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# Integration of flow battery for resilience enhancement of advanced distribution grids



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#### ABSTRACT

This paper presents a real-time simulation and hardware-based approach for systematic integration of Distributed Energy Resources (DERs) in advanced distribution grids with a special focus on resilience. Advanced distribution grids are considered to be functionally more sophisticated than traditional ones. The desirable advanced functionalities include - reconfiguration, real-time sensing, DERs, self-healing, etc. Some of these functionalities are currently being realized by microgrids as well. However, it is not feasible to convert each section of a distribution grid into a microgrid, but can be instituted with functionalities by design and controls at relatively lower costs. Interconnection of DERs, including energy storage to improve reliability and resilience is presented in details. Resilience of distribution grids is gaining greater importance and research towards enhancing it utilizing DERs is a key area. A real-time resilience framework with Analytical Hierarchical Processes (AHP) is developed that adapts to changing configurations, DERs, switching operations, grid conditions, etc. to provide an accurate and adoptable composite resilience metric. This framework and the composite resilience metric can play a unique role in operational and design decisions for operating future distribution grids. Advanced functionalities such as scenario-based reconfiguration in distribution grids are considered, with resilience metrics as performance criteria for choosing a preferred combination. Simulations are performed using Digital Real-Time Simulator (DRTS) and characterized response of flow battery validated against actual flow battery hardware is imposed to provide realistic results. Reconfiguration program is interfaced with DRTS for bidirectional real-time communication. Key contributions include enhancement of resilience of distribution grids using energy storage system under dynamic operating conditions.

#### 1. Introduction

Advanced distribution grids consist of functionalities such as realtime sensing, smart reconfiguration, volt-var control and optimization, operation with Distributed Energy Resources (DERs), and advanced control and protection [1–3]. Extensive connection of DERs to enhance utilization of local energy, enhance reliability, lower costs, and rural electrification are enabled by automation and real-time sensing, communication, controls, and concepts such as microgrids. Although microgrids can envelope several of these features, it is more cost-effective choice to introduce advanced automation in distribution grids than designing several microgrids, especially for large distribution systems [2]. Resilience, DERs, reliability, and efficiency have been identified as key drivers for the evolution of advanced distribution grids [1]. Adoption of advanced control methodologies provides an economical pathway than investing in additional generation and grid assets. Thus, upgrades must be carefully planned and designed to optimize the performance benefits. In this context, advanced functionalities of reconfiguration and resilience enhancement methods under DER-integrated distribution grids are presented. Some of the challenges associated with realization of resilience and reliability in DER-integrated grids require dynamic assessment of integration and interoperability using advanced analysis methods such as hardware-based testing and real-time simulations [4–9].

Several advanced attributes and functionalities are being systematically addressed, formulated, and established under a Department of Energy initiative called Grid Modernization Initiative (GMI) [3]. As per GMI, specific metrics have been proposed for characterizing U.S. electric grid, including resilience [10]. There are several definitions of resilience and one of the most adopted ones is reiterated by the Presidential Policy Directive 21 (PPD-21) [11]. The term 'resilience' means the ability to prepare for and adapt to changing conditions and

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withstand and recover rapidly from disruptions. Resilience includes the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents. Several other definitions of resilience as applied to power grids are accounted below [12]:

- 1. NARUC: robustness and recovery characteristics of utility infrastructure and operations, which avoid or minimize interruptions of service during an extraordinary and hazardous event.
- 2. Dominion Power Virginia: ability to reduce the magnitude and/or duration of a disruptive event.
- 3. Sandia National Laboratories: Resilience is the ability of system to respond and remain functional during an event X, given there is a threat Y of it happening.

A comprehensive review of definitions of cyber-physical resilience is also presented in [13]. As there are several definitions of resilience, the mathematical formulation varies based on the definition. In this paper, we focus on resilience metrics by considering power system characteristics and present formulation of metrics for evaluation of flow battery energy storage functionalities for electric distribution grids. Other forms of energy storage technologies such as flywheels, supercapacitors, and batteries can be investigated as well. Energy storage has been traditionally designed for support and reliability improvements in electric grids. Optimal energy storage design for a microgrid has been explored from a reliability-constrained viewpoint in [14] for expansion planning. The authors show that a single energy storage design optimization can enhance the reliability (with metrics such as Loss of Load Expectation) in a microgrid. The cost-benefit analysis also shows that increasing the size of storage provides economical benefits only up to an extent, after which the normalized cost increases for meeting the reliability criteria [14]. The work in [15] addresses the unit commitment problem in microgrids with Li-ion energy storage while considering forecasting errors and spinning reserves, in grid-connected and islanded modes of operation. The analysis showed that optimal size of energy storage varies in both modes of operation. [16] presents a reliability-based analytical approach for design of backup power supply to meet a specified reliability target. Most of the above resilience-related work discussed so far is based on software simulation and analysis.

Hardware-In-the-Loop (HIL) is regarded as a high-fidelity method of testing novel energy technologies for performance verification. HIL is performed by interfacing power systems represented as software model in real-time simulation and communicate with the device-under-test. Two accepted methods of integrated hardware-based simulation are (i) real-time in-loop simulation [17-21] or (ii) hardware-characterized data that can be imposed in real-time simulation through a transfer function [22]. Performance validation of storage technologies under dynamic grid conditions is a key barrier in widespread deployment in electric grids to support DERs. Accelerated testing and demonstration using actual hardware has been identified as a possible measure to alleviate this issue [23]. Thus, hardware-based simulation and testing provides more than just a component functionality evaluation of unique technologies but also impacts of their inclusion for long-term planning and adoption in real world electric grids. Power-HIL (PHIL) is used in [24] to investigate impacts of the factors such as temperature, age, premature capacity loss, including four-quadrant power inverter operation on battery performance. Static and dynamic model validation is done using real-time simulations to study impact of charge/discharge cycles on battery life, and integrated operation with power grid. An important aspect investigated in [24] is the cell-level energy management from the lower level energy management algorithm that maintains charge balance at stack level. The above-mentioned reasons make hardware-based simulation a promising technique for performance valuation, especially for concepts that cannot be well-represented and studied solely with model-based representation.

earlier, this is one of the two ways to include HIL-based characterization of devices into for accurate representation in power grids. Flow battery ESS utilized in this research are relatively newer and are being explored to provide the necessary storage for high DER penetration. Liion batteries have been explored in these regards and hence another incentive to study an alternate battery technology. The ESS sizing and selection needs to be also based on resilience metrics that are evaluated every one second, a dynamic response at a minimum of one second resolution is desirable, and sub-second response is preferred. Using actual hardware provides a flexible environment to obtain data at a desired resolution. The hardware characterization data used in this paper is in millisecond range, an order of magnitude higher than minimum requirements, tested over a wide range of operation control setpoints. However, for future work related to stability analysis of distribution networks with high DER penetration, dynamic performance is necessary. Following this approach does not restrict the simulation study to a single point imposition as would happen with a single hardware device connected to DRTS, but can be imposed in a time-synchronized manner at several locations in a simulated grid model. This methodology is also appropriate for obtaining a system level response of appropriate granularity for high fidelity response for phenomenon under investigation, which is real-time dynamic response from flow battery ESS for resilience computation in this work.

hardware characterized dynamic response of flow-battery energy sto-

rage system (ESS) is imposed in real-time simulations. As mentioned

Various operating scenarios are considered as reconfiguration criteria for the distribution grid. ESS design is explored by varying powerto-Energy (P/E) ratio under various dynamic grid conditions. Results show that improvement in P/E ratio provides resilience improvement in most cases. Adopting a resilience-based approach, under reconfiguration algorithm to serve critical loads in the distribution grid, can provide optimal results for the accurate design of ESS. Hardware-characterized data can be used for DERs including other types of ESS for an optimal design. Such an analysis could provide a comparative assessment between technologies for optimal design of hybrid technology ESS. The approach presented here can also benefit the distribution system operator by providing an insightful understanding of the absolute threshold of resilience metrics, at any given time. The two main contributions of the paper are:

- 1. Real-time resilience framework based on analytical hierarchy process is used for analysis and design of energy storage with different power-to-energy ratios.
- 2. Inclusion of reconfiguration algorithms as advanced operation functionality in distribution grid with solar photovoltaic and flow battery energy storage as DERs based on actual battery as HIL.

#### 2. Real-time resilience framework

#### 2.1. Resilience based on AHP

Resilience of an electric power distribution system refers to the ability of the network and its constituent loads to remain functional during adverse operating conditions, and recover from damages incurred due to the contingencies in minimum time [12,25–27]. There are multiple ways in which the inherent redundancy in topology or resources can leveraged to maximize the resilience of the distribution system to disruptive events - ranging from hurricanes to denial of service-based cyber-attacks. Under such events, it is incumbent upon the distribution system operator to maintain service continuity to the critical loads in the network, using a reduced number of available resources. To aid the operator during such events, [12] proposed quantification of the system operating state using a 'resilience metric'. Resilience metric (say, R) succinctly expresses the fragility of the network after or during an attack, availability of resources that can be used immediately, and, aids the operator to take actions that ensures

In this paper, the electric microgrids are modeled in DRTS and

maximum loads are restored in minimum possible time and resources are most optimally utilized. When operational resilience quantification is required, the weighted AHP-based approach performs with higher computation efficiency than several other resilience quantification approaches [28–30].

#### 2.2. Resilience computation

In order to compute *R* for every operating point, the power system is represented as a graph - and the following graph theoretic parameters are computed simultaneously: (i) fraction of damaged nodes (*f*), (ii) algebraic connectivity ( $\lambda_2$ ), (iii) graph diameter (*d*), (iv) characteristic path-length (*l*), (v) betweenness centrality ( $b_c$ ), and (vi) redundancy coefficient ( $r_c$ ).

For each network configuration, these six parameters and its computations are unified using AHP [12] to quantify the structural robustness of the network. In a broader sense, AHP is used to consider a set of evaluation criteria, and a set of alternative options among which the best decision is to be made. The resilience of power systems is a phenomenon dictated by multiple non-commensurate factors. Thus, to evaluate resilience using a standard equation that captures all the factors is not going to lead to the most accurate representation and analysis. It is important to note that, in resilience analysis, the criteria that influences resilience may sometimes negate the positive impact of another enabling factor. For example, adding edges in the topology increases the number of paths that can be used for restoration but also introduces additional points of failure. Thus, it is the responsibility of an operating engineer to choose the best option which optimizes each criterion. Preferably this option achieves the most suitable trade-off among the different resilience-enabling factor. Resilience metric is normalized on a scale of 0-1, where 0 means there is no restoration of critical load is possible and 1 means that all loads are restored. Now, 0.3-0.9 difference would depend upon the graph complexity of the network and the weights allotted to different nodes. For the same network, any one operating condition will produce one resilience number. If resilience number decreases - since it is a multivariate problem - the sensitivity of values depend upon factor allotted the highest weight using AHP.

The AHP generates a weight for each resilience-enabling factor according to the distribution management systems' access to comparisons of the important criteria. The higher the weight, the more important the corresponding criterion. Next, for a fixed criterion, the AHP assigns a score to each option that is possible. The global score for a given option is a weighted sum of the scores it obtained with respect to all the individual enabling factors.

$$\mathfrak{R}_{\tau} = [f_c, D, l_G, C_B, C_n, \lambda_2] \tag{1}$$

where  $f_c$  represents the critical fraction of the complex network representing the distribution system, *D* represents the diameter of the complex network, i.e., a metric to represent the length of the shortest path between the farthest nodes,  $l_G$  shows the length of the graph,  $C_B$  represents the betweenness centrality of the graph,  $C_n$  represents the clustering coefficient of the network, and  $\Lambda_2$  represents the algebraic connectivity of the network. Eq. (1) only represents one example of integrating multiple possible resilience metrics and how to find trade-off to converge on integrated resilience metrics.

Distribution system components can be abstracted as nodes and connected to describe a functional system. During normal conditions, when all components are working as they should be, all the nodes are assigned a probability p = 1. Most modern distribution systems have normally open (N.O.) redundant feeder switching options [31,32], and that is expressed by the green nodes. This model is used in this approach, as it enables easier observation of the percolation threshold of the network.

During a powerful unfavorable event, all the nodes of the

distribution system are affected such that each node is functional with a probability p and damaged with a probability 1 - p, where p < 1. The value of p is ascertained by distribution system operator or planning engineer to test the system in several scenarios, or this value of p may come from other modeling software, like weather or climate modeling tools. Based on these studies, the average size of islands can be determined, and secondary sources of energy like distributed generators, solar panels, fuel cells, battery storage, plug-in electric vehicles can be planned, so as to enhance the overall resilience of the distribution system.

This threshold value of probability of each node being functional is referred to as *percolation threshold*  $p_c$ . It is used to determine the critical fraction of the nodes that can *afford* to be damaged from any unfavorable event. Whenever  $p > p_c$ , there would be at least one critical load which would remain connected to a power supply irrespective of the damages sustained by the whole network.

**Definition 1.** A power distribution system network is resilient enough to maintain connectivity of one critical load to the main grid if the probability of random damage of node being functional in the event of a disruptive event is higher than the percolation threshold for the network.

If the percolation threshold is determined for a given network, then by direct comparison of the probability value of node failure against a threat assigned by other modeling tools to the percolation threshold, it is possible to determine whether at least one path will remain connected to the main power grid during the attack. This information provides useful insights into amount of power to be generated from secondary sources during an attack or post-contingency. This concept is demonstrated using a simple example as follows.

**Example:** Consider a three feeder distribution system microgrid, such that it has a structure of a Bethe Lattice of coordination number z = 3, as shown in Fig. 1. This distribution is intentionally chosen as it allows an intuitive and analytical solution, and is equivalent to the study of percolation theory in an hypercubic lattice ( $d = \infty$ ) [33–36].

Since the distribution system is radial and free from loops, the node percolation problem can be easily solved. During normal operation, the distribution system is fed by the substation and power flows in the infinite path of edges between the functional nodes, starting from the substation node. Following any section in the network shown in Fig. 1, it is found that z - 1 (i.e., 2 new sections in the example). An infinite path can be constructed only if there exists at least one functional terminal load node at the end of any of the z - 1 sections. So the probability of finding a functional node during an contingent situation becomes p(z - 1), from the law of probability of equally likely and independent events. Since the percolation threshold is defined at the moment of certainty of existence of an infinite path (when  $p = p_c$ ):



Fig. 1. Example distribution system for analytical study of percolation.

$$p_c(z-1) = 1$$
  
 $p_c = \frac{1}{z-1}$ 
(2)

Putting z = 2 in Eq. (2), it might be concluded that there will be an infinite path in the network even when probability of each node being damaged is high as 0.50. Using a simple graphical model, it is possible to show that using percolation theory, it is possible to determine the topological resilience of a distribution system using a probabilistic method. In an uncorrelated network with degree distribution P(k), the probability that an undamaged section is connected to a functional node of degree k is given by  $kP(k)/\langle k \rangle$  [37–39]. The percolation threshold is possible iff any two nodes,  $n_i$  and  $n_j$ , in the infinite path is also connected to another node. Molloy-Reed criteria can be used to determine if at one least critical load may be fed using the main when a large number of faults have simultaneously occurred in the network under study.

Also according to Molloy-Reed criterion [37], this is feasible if percolation threshold can occur. Percolation threshold transition is observable when  $\langle k^2 \rangle = 2 \langle k \rangle$ , where  $\langle k^2 \rangle$  is the second moment of degree distribution <sup>1</sup>, and  $\langle k \rangle$  is the first moment of degree distribution <sup>2</sup>.

An electric power distribution system assumes several configurations due to redundancy, demand response, renewable generation, restoration algorithms - each having own lattice model patterns and varying values of degree distribution moments. The distribution system changes its nature from a non-resilient system to a resilient one in the limiting case when  $\langle k^2 \rangle \rightarrow 2\langle k \rangle$ . However, those lattices with  $\langle k^2 \rangle < 2\langle k \rangle$  cannot have an infinite path from the substation to the last node of any one feeder in the distribution system, and is not resilient. On the other hand, if the configuration has  $\langle k^2 \rangle \ge 2\langle k \rangle$  there must exist an infinite path, probabilistically speaking, which will continue to be functional irrespective of the damage suffered by the entire network.

**Definition 2.** A power distribution system network is resilient enough to maintain connectivity of one critical load to the main grid if the second moment of degree distribution of nodes in the distribution system is greater than twice the first moment of degree distribution of the network configuration.

Hence the difference of fraction  $\langle k^2 \rangle / k$  from 2 can be used to compute the topological resilience of a network. It is important to ascertain whether at least one critical node can be fed, because depending upon which critical node is fed, reconfiguration algorithms can be modified to pick up other loads, and resilience of the network can be improved. It also helps to determine the fraction of nodes that can afford to be damaged, even with uninterrupted supply to at least one critical load. In the following section, this fraction is determined, and is an important metric for understanding the topological resilience of the network.

#### 3. Critical fraction of damaged nodes

So far, an effort has been made to establish a threshold, using which it would be possible to comment whether a particular configuration is resilient or not to supply at least one critical load. Even if one critical load can draw power from the main grid, it may be used as a resource point to restore other loads, and offer additional black-start capabilities. During most common unfavorable weather events, not all nodes are always usually affected but a fraction *f* of it is. For example, if there is an earthquake (Magnitude 9 in the Richter Scale) with an epicenter in the region of the distribution system, the network is not going to be resilient as  $f \rightarrow 1$ . There are going to be strong weather events where  $f < f_c$  and the network will be resilient to those sort of damages, but not resilient to damages where the critical fraction  $f_c$  is exceeded.

From the distribution system network analysis point of view, it would be useful to determine  $f_c$  of the nodes can afford to get damaged while maintaining the resilience. This would be helpful to ascertain to what sort of events the network can be resilient and optimize the design of the systems such that  $f_c$  can be maximized. In other words, the fraction for which  $\langle k_i^2 \rangle \ge 2 \langle k_i \rangle$  can also be determined.

The analytical approach proposed in [38] can be used for distribution systems considered as a generalized random graph. Let the distribution network have a degree distribution of P(k) and the disruptive event damaged f fraction of its nodes. This may also be interpreted as equivalent to damage of f fraction of neighboring nodes of any undamaged and functional node. The degree distribution of this node would also be changed to k' instead of the original k as a result of random deletion of k' - k neighboring nodes. Thus the new connectivity distribution of the remaining network can be written as a function of

$${}^{k'}_{k} \mathbf{C} \cdot (1-f)^{k} f^{k'-k} \tag{3}$$

From (3) it is possible to compute the variance in degree distributions and the average degree distribution of the damaged networks as follows,

$$\langle k^2 \rangle = \sum_{k} k^2 P_f(k)$$
  
=  $(1 - f)^2 \langle k^2 \rangle + f(1 - f) \langle k \rangle$  (4)

Using the results from (4) and (5) in the Molloy-Reed criterion, it is possible to compute the critical fraction of sustainable network damage  $f_c$ .

$$f_c = 1 - \frac{\langle k \rangle}{\langle k^2 \rangle} \tag{6}$$

Some of the direct interpretations from (6) are as follows:

- The critical ratio of damaged to undamaged nodes in a network that sustained damages, is dependent on the ratio of variance and average degree distribution of the network configuration under configuration.
- Resilience of a distribution system configuration is dependent on the heterogeneity of the network. In highly heterogeneous networks, (k<sup>2</sup>) → ∞, consequently, f<sub>c</sub> → 1 which indicates theoretically infinite resilience of the distribution system network to any sort of damages. So, the more resilient design (or re-design) of the distribution system is such that the variance in its degree distribution be maximized.

#### 4. Formulation of topological resilience metrics

Power distribution systems are planar graphs, and there exists a variety of statistical ways to capture resilience of the network [40–42]. Building upon some of the concepts and definitions about graphs presented in earlier section, there are several metrics which can be defined and used to study the topological resilience of the distribution system. The metrics introduced are mainly divided into two groups: (i) statistical metrics, and (ii) spectral metrics.

#### 4.1. Statistical metrics

Statistical measurements are used to quantify the constructional properties (for example, radial network or meshed network) and relate them to network resilience and the operational dynamics. Such measurements range from more basic metrics such as graph order, size, link

 $<sup>^{1}\,\</sup>mathrm{The}\,$  second moment provides the variance measuring the spread in the degrees. Its square root is the standard deviation

 $<sup>^{2}\,\</sup>mathrm{The}$  first moment is the average degree of the nodes in the distribution system



Fig. 2. Weighted Distribution System Graph Model.

density *D*, diameter  $d_G$ , degree distribution, average node degree  $\langle k \rangle$ , clustering coefficient  $C_N$  and central point dominance as a measure of network centralization or relative betweenness.

## smallest eigenvalue of Laplacian matrix of the network, the network is more resilient [44–46]. The Laplacian Matrix is obtained as follows

#### 4.2. Spectral metrics

Spectral metrics are derived from analysis of eigenvalues of finite sets. Thus the first step of a more accurate analysis is determining the most important nodes from the weighted adjacency matrix A(G) of the graph.

Consider the example distribution system as shown in Fig. 2(b), which shows the graph representation of the LV network. For the sake of proof of concept, only integer weights are used to indicate the weight of sections and terminal loads. The critical load has a weight of 3, while the normal loads have weights of 1. All the nodes are labeled from A, B, ..., F and a  $6 \times 6$  matrix is created. Any section connecting two nodes is represented by 1 or the weight corresponding to that connection as shown in Fig. 2(b). If there is no connection between the two nodes, it is represented as 0. The adjacency matrix of this network is given by:

$$A \quad B \quad C \quad D \quad E \quad F$$

$$A \begin{pmatrix} 0 & 4 & 0 & 0 & 0 & 0 \\ B \\ 0 & 4 & 0 & 3 & 0 & 0 \\ 4 & 0 & 3 & 0 & 0 & 0 \\ 0 & 3 & 0 & 3 & 1 & 1 \\ 0 & 3 & 0 & 3 & 1 & 1 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ F \begin{pmatrix} 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \end{pmatrix}$$
(7)

The centrality vector of A(G) can be used to determine the most important node of the network, which leads to most fragmentation. The centrality vector computes the importance of the node in terms of degree, betweenness, closeness or eigenvectors. The elements of the dominant eigenvector of the adjacency matrix represent the nodes whose functionality is crucial to the resilience of the network. In Fig. 2, it can be deducted by inspection that the third node, node *C*, is the most critical node. Damage to C renders the network in 4 islands. Centrality vector of this system is C(A(G)) = [0.11, 0.48, 0.69, 0.46, 0.15, 0.15],which suggests that the third node C is the most important node of the network as well. This approach is effective to determine the most critical nodes for more complex distribution systems with a lot of nodes. A more realistic 12.47 kV network based on a prototype feeder proposed by PNNL [43] has been analyzed using the adjancency matrix approach and the result is shown in Fig. 3. The most critical nodes of the network are visualized using a color map, for ease of analysis.

Spectral metrics of a complex network are derived from the adjacency matrix of the network [41]. Metrics such as 'Algebraic Connectivity' and 'Spectral Gap' are often used to quantify the 'strength of connectedness' of the network. *Algebraic Connectivity* ( $\lambda_2$ ): It is an indicator that captures the fact that the higher the value of second

$$L_{(i,j)} = \begin{cases} \deg(n_i) \text{ if } i = j \\ -1 \text{ if } i \neq j \\ 0, \text{ otherwise} \end{cases}$$
(8)

Spectral Gap ( $\Delta\lambda$ ): It is used to identify the Good Expansion (GE) properties of a graph [47,45]. GE graphs are sparse graphs with enhanced robustness. It is quantified by measuring the difference between first and second eigenvalues of the adjacency matrix of the network. If this difference increases, the 'strength of connectedness' of the graph also increases, thus increasing the resilience of the graph.

#### 4.3. Topological resilience Vector

Topological resilience of a distribution network depends on the spectral and statistical metrics discussed thus far. All the metrics are dependent on each other, and changes in the network configuration affect other parameters. Thus in essence, there is a vector of metrics, providing various insights into the topological resilience of a given network. It can be represented as Eq. (1) only represents one example of integrating multