SAND2024-15968C

An Open-Source Tool for Energy Storage Sizing and Placement in Electric Grids

Ujjwol Tamrakar[†], William Vining, and John Eddy
Sandia National Laboratories
Albuquerque, New Mexico, USA
Email: [†]ujjwol.tamrakar@ieee.org

***Abstract*—Energy storage systems have the potential to enhance the operation and value of grid resources while also improving system resilience and reliability. Accurate evaluation of storage performance requires tools and processes capable of modeling various domains effectively. In this paper, we introduce QuESt-SSIM, an open-source tool that employs discrete event simulation to assess the impact of energy storage on electric grids. QuESt-SSIM integrates aspects of grid physics, reliability, and disruptions caused by extreme events. By leveraging co-simulation approaches, the tool offers a flexible architecture that supports diverse simulations, including weather, reliability, load management, and energy storage. This flexibility enables users to optimize the size and placement of storage systems across multiple objectives using a metric-driven approach. We illustrate the tool's capabilities through a case study that demonstrates its application in sizing and placing storage for voltage regulation in a distribution system.**

***Index Terms*—Energy storage, Storage sizing, Storage placement, Voltage regulation**

I. Introduction

The continuous push towards renewable and distributed energy resources has led to many issues with grid stability and reliability. Furthermore, modern power systems are exposed to a variety of threats including increased frequency of natural disasters, wildfires, and other weather-related events [1]. Energy storage systems (ESSs) have the potential to enhance the operation and value of grid resources under these new challenges while improving system resilience and reliability. However, appropriate engineering tools are needed for these capabilities to be accurately valued and to maximize the benefits from ESSs [2]. Open-source tools such as the one presented in this paper are essential for quantifying the potential impact that ESSs can have on power system operations and planning.

This paper introduces an open-source tool called, QuESt-SSIM, for sizing and placement of storage assets in a power system. The objective of the tool is to address the technical difficulties faced by various stakeholders to decide the size and location of storage assets in a distribution network to accomplish their desired objectives. QuESt-SSIM adds to the existing capabilities of the QuESt suite of applications (developed by Sandia National Laboratories) [3] by adding discrete-event simulation capabilities for evaluating the impact of ESSs on distribution grids. The tool incorporates aspects of – grid physics, reliability, and disruptions caused by extreme weather events allowing users to perform high-fidelity simulations to answer questions related to storage sizing and placement. The tool leverages a co-simulation platform to provide a flexible architecture and support different simulations of weather, reliability, load management, energy storage, and other relevant components which can all interact with each other. The tool also introduces a metric-based approach to evaluate performance and facilitates optimization over multiple objectives that can span several domains.

Several open-source tools aimed at addressing the question of storage sizing and placement exist in the literature. Tools such as the ESET suite from PNNL [4], REopt tool from NREL [5], DER-CAM from LBNL [6] are optimization-based *planning* tools that can inform recommended technology, location, and optimal sizes of ESSs for different grid services. StorageVET (recently upgraded to DERVET) [7] is a software tool developed by EPRI that supports assessment of ESSs to maximize economic benefits for a target use-case. While these tools are powerful, they typically do not incorporate higher-fidelity grid models into their optimization and simulation frameworks out-of-the-box. The QuESt-SSIM tool presented in this paper is an attempt to fill this gap. The main distinguishing feature of this tool is the ability to incorporate grid physics into the decision process. The tool also provides a high-fidelity simulation platform enabling better decision making by integrating multiple domains into the decision process. It should be noted that there are commercial tools that can possibly address this gap but the aim here is to leverage open-source tools.

The paper is organized as follows: Section II provides an overview of the features and capabilities of the tool, Section III describes ways to use the tool, Section IV presents a case study where the tool is utilized to size and place ESSs in a distribution system for voltage regulation objectives. Finally, Section V concludes the paper and presents future work.

