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RESEARCH ARTICLE

Scalable Resilience Analysis Through Power Systems Co-Simulation

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ABSTRACT The ability to robustly characterize transmission and distribution grid resilience requires the ability to perform time-scale analysis that interweaves communications, control, and power contributions. This consideration is important to ensuring an understanding of how each individual aspect can affect the resulting systemic resilience. The combination of co-simulation of these time-based characteristics and a resilience-specific metric provides a likely method to inform both design planning and implementation/operational goals to ensure resilience in power systems. The Microgrids, Infrastructure Resilience, and Advanced Controls Launchpad co-simulation platform (MIRACL-CSP) has been developed to allow the modular integration of power grid models with control and metrics applications. This paper introduces MIRACL-CSP as a fundamental platform to study and improve the resilient operation of a microgrid. It offers a holistic investigation environment for systemically comparing the cyber-physical resilience to natural and manmade events. We emphasize the importance/advantage of intertwining the distribution system simulator GridLAB-D with the Power Distribution Designing for Resilience (PowDDeR) application to analyze the resilience of the St. Mary's microgrid in Alaska. The resilience is evaluated in both short-term (frequency stability) and long-term (energy constrained) metrics. The results of the analysis of the St. Mary's microgrid show that there is a trade-off between the two. As inertia-based generation assets are taken off-line, short-term resilience drops. However, the long-term resilience is retained longer as less fuel is being used.

INDEX TERMS Resilience, co-simulation, microgrid, distributed wind, cyber-physical.

I. INTRODUCTION

To assess options in the advancement of modern distribution system (MDS), a set of quantifying metrics are necessary to correlate a value proposition for industry. In alignment with the recently released National Electric Grid Security and Resilience Action Plan,[1] a framework will correlate the overall resilience of MDS options to performance degrading impacts from threats.

Within the power system community, quantitative metrics have been proposed as mathematical formalism to objectively measure the resilience of a system. Based on how the power system and its associated controls perform, these resilience metrics quantify the impact in direct measures associated with loss of generation, ability to maintain critical functionality, and often an integration of the cyber-physical system characteristics. State-of-the-art resilience assessment and quantification methods are reviewed in [1], [2], and [3]. While [1] focuses on frameworks, resilience curves, and quantitative metrics, [2] presents the challenges faced by researchers and power utilities due to nonstandard frameworks and tries to release that burden by categorizing them.

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[1]https://obamawhitehouse.archives.gov/sites/whitehouse.gov/files/images/National_Electric_Grid_Action_Plan_06Dec2016.pdf

In [3] the authors evaluate and compare common metrics for short- and long-term resilience assessments focusing on microgrids' potential for power system resilience improvement. The review of all proposed resilience metrics for electrical power systems, or any other complex system, is not within the scope of this study. However, an established resilience metric that allows for systemic comparison of distributed systems will be leveraged, as will be differentiated in what follows. The ability to recover from an attack, provided the attack is discovered within a fixed time interval, is quantified through the metric proposed in [4]. Metrics to assess the two stages of smart grid operation, that is the duration before a failure occurs and the recovery time after the event, are presented in [5]. The metrics in [6] are directed towards the hardness and asset health as measures of stress, and towards capacity and efficacy as measures of strain. The works of [7] and [8] introduce a quantitative metrics basis to integrate the cognitive, cyber-physical aspects, which should all be considered when defining solutions for resilience. This approach is applied together with considering the uncertainties of solar and hydro renewables in [9], [10], and [11]. In these studies the performance index that provides the basis for resilience is the system adaptive capacity and its inertia. It considers several MDS design variables including generation or demand response delivery capacity, reactive power, power network topology, and control system architecture.

Resilience of complex systems is not a short-term or long-term measure. It encompasses many time scales from prior to an event to potentially days or weeks after. This is shown notionally by the disturbance and impact resilience evaluation (DIRE) curve in Fig. 1. It can be seen that the resilience is broken into five different time scales, known as the "R's" of resilience: recon, resist, respond, recover, and restore. To account for this time-dependent behavior, a dynamic resilience study approach is explored in this paper. In the context of the electrical power grid, resilience depends on supportive and responsive relationships between all the components at the transmission and distribution levels. Mastering a set of capabilities that could help the system respond and adapt to adversity at each individual aspect in a timely and appropriately healthy manner is of utmost importance. For the quantitative metrics to robustly characterize the transmission and distribution grid resilience, there is need for them to capture the interactions of grid components in response to adversity. Therefore, it is imperative to be able to perform time-scale analysis of the intertwined communication, control, and power systems.

