also scaling up techno-economic optimization.
- **10 Years**: the ability to conduct electromagnetic and full-scale optimization-based co-simulations to support planning and operations, with a level of detail and the necessary models, to examine various architectures for how networks of microgrids would operate during normal and abnormal conditions.

6.3 Co-simulation Program Goals

While the previous section identified the technical goals of co-simulation capabilities, this section will outline the specific Microgrid R&D Program Target and Goals for the next 5-10 years. Specifically, it will combine the technical focus areas of Section 6.1 with the technical targets for co-simulation of Section 6.2, while referencing the use-case scenarios of Section 5.0.

6.3.1 Research Targets & Goals- 3 Years

Within the three-year timeframe, the Microgrid R&D program should focus on the ability to leverage existing time-series co-simulation capabilities and adapt them for microgrids. While also laying the foundation for electromechanical dynamics, electromagnetics, and optimization which include microgrids for planning and operations. Specific targets and goals include:

- Developing controller models that can support microgrid and networked microgrid operations, including coordination and resource sharing.
- Developing models for responsive/controllable edge devices. (e.g., inverters, variable frequency drives, solid state transformers, power electronics-based voltage regulation devices, electric vehicles, etc.)
- Developing modeling and interfacing approaches to support transitions from one large grid simulation to multiple separate sub-grids and back within the same co-simulation. Initially these may only include time-series models and focus on enabling models and interfaces to swap between having exogenous boundary conditions (e.g., transmission voltage) and developing alternatives internally.
- Demonstrating the ability to conduct utility/ISO-scale time-series co-simulations with detailed microgrid controller interactions. Specifically, the ability to examine the elements of use-case #1-#4 at the time-series level.

6.3.2 Research Targets & Goals- 5 Years

Within the five-year timeframe, the Microgrid R&D program should focus on expanding time-series capabilities to more complex operations, implement electromechanical dynamic simulations at the system level, and continue building devices models and workflows for electromagnetic and optimizations which include microgrids for planning and operations. Specific targets and goals include:

- Evolved controller models for microgrid and networked microgrid operations to support frequency and voltage control during normal and transient conditions.
- Evolved models for responsive/controllable edge devices to effectively simulate faster (msec-scale) interactions
- Enhanced support for separate vs. combined co-simulations to support mixed timestep simulations, such as the ability of both tools and interfaces to support using dynamic-scale simulation during transitions and as needed in islanded operations within an otherwise time-series-based co-simulation.
- The ability to conduct full-scale utility/ISO electromechanical co-simulations with detailed microgrid controller interactions. Specifically, the ability to examine the elements of use-case #1-#4 at the electromechanical level.

6.3.3 Research Targets & Goals- 10 Years

Within the ten-year timeframe, the Microgrid R&D program should focus on expanding time-series and electromechanical capabilities to more complex operations and beginning implementing electromagnetic and optimizations at the system level which include microgrids for planning and operations. Specific targets and goals include:

- Develop controller models that can support networked microgrid operations with respect to frequency and voltage control, during normal and transient conditions.
- Develop models for responsive/controllable edge devices. (e.g., inverters, variable frequency drives, solid state transformers, power electronics-based voltage regulation devices, electric vehicles, etc.)
- The ability to conduct utility/ISO scale electromagnetic and optimization co-simulations with detailed microgrid controller interactions. Specifically, the ability to examine the elements of use-case #1-#4 at the electromagnetic and optimization level.

7.0 Why Should DOE be Funding these Goals and Visions

Funding the examination of the future role of microgrids, via co-simulation, is ideally suited for DOE funding because it is building the foundation for future power system planning and operations that are currently not being explored by industry. With proper DOE investment, the industry will be better situated to support the future power visions, which is being driven by factors that typically move faster than the industry. This includes the development of analysis tools and capabilities, as well as the standards that are necessary for their broad industry adoption.

The current generation of industry tools is still focusing on their legacy client base and there are limited investments in the capabilities that will be needed to fully evaluate the range of potential microgrid operations. In particular, traditional tools are still examining either distribution or transmission with the other treated as a boundary condition. Based on past industry trends, once the utilities begin to “ask” for T&D co-simulation capabilities, it will take industry at least 3-5 years to develop these capabilities, during which time there will be competing approaches and standards. This provides DOE with a leadership opportunity.

By continuing to invest in technologies that integrate microgrid technologies into co-simulation platforms, DOE can ensure that ongoing efforts in the Microgrid R&D Program continue to contribute to the modernization of the nation’s electrical Infrastructure. Ensuring a more reliable, lower carbon, more cost effective, and more equitable critical electrical infrastructure for the nation.

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