II. QuESt SSIM - Storage Sizing and Placement Tool Overview

A. Simulator Architecture

The overall architecture of the simulator is presented in Fig. 1. The simulator leverages a co-simulation framework that provides a flexible architecture to support different simulations of weather, reliability, load management, energy storage, and other grid components and can capture interactions between multiple domains. To this end, QuESt-SSIM has been built using the HELICS framework. HELICS is an open-source co-simulation framework that allows simulators of different domains to exchange information during run-time, allowing larger and complex simulations that capture dynamics from different domains [8]. The co-simulation couples an OpenDSS-based grid simulation, grid reliability simulation, storage controller simulations, and energy management simulation. Each of these components are simulated as *federates* within HELICS. A brief description of these federates is provided below:

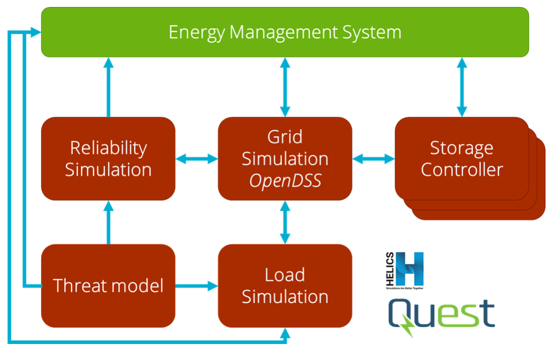


Fig. 1: Simulation architecture of QuESt-SSIM.

- *Grid simulation federate*: This federate performs a Quasi-Static Time Series (QSTS) simulation which captures time-varying and time-dependent aspects of power systems [9] based on OpenDSS [10]. The federate advances the simulation time capturing control actions which can be triggered by events such as changes to output of storage controllers, reliability events (component failures and restorations), and/or commands from the energy management system (EMS). In every step, a power flow is solved to update the grid state and hence capture the time-dependent aspects of power flow. Several grid components such as generators, transformers, ESSs, and photovoltaic (PVs), along with the associated controls can be simulated within this federate.
- *Reliability simulation federate*: The reliability federate observes the operation of the grid, updating probabilistic failure models and generating failure and restoration events when they are indicated by the models. Currently simplistic failure models are used, but the tool is flexible enough to be replaced with different sophisticated user models. The tool will respond to input from the *threat federate* to activate fragility models for grid components.
- *Storage controller federate*: Various storage control modes as described in the IEEE1547 standard [11] can be implemented in the simulator. Each storage device also supports its own external controller which can be used to implement custom controls to dispatch energy storage. The storage devices can be independently controlled or globally controlled through an EMS. This federate facilitates the evaluation/optimization of energy storage controls along with its sizing and placement. This is critical as the operation strategy of ESSs in the grid depends largely on the control strategy and consequently impacts the sizing and placement decisions.
- *Energy management system (EMS) federate*: A simple heuristic-based EMS is currently implemented. We are in the process of integrating an EMS that combines optimal power flow and heuristics for better control. The modular architecture means using a different EMS can be a relatively simple task.

B. Metrics-based Approach to Quantify Performance

In this tool, a metrics-based approach is used to quantify the performance of grid configurations. This is done by a custom *metrics federate* that communicates with other federates within the simulator to get calculated values for quantities of interest. Each measured value is assigned target values (limits and objective) and an improvement type (minimize, maximize, seek-value). This metric system must allow for simultaneous evaluation of many, potentially hundreds, of metrics and to support direct comparison of different grid configurations to determine which is better. The metrics federate normalizes the values it receives using a non-linear normalization curve with specific properties to support optimization over many (hundreds or thousands) of values. Normalized metrics allow different quantities of interest to be compared directly. For example, we can examine trade-offs between voltage across the grid, line loading, energy service, or any other quantity of interest. As an example, a user may indicate that they are interested in the voltage level at a particular bus. To stipulate their goals for it, they may indicate that they would like the voltage to remain as close to 1 p.u. as possible. The metrics framework allows for three types of metric valuations, also referred to as “sense” or “improvement type”. Those are:

1) *Minimize* which indicates that a value is better the smaller it becomes.
2) *Maximize* which indicates that a value is better the larger it becomes.
3) *Seek Value* which indicates that a specific value is sought and the closer to it, the better.

An example, of how the metrics can be used to compare performance of different grid configurations is illustrated through a case study presented in Section IV. More details about the metrics federate and the normalization procedure can be found in the documentation of the tool in [12].

III. Tool Usage

The tool can either be used through a command line interface (CLI) or through a user-friendly GUI that is made available through the QuESt platform [3]. The QuESt-based GUI provides a simple entry-point but advanced users can leverage the CLI to tailor the tool to their specific needs. Detailed documentation of the tool including installation and usage instructions are available on the GitHub repository [13]. As stated before, the tool uses a flexible approach based on HELICS so that it can be easily customized. The application allows a user to define the possible sizes and location of ESSs on an existing grid model defined in OpenDSS. Given

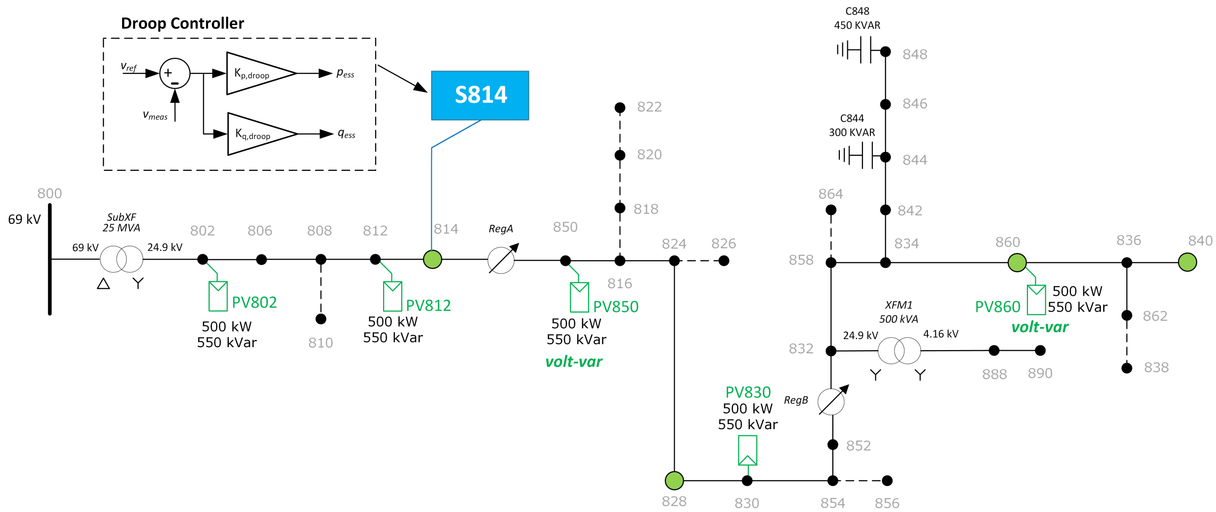


Fig. 2: IEEE 34 bus test system used for case study. A single ESS at Bus 814 with the custom droop controller is shown which matches configuration 1. The same test case is used for other configurations with additional ESSs placed at different locations.

these possibilities, the tool will search through every possible configuration and provide metrics to compare overall performance. The users also have the option to choose a subset of the configurations to evaluate. Future versions of this tool will leverage optimization tools to reduce the search-space based on certain conditions to reduce simulation/evaluation time. The simulator is configuration-driven. One configuration file specifies – the OpenDSS model, connected storage and PV devices, reliability parameters, etc. The configuration files are JSON files to enable human readability while keeping it easy to generate configurations from other programs. The overall workflow is summarized in Fig. 3

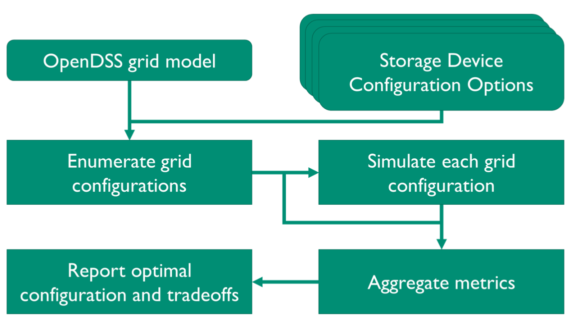


Fig. 3: Flowchart illustrating the work flow in QuESt-SSIM.

IV. Case Study: Storage Sizing and Placement for Voltage Regulation

As an example case study, in this paper the tool has been used to study best size and locations of distributed energy storage for voltage regulation purposes in the IEEE34 bus test system. All the necessary files and instructions to replicate this case study can be found in [14]. A "getting stared guide" is also provided so that readers can replicate the presented case studies on their own and start exploring the features of this tool [15].

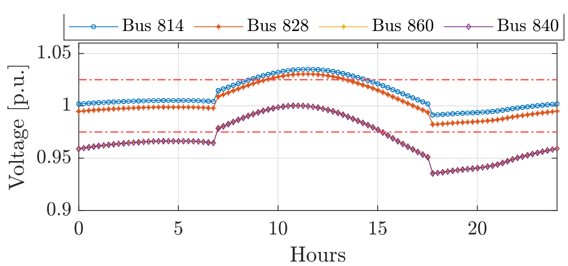
A. Simulation Setup

The system under consideration is an IEEE34 bus test distribution feeder as shown in Fig. 2. The OpenDSS model of the test system used for this case study is available for download in [14]. More details about this test system can be found in [16]. It is assumed that a large amount of PV generation has been installed along the test feeder – units PV802, PV812, PV850, and PV860 represent the PV generators located along the feeder. Each of these PV units are rated at 500 kWp. PV850 and PV860 have volt-var control modes enabled. Other PV units are operating with maximum power point tracking (MPPT) control injecting all the available active power into the system. The PV units and the controls are added to the model through the JSON configuration files. A simple test irradiance has been used as the input to the PV systems. Bus 814, 812, 860 and 840 are assumed to be "critical" from the point of the system operator where the desired voltage range is between 0.975 and 1.025 per unit. These assumptions are arbitrary just for the sake of demonstration in this case study. The readers can easily modify these assumptions as the per the instructions provided in the "getting started guide".

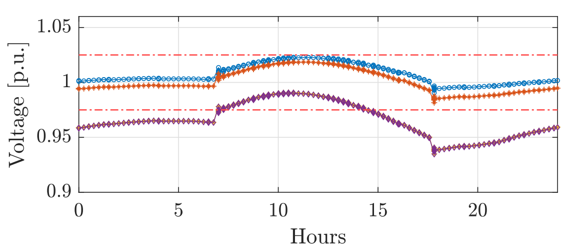
The question being addressed here is – "What would be the size of storage required, and where should it be placed to best meet the voltage regulation objectives?" QuESt-SSIM will be utilized to analyze voltage regulation with PVs and explore a few possible configurations of energy storage size/placements. In the subsequent sections, three configurations that were considered will be described and the performance of each configuration will be evaluated. Each configuration considers different number of ESSs at different locations. Again, these selections are arbitrarily chosen for demonstration purposes in this paper. It is important to note that for discussion purposes these configurations are demonstrated individually through the CLI, users can perform these analyses in tandem through the GUI as well.

B. Configuration 1: Single ESS placed at bus 814

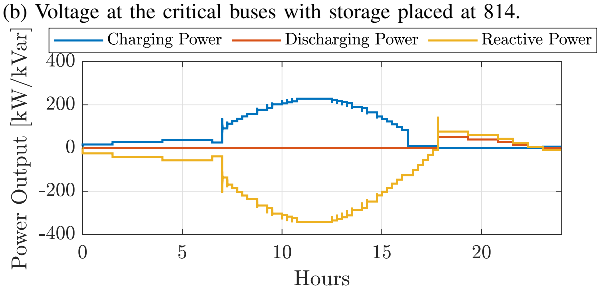
In this first configuration, a single ESS is assumed to be placed at Bus 814 (near the substation) as shown in Fig. 2. The ESS operates on a “droop-based” control strategy (shown within the dashed box in Fig. 2) based on voltage measurement obtained at Bus 814. The active and reactive power dispatch for the ESS is computed based on this control strategy. Relatively high gains were used to achieve the desired voltage regulation. The simulation results for Configuration 1 are illustrated in Fig. 4. The voltage of the critical buses without any storage in the system is shown in Fig. 4a. The voltage at the critical buses exceed the voltage limits especially during hours of high PV generation during mid-day. There are also significant undervoltage issues during the late evening periods. With the storage unit placed at Bus 814, the charge/discharge and reactive power output from the storage unit does limit the overvoltage in the system as shown in Fig. 4b. However, a single storage unit was not able to limit the undervoltages. The charging/discharging powers and the reactive power output from the storage unit are shown in Fig. 4c. Analyzing results show that a 450kW, 500 kVA storage system is required with capacity of around 1500 kWh. The kWh requirement is computed by evaluating the energy usage throughout the day.



(a) Base case voltage at the critical buses without storage.



(b) Voltage at the critical buses with storage placed at 814.



(c) Power outputs from the storage at 814.

Fig. 4: Simulation results for Configuration 1 with single storage at Bus 814.

C. Configuration 2: ESS placed at bus 814 and 840

Based on the results from Configuration 1, it can be concluded that a single ESS near the substation (at Bus 814) was not able to regulate the voltage within the desired limits. The ESS was not able to regulate the undervoltage near the end of the feeder (at Buses 860 and 840). So, another option is considered in Configuration 2, where ESS units are placed at Bus 814 and another one at Bus 840 (at the end of the feeder). To save space, only the voltages of the feeder with this configuration is shown in Fig. 5. This configuration did reduce the undervoltage during the late evening compared to Configuration 1 but the overvoltage during mid-day was slightly higher. The requirements of the ESSs for this particular configuration is summarized in Table I.

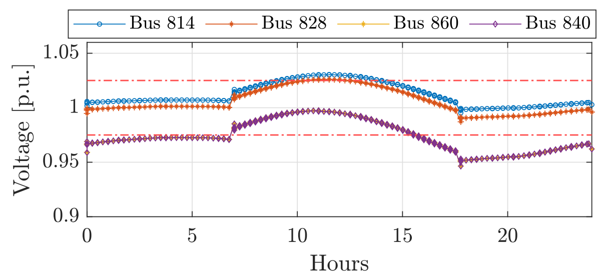


Fig. 5: Voltage of the critical buses with Configuration 2.

TABLE I: Storage Requirements for Configuration 2

Storage Unit	kW, kVA Requirement	kWh Requirement
S814	175 kW, 200 kVA	1800 kWh
S840	250 kW, 275 kVA	750 kWh

D. Configuration 3: ESS placed at each of the critical buses

A final configuration is considered for a potential solution. For Configuration 3, 4-smaller sized distribution energy storage units are assumed to be placed at each of the critical buses. Again to save space, only the voltages of the feeder with this configuration is shown are Fig. 6 . The storage requirements are summarized in Table II. This configuration seems to provide the best compromise between the three evaluated configurations. In the next subsection, the metrics generated by the simulator will used to compare the performance of the three configurations.

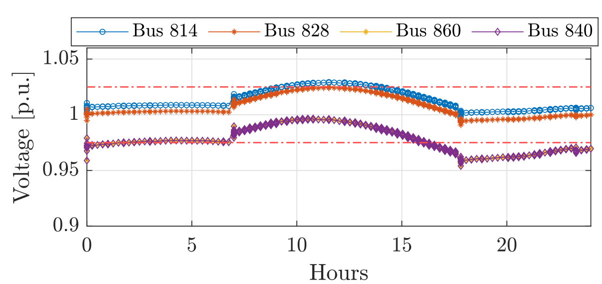


Fig. 6: Voltage of the critical buses with Configuration 3.

E. Metrics-based Comparison

To compare the performance of the three configurations the metrics generated by the tool for the three cases are plotted in Fig. 7. The metrics federate was configured as follows:

TABLE II: Storage Requirements for Configuration 3

Storage Unit	kW, kVA Requirement	kWh Requirement
S814	150 kW, 175 kVA	650 kWh
S828	150 kW, 175 kVA	350 kWh
S860	250 kW, 275 kVA	1500 kWh
S840	250 kW, 275 kVA	1500 kWh

1) *Sense* is to Seek Value.
2) *Lower Limit* is set to 0.975 p.u.
3) *Upper Limit* is set to 1.025 p.u.
4) *Objective Value* is set to 1.0 p.u.

As voltage deviates from target, the metric value moves downward, toward negative infinity (or just increasingly negative values). A more negative metric indicates poor performance in context of the set objective. Comparing the three plots, the plot for configuration 3 performs the best for the set objective. The accumulated metric value is also noted on top of each plot. Again, a large negative number indicates poor performance. The performance indicated by the metrics is consistent with the observations made in Section IV.

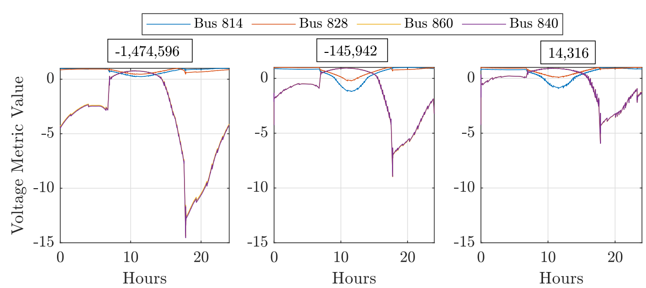


Fig. 7: Metrics-based comparison of the three configurations illustrated in the case study.

V. Conclusions and Future Work

An open-source tool that allows various stakeholders to optimize the size and location of ESSs in an electric grid was presented. The tool uses a co-simulation framework to capture interaction between grid components and multiple domains to provide a high-fidelity simulation environment that allows users make more informed decisions. A case study was presented where the tool was used to evaluate possible locations of ESSs for voltage regulation purposes in a distribution system. It was shown that the tool can evaluate how different configurations (the size and location) and controls of ESS impacts the voltage regulation of the system. The capability of the metric-based approach to compare the performance was also demonstrated. The capability can be extended to easily compare performance of numerous configurations and objectives. The immediate future plans for this tool include – automating the optimization over configurations, incorporating threat models to capture weather related events, and enhancing the storage models to capture specific ESS technologies.

Acknowledgment

This material is based upon work supported by the U.S. Department of Energy, Office of Electricity (OE), Energy Storage Division. The authors would like to thank Niranjan Bhujel from Sandia National Laboratories for the technical review of this paper.

This article has been authored by an employee of National Technology & Engineering Solutions of Sandia, LLC under Contract No. DE-NA0003525 with the U.S. Department of Energy (DOE). The employee owns all right, title and interest in and to the article and is solely responsible for its contents. The United States Government retains and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this article or allow others to do so, for United States Government purposes. The DOE will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan https://www.energy.gov/downloads/doe-public-access-plan. This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

References

[1] T. A. Nguyen and R. H. Byrne, "Software tools for energy storage valuation and design," *Current Sustainable/Renewable Energy Reports*, vol. 8, no. 3, pp. 156–163, 2021.
[2] "Energy Storage Grand Challenge Roadmap," U.S. Department of Energy, Tech. Rep., 2020.
[3] "QuESt 2.0 – Open-source platform for Energy Storage Analytics," https://www.sandia.gov/ess/tools-resources/quest/, Accessed: 2024-08-26.
[4] "Energy Storage Evaluation Tool (ESET) – Model, Optimize and Evaluate Energy Storage Systems," https://eset.pnnl.gov/, Accessed: 2024-08-26.
[5] "REopt – Renewable Energy Integration and Optimization," https://reopt.nrel.gov/tool, Accessed: 2024-08-26.
[6] "DER-CAM – Distributed Energy Resources Customer Adoption Model," https://gridintegration.lbl.gov/der-cam, Accessed: 2024-08-26.
[7] "DER-VET – Distributed Energy Resource Value Estimation Tool," https://www.der-vet.com/, Accessed: 2024-08-26.
[8] T. D. Hardy, B. Palmintier, P. L. Top, D. Krishnamurthy, and J. C. Fuller, "HELICS: A co-simulation framework for scalable multi-domain modeling and analysis," *IEEE Access*, vol. 12, pp. 24 325–24 347, 2024.
[9] M. J. Reno, J. Deboever, and B. Mather, "Motivation and requirements for quasi-static time series (QSTS) for distribution system analysis," in *IEEE Power Energy Society General Meeting*, 2017, 5pp.
[10] "OpenDSS - An electric power distribution system simulator (DSS) designed to support distributed energy resource (DER) grid integration," https://www.epri.com/pages/sa/opendss, Accessed: 2024-08-26.
[11] "IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces," *IEEE Std 1547-2018 (Revision of IEEE Std 1547-2003)*, 2018.
[12] "QuESt SSIM Metrics- Procedures for Metrics Computation," https://sandialabs.github.io/quest-ssim/metrics.html, Accessed: 2024-08-26.
[13] "QuESt SSIM - Discrete Event Simulator for evaluating energy storage systems connected to electrical power distribution systems," https://github.com/sandialabs/quest-ssim, Accessed: 2024-11-25.
[14] "QuESt SSIM - Demo Examples," https://github.com/sandialabs/quest-ssim/tree/master/examples, Accessed: 2024-11-25.
[15] "Getting Started Guide - Instructions on Running Demo Examples," https://sandialabs.github.io/quest-ssim/demo˙examples.html, Accessed: 2024-11-25.
[16] M. E. Baran and F. F. Wu, "Network reconfiguration in distribution systems for loss reduction and load balancing," *IEEE Transactions on Power delivery*, vol. 4, no. 2, pp. 1401–1407, 1989.