The study in [12] proposes co-simulation as means at different design stages to analyze the resilience of complex and multi-disciplinary cyber-physical systems. Co-simulation of domain-specific simulators is involved in [13] to study the resilience of microgrids including smart grid technologies connected through cyber networks. Similarly, [14] presents co-simulation as the approach when studying integrated energy systems resilience. Though studying system resilience is among the goals of the co-simulation, no metrics are

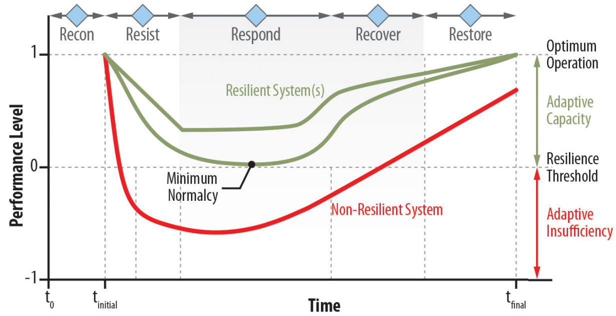


FIGURE 1. The Disturbance and Impact Resilience (DIRE) curve showing "R's" or time scales of resilience. Image taken from [11].

integrated to evaluate it for multiple scenarios and at different time scales.

In this study, co-simulation considers the temporal nature of integrating disparate models to achieve relevant results. The benefit of having the resilience metric in [9], [10], and [11] in parallel is to be able to address in real time short-term and long-term resilience concerns when adaptive capacity and inertia problems arise. The need to integrate disparate models has been the subject of a number of architectures, including the standardized high level architecture, some decades ago. However, the ability to achieve this integration requires that the time scale of the integrated simulation recognizes the artifacts necessary to characterize a judgment, which for resilience considers the man-made and natural threats.

Under the Microgrids, Infrastructure Resilience, and Advanced Controls Launchpad (MIRACL) project[2] at PNNL, the MIRACL co-simulation platform (CSP) in [15] has been developed to provide a real-life-like utility operation system incorporating data monitoring and control systems. In this work, MIRACL-CSP is leveraged to convey distribution system simulation measurements to the resilience metrics at run time. Through the holistic approach of co-simulation, the platform developed in this paper offers an environment that allows the study of complex systems under the specific conditions of dynamic use cases, and, moreover, scaling not only the size of the analyzed distribution system, but also the number of adversaries that could affect it.

The paper is organized as follows. Section II introduces the particular components of the MIRACL-CSP built for this application. Section III details the use cases, while Section IV discusses the results of the current study. Conclusions end the manuscript in Section V.

II. DECOMPOSITION OF CO-SIMULATION ARCHITECTURE

The Microgrids, Infrastructure Resilience, and Advanced Controls Launchpad co-simulation platform (MIRACL-CSP) [15] was developed to allow operational coordination between distribution system models and distribution system applications and technologies. This is particularly important

[2]https://www.pnnl.gov/distributed-wind

for cases where more realistic and dynamic data exchange is required while all simulation instances run in a synchronized manner regardless of their time periods, either continuous or discrete.

MIRACL-CSP offers a modular integration of distribution systems modeled in GridLAB-D [16] and custom-built distribution system monitoring and control applications modeled in Python™ through the Hierarchical Engine for Large Infrastructure Co-Simulation (HELICS) [17], [18] environment. Fig. 2 illustrates the integration of the power distribution system, control, and resilience modeling aspects for our co-simulation.

The software comprising the MIRACL-CSP has been packaged in a Docker image. It ensures rapid application development and testing. Moreover, it offers portability, deployment and execution on different platforms. The MIRACL-CSP depicted in Fig. 2 currently includes:

- Ubuntu[3] 20.4 as the base operating system,
- HELICS[4] version 3 as the co-simulation environment,
- GridLAB-D[5] as the distribution system modeling and simulation environment,
- Python[6] 3.9, with appropriate modules, as the wrapper around the utility control center (UCC) applications for monitoring, optimization-based control, and system resiliency metrics calculation with Power Distribution Designing for Resilience[7] (PowDDeR).

A. HELICS

At the core of the MIRACL-CSP is HELICS, an open-source co-simulation platform that coordinates off-the-shelf simulators and applications, including electric transmission systems, electric distribution systems, communication systems, market models, and end-use loads [17], [18]. HELICS performs the two main functions of a co-simulation, that is time management and synchronization of simulators, in particular, GridLAB-D and Python federates, as well as data exchanges between them.

B. GRIDLAB-D

GridLAB-D is the power system simulator integrated in the MIRACL-CSP. It models and performs power flow calculations of the distribution system. In GridLAB-D, the distribution system is modeled as a three-phase, unbalanced system and can be simulated in either quasi-steady-state or dynamic modes [16], [19]. Moreover, distributed energy resources (DERs), including diesel and wind turbine generators are also modeled in GridLAB-D.

[3] https://ubuntu.com/
[4] https://www.helics.org/
[5] https://www.gridlabd.org/
[6] https://www.python.org/
[7] https://github.com/IdahoLabUnsupported/PowDDeR

C. UTILITY CONTROL CENTER

An application-specific utility monitoring and decision-support system is developed in Python [20] as the UCC in Fig. 2. The UCC incorporates an asset data (e.g., DERs, switches, sensors, loads) monitoring and analysis procedure necessary to run the resilience study with the PowDDeR application [21]. It also extracts different wind power generation profiles from measurement data files and dispatches them to the wind turbine model in GridLAB-D.

D. POWER DISTRIBUTION DESIGNING FOR RESILIENCE APPLICATION

PowDDeR is a software application developed to provide a specific resilience metric for a power system. It is based on the systems adaptive capacity and inertia. Given a set of generation assets in the system, PowDDeR captures the systems real-time inertia and the available adaptive capacity in real and reactive power looking forward in time. It gives a measure of a power system's ability to respond to disturbances, either natural, such as weather related, or human, such as cyber-physical attacks.

The adaptive capacity of a generation asset is bound by its operational generation limits based on its current operation point and the speed it can ramp up and down its output power. The operational limit is the maximum real and reactive power output capability at any power factor angle θ. The real and reactive power components at any power factor are given by

$$P(\theta) = S\cos(\theta) \tag{1}$$

and

$$Q(\theta) = S\sin(\theta) \tag{2}$$

respectively. Here S is the apparent power limit calculated with the nameplate real and reactive capacity, given as

$$S(\theta) = \sqrt{P^2 + Q^2}. \tag{3}$$

The operational limit of the asset must be translated based on its real-time generation in real power, P_0, and reactive power, Q_0, resulting in components given by

$$P_\Delta(\theta) = S\cos(\theta) - P_0, \tag{4}$$

for the real power and

$$Q_\Delta(\theta) = S\sin(\theta) - Q_0, \tag{5}$$

for the reactive component. The temporal limits of real/reactive power outputs are defined by the latency λ and ramp rates, as mathematically expressed in equations (6), (7),

$$P(t) = \begin{cases} 0, & t \le \lambda \\ \frac{dP}{dt}(t-\lambda), & t > \lambda \end{cases} \tag{6}$$

$$Q(t) = \begin{cases} 0, & t \le \lambda \\ \frac{dQ}{dt}(t-\lambda), & t > \lambda \end{cases} \tag{7}$$

where t is the future time, dP/dt is the real power ramping rate, and dQ/dt is the reactive power ramping rate.

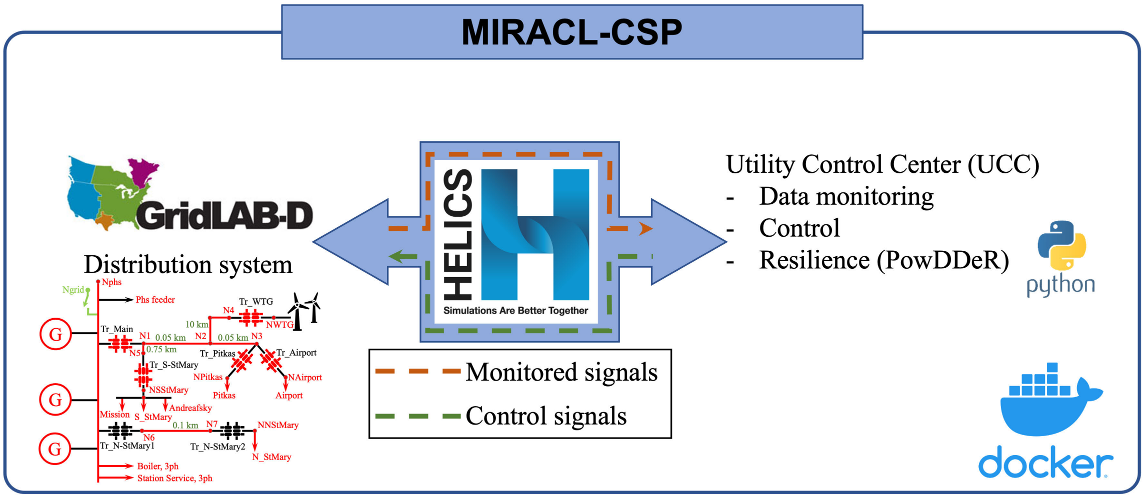


FIGURE 2. **MIRACL-CSP architecture.**

The adaptive capacity is therefore bound by the real and reactive power component limits given in equations (4) and (5) and the temporal limits defined in equations (6) and (7). This results in a ''manifold'' that represents the adaptive capacity of an asset. The manifold and a more detailed derivation, which covers the aggregation of assets can be found in [9]. Further derivations including uncertainty in solar PV and battery assets have been shown in [10], as well as hydropower generation assets in [11].

The inertia of power systems comes from generation units that have rotating masses or stored kinetic energy. The kinetic energy slows the rate of frequency response to disturbances on the system, given as

$$\frac{df}{dt} = \frac{f \Delta P}{2H} \tag{8}$$

where ΔP is the disturbance or difference between generation and load, and H is the inertial constant. A large amount of inertia on the system allows for additional time for generation units to ramp up or down output to arrest the frequency before it reaches the point of under frequency load shed (UFLS) or over frequency generator tripping. The kinetic energy of a generator is given as

$$K_0 = \frac{1}{2}\left[\frac{2\pi f_0}{N_p/2}\right]^2 J \tag{9}$$

where f_0, N_p, and J are the real-time frequency, number of poles, and the mass moment of inertia, respectively. The kinetic energy can also be evaluated at the maximum and minimum frequency limits of the system to give the available kinetic energy. In the case of UFLS, this is given as

$$K_{\text{UFLS}} = K_0 - K_{\min} \tag{10}$$

The available kinetic energy is used to find the amount of time it takes for a disturbance to result in a limiting frequency being reached, given as

$$t = \frac{K_{\text{UFLS}}}{P_d} \tag{11}$$

where P_d is the size of the power disturbance.

The short-term resilience in this paper is based on the ability of the system to arrest frequency prior to an UFLS event. This occurs when a disturbance results in load being greater than the generation. In this scenario, the frequency begins to drop and generation assets begin to increase their output power to re-balance the load. Therefore, the short-term resilience is the maximum size of disturbance the system can withstand and is calculated using the aggregated adaptive capacity in the positive real-power direction and the inertia or time it takes to reach the UFLS after the disturbance. The short-term resilience in regards to the DIRE curve (Fig. 1) relates to the 'resist' phase and its derivation can be seen in more detail in [22].

The long-term resilience is defined by the positive real power adaptive capacity over a large time span. It relates to the energy left in the system and gives a measure of the time the system can maintain generation. With regard to the DIRE curve, the long-term resilience is in the time frames of the 'respond' and 'recover' phases. In the St. Mary's microgrid it relates to the amount of time a generator can run based on its remaining fuel, its fuel burn rate, and the generators power output. The simulations ran in this study were over a short time duration of 350 seconds. In order to demonstrate the long-term resilience, the time axis is changed from seconds to hours. The longer time horizon allows a measurable reduction in the amount of fuel remaining, resulting in a change to the long-term resilience.

In this study framework, PowDDeR becomes part of the UCC. Through the HELICS Python APIs, the UCC monitors and processes required GridLAB-D asset information. Data is then loaded through the PowDDeR APIs to calculate the adaptive capacity of each asset and of the overall system, and the results are saved into a Hierarchical Data Format Version 5 (HDF5) file for post-processing.

III. RESILIENCE STUDIES DESIGN

In what follows, the testing methods and design will be presented for an infrastructure based upon an Alaskan renewables integration in the St. Mary's microgrid.

A. ST. MARY'S USE CASE

St. Mary's is a remote rural community in western Alaska, located on the Yukon River and served by its own isolated electrical power grid. The St. Mary's power distribution feeder system is a 12.47 kV and 400 V system. The total load of the system can reach a peak of approximately 600 kW, with a minimum load hitting approximately 150 kW. Because it is situated in such a remote location with the associated challenges to supply energy to consumers, the price of energy is rather high, more than double the average U.S. household in 2022 according to [23] and [24]. The power demand of the St. Mary's community is served by three diesel generators listed in Table 1. The generators are assumed to have an inertia constant of 2, have ramping capability of reaching full output in 10 seconds, and their rate of burning fuel for this study are constant.

TABLE 1. St. Mary's gensets.

	Capacity (kW)	Ramp Rate (kW/s)	Efficiency (gal/hr)	Generator Model
1	499	49.9	17.2	Cummins QSX15G9
2	611	61.1	30.0	Caterpillar 3508
3	908	90.8	22.0	Caterpillar 3512

By January 5, 2019, the Alaska Village Electric Cooperative (AVEC) had installed a 900 kW, 52-meter rotor diameter type IV pitch-controlled wind turbine generator manufactured by Emergya Wind Technologies and started producing power. Schematically illustrated as a single-line diagram in Fig. 3, the St. Mary's power distribution feeder details can be found in [25] and [26].

Located in a remote geographical area falling within the transitional climate zone with seasons changing from long, cold winters to shorter, warmer summers, the St. Mary's microgrid is predisposed to seasonal and operational disturbances, such as, failures due to diesel fuel delivery, high wind speeds, or cyber-physical security attacks. Therefore, it is imperative for the owner operators to have access to real-time information about how much uncertainty the system can sustain during its operation given the current operation points and disturbances.

The MIRACL-CSP has been designed to build use-case scenarios to evaluate the ability of a distribution system, specifically the St. Mary's microgrid, to resist, adapt, and recover from possible disturbances by measuring its resilience metric at simulation time. This operational

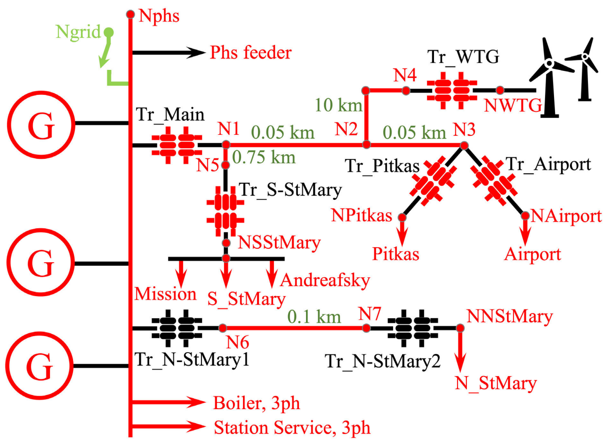


FIGURE 3. St. Mary's distribution feeder single-line diagram.

TABLE 2. St. Mary's gensets running capacity.

Generator	Power generation [kW]	Running capacity [%]
1	≈ 185	≈ 37
2	≈ 128	≈ 21
3	≈ 191	≈ 21

resilience metric depends on monitoring the system inertia and aggregating all the generation assets adaptive capacity in real and reactive power domains. According to [9], given the nameplate rated capacity, latency, ramp rates, and energy constraints, the adaptive capacity of an asset can be explored by calculating its control domain in real and reactive power from the current point of operation.

The St. Mary's power distribution system in Fig. 3 has been modeled in GridLAB-D [16] as an isolated grid with the diesel generators being represented by the synchronous machine model. The unbalanced operation of three-phase synchronous machines is modeled with a simplified fundamental frequency model in phasor representation.[8]

The wind turbine generator is modeled as an inverter-interfaced resource operating as a constant real and reactive power generator.[9] This allows the application to emulate the real wind turbine behavior, by dispatching actual measured wind generation profiles in different scenarios.

The loads in the St. Mary's microgrid are modeled as constant power loads[10] and have no voltage dependency. They all sum up to approximately 501 kW of real power demand on all three phases.

If the wind turbine is inactive, given the current configuration, to supply all loads and cover the line losses, the GridLAB-D powerflow solver calculates that the diesel generators would run according to the data in Table 2.

[8] http://gridlab-d.shoutwiki.com/wiki/Generators_Module_Guide#Diesel_DG_Model
[9] http://gridlab-d.shoutwiki.com/wiki/Inverter
[10] http://gridlab-d.shoutwiki.com/wiki/ZIPload

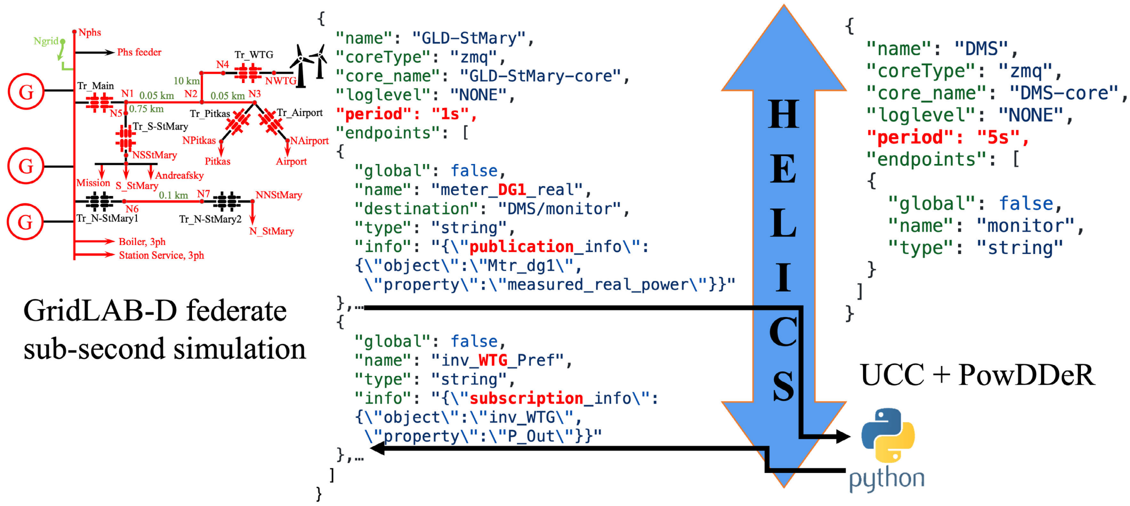


FIGURE 4. HELICS integration architecture.

GridLAB-D models for the diesel generator dynamics do not include parameters to specifically control generator efficiency and priority. Rather, their generation will vary following the bus frequency deviation due to an imbalance in the system supply and demand, which in this case is assumed to be constant.

From [27], it can be concluded that the primary resilience challenge for the St. Mary's microgrid is fuel availability for the diesel generators. Fuel gets delivered by boat on the Yukon River, which is impassable from August through April due to the long and very cold winters. Therefore, life threatening situations could arise during winter as consequences to diesel fuel depletion. The addition of the distributed wind (DW) turbine to the grid reduces the community's dependence on diesel fuel.

AVEC, as the electric utility serving the city of St. Mary's, has provided wind speed (m/s) and power generation (kW) measurement data for the wind turbine for years 2019, 2020, and 2021.

Within MIRACL-CSP, the UCC loads similar profiles and dispatches them to the GridLAB-D inverter-based wind turbine model to follow the generation profile, thus creating more realistic use-case scenarios inside the co-simulation environment.

To perform a quantitative analysis of the value of DW, MIRACL-CSP integrates the GridLAB-D model of St. Mary's microgrid with PowDDeR leveraging its capabilities to establish performance under uncertainties. The integration is realized through the HELICS API[11] [28]. In particular, for this co-simulation integration, the GridLAB-D and Python federates are treated as message federates[12] and data exchange is configured using JSON config files[13] by defining corresponding endpoints.[14] Fig. 4 exemplifies how the connection between simulators/federates is realized. Specifically, the *monitor* endpoint of the UCC federate communicates the wind turbine generation profile loaded from real-life acquired measurements. The *inv_WTG_Pref* endpoint of the GridLAB-D federate subscribing to those values captures them and feeds them in the distribution system power flow calculations. Similarly, endpoints, such as *meter_DG1_real*, publish the measured generation of the diesel generators to the HELICS environment to be picked by the UCC federate and loaded into the PowDDeR application for processing and metrics calculation.

B. USE-CASE SCENARIOS

With the St. Mary's GridLAB-D model running with a 501 kW peak load demand, the diesel generators need to run at the capacities listed in Table 2. When a DW resource is added to the system, its dynamics are modified according to the variability of wind power generation. Using different wind profiles provided by AVEC, the St. Mary's microgrid can be simulated under various wind conditions to study its resilience in the presence of variable generation and uncertainties. MIRACL-CSP offers the platform to easily create these scenarios and supply the simulated data directly to PowDDeR for resilience metrics calculation during runtime. Two scenarios have been considered, with wind generation profile selected from the AVEC data presenting a decreasing trend over the simulated time, natural uncertainties that could affect the grid, and fuel depletion:

S.1: When the wind speed varies from higher to lower speeds (max 11.17 m/s, min 4.7 m/s, mean 7.74 m/s, and standard deviation 1.65), analyzing the system resilience through its assets' adaptive capacity can

[11] https://docs.helics.org/en/latest/references/api-reference/C_API.html

[12] https://docs.helics.org/en/latest/user-guide/fundamental_topics/message_federates.html

[13] https://docs.helics.org/en/latest/user-guide/fundamental_topics/interface_configuration.html#json-configuration

[14] https://docs.helics.org/en/latest/user-guide/fundamental_topics/message_federates.html#message-federate-endpoints

answer questions related to possible needs for diesel generation curtailment or load shed.

S.2: This scenario assumes the same wind profile as S.1: with the addition of large disturbances. These system dynamics force a drastic change in generation to meet the load. The resilience metric is very important in this case. The disturbances here are based on loss of diesel generators due to lack of fuel. However, the loss of these generators could occur from physical degradation, storms, or cyber threats.

IV. STUDY RESULTS AND DISCUSSION

This section provides the testing results following the use case breakdowns previously discussed. During the co-simulation runtime of the St. Mary's microgrid, PowDDeR gathers the current states of the considered system assets, that is diesel generators and the wind turbine, constructs the adaptive capacity manifolds, gets the system inertia, and calculates the short-term and long-term resilience.

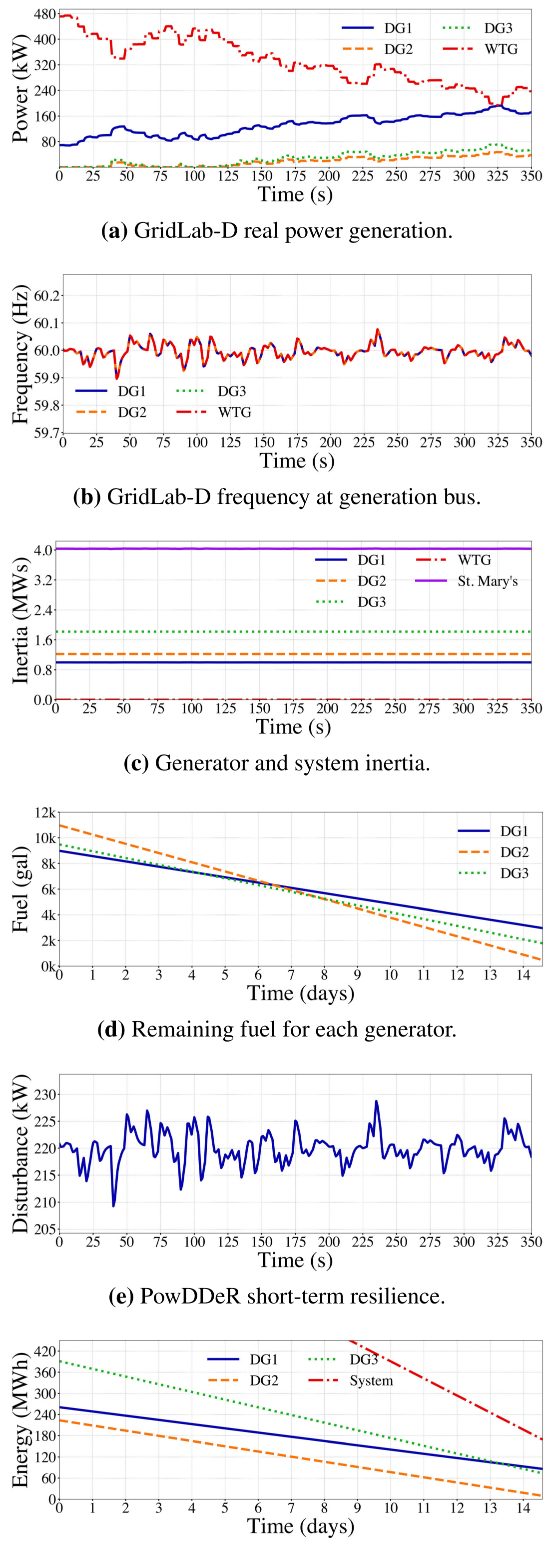
A. CO-SIMULATION SCENARIO 1

The simulated wind and diesel generation output and frequency at the bus from GridLAB-D are shown in Figs. 5a and 5b, respectively. It can be seen that the wind turbine generator (WTG) and diesel generator 1 (DG1) support the majority of the load. The loss of wind generation over the simulation is compensated by the ramping of output of generator 1. However, diesel generators 2 and 3 are both online over the duration of the simulation and can be seen by the inertia plot in Fig. 5c. Here, each generator is supplying inertia to the system. It is assumed that each generator has an inertia constant of 2. Since each generator is running, they are burning fuel at the rate given in Table 1 and the resulting fuel remaining is shown in Fig. 5d.

The resulting short-term resilience, which is a measure of the size of disturbance the system can withstand without dropping below a frequency limit of 58Hz, is shown in Fig. 5e. Here, it can be seen that the short-term resilience has small variation and it follows the same profile as the system frequency. As the system frequency falls, the short-term resilience also falls. The long-term resilience is shown in Fig. 5f. Here, it can be seen that the system resilience is the aggregation of each generator and is continually reduced over time. It is based on the available fuel left, the fuel consumption of the generators, and their maximum outputs.

B. CO-SIMULATION SCENARIO 2

The power generation and frequency from the GridLab-D simulation for this scenario are shown in Figs. 6a and 6b, respectively. Again, it can be seen that the wind generation and diesel generator 1 support the majority of the load. However, in this scenario, generator 1 and 3 run out of fuel and are taken off-line at 250 and 75 seconds, respectively. The loss of wind generation is initially compensated by ramping of generator 1. When this generator runs out of fuel, generator 2



(a) GridLab-D real power generation.

(b) GridLab-D frequency at generation bus.

(c) Generator and system inertia.

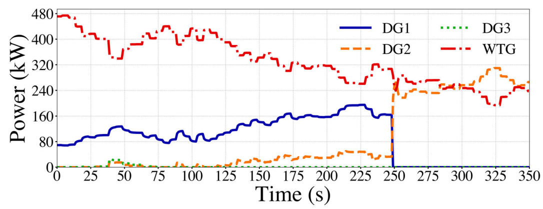
(d) Remaining fuel for each generator.

(e) PowDDeR short-term resilience.

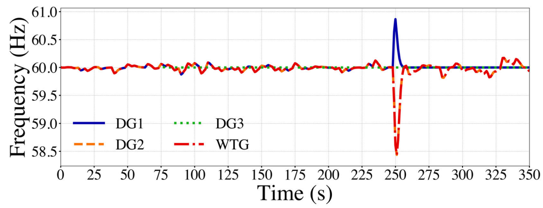
(f) PowDDeR long-term resilience.

FIGURE 5. Scenario 1, without any large disturbances, there is little change in the short-term resilience while the long-term resilience is continually reduced as fuel is depleted.

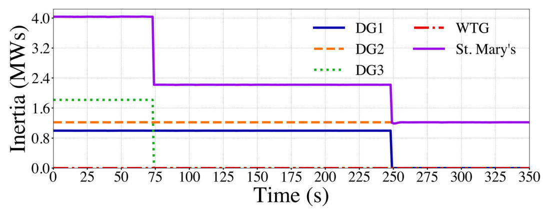
is ramped up to balance the load demand. The loss of generation units has a direct impact to the system inertia, shown in



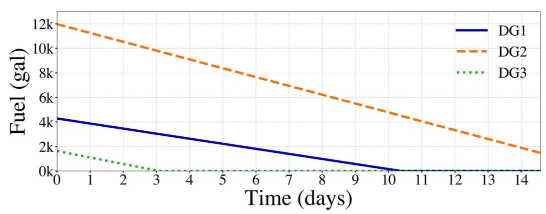
(a) GridLab-D real power generation.



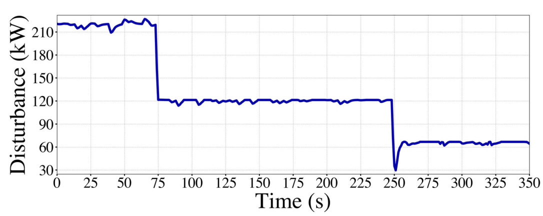
(b) GridLab-D frequency at generation bus.



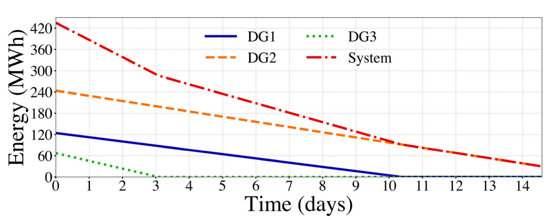
(c) Generator and system inertia.



(d) Remaining fuel for each generator.



(e) PowDDeR short-term resilience.



(f) PowDDeR long-term resilience.

FIGURE 6. **Scenario 2, the loss of a generator from running out of fuel has a large negative impact on the short-term resilience. However, the rate of reduction of the long-term resilience is slowed.**

Fig. 6c. When they are taken off-line, they no longer add any inertia to the system.

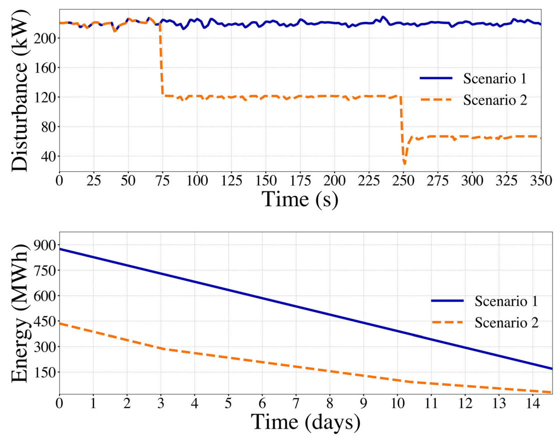


FIGURE 7. **Short-term and long-term resilience for each scenario. The impact of losing or taking a generator off-line has a reduction of short-term resilience but increases the long-term resilience.**

In this case, the resulting short-term resilience is shown in Fig. 6e. Here, it can be seen that the short-term resilience not only follows the frequency of the system, but, more importantly, it takes a large step reduction when a generator is taken off-line. This results in the system not being able to withstand large disturbances before frequency limits are reached. The long-term resilience is shown in Fig. 6f. Here, the long-term resilience contribution of each generator is shown along with system's resilience. The system resilience is actually reduced at a slower rate after each generator is taken off-line. It should be noted that this is only possible as there is adequate generation still online to support the load demand.

C. CO-SIMULATION RESILIENCE TAKEAWAY

The results of the short-term and long-term resilience for each scenario are shown in Fig. 7. The key takeaway that can be seen is the trade-off between short-term and long-term resilience. Examining scenario 2, you can see that when a generator goes off-line it has a large negative impact to the short-term resilience because of the reduced inertia and generation ramping capability. However, it has a positive effect on the long-term resilience. This is due to the system no longer burning as much fuel to support the load. It should be noted that this is only possible because the generators are not being run near their maximum generation capability, therefore they can be ramped up to support the load demand.

Another key takeaway is that the short-term and long-term resilience metrics do not directly show the impact of wind generation. In the case of the short-term resilience, wind does not directly add inertia to the system and it is ran at its maximum output. In order to add to the short-term resilience, the wind turbine generator can be ran below its maximum capability. The impact to resilience based on the dynamics of different generation assets has been demonstrated in [22]. Here, it was shown that the quick ramping capability of inverter-based generation can have a large impact to maintain frequency stability. For the long-term resilience, wind generation allows for diesel generators to be taken off-line, conserving the fuel, and therefore increasing the long-term resilience.

V. CONCLUSION

In this paper, to account for the time-dependent behavior of a power distribution system under uncertainties and dynamically study its resilience, a co-simulation platform, also known as MIRACL-CSP, has been developed and detailed. The intended purpose of this platform was to integrate the dynamics of the distribution system with the resilience assessment and quantification metric. As a use case for the proposed platform to quantitatively study the resilience of a microgrid in a holistic manner, we analyzed the resilience of the real world St. Mary's microgrid incorporating a 900 kW wind turbine generator under different scenarios dictated by real-life uncertainties using PowDDeR, a software application providing resilience metrics for power systems based on their adaptive capacity and inertia. The integration of PowDDeR with GridLAB-D, the St. Mary's microgrid power flow simulator, is facilitated by MIRACL-CSP so that the resilience application could monitor and analyze distribution system measurements in real time. The co-simulation environment allowed us to collect system dynamics data to characterize its resilience at different time scales.

The resilience results of the St. Mary's microgrid show a trade-off between short-term and long-term resilience. Having diesel generators online add to the short-term resilience as there is more inertia in the system and a quicker ramping capability if a disturbance occurs. However, this results in faster reduction of fuel and therefore a quicker reduction in long-term resilience. The contribution of wind generation has the ability to increase either the short-term or long-term resilience depending on how it is utilized. If it is run at maximum output, diesel generation can be taken off-line. If it is run below its maximum output, the fast ramping capability of inverters allows for increased short-term resilience of the system. Future work includes leveraging MIRACL-CSP as the practical framework for asset owners and operators, and original equipment providers to understand benefit versus risk through co-optimization of resilience and economic considerations for applications. With DW as a resilience enhancement, the resilience metrics can be used as control decisions to benefit the overall system efficiency, and the cost of operation in particular.

Moreover, MIRACL-CSP serves as a prototype for complex systems integration with dynamic resilience quantitative metrics, and could be adapted and/or extended for studies pertaining to other domains, such as chemical and water infrastructure systems.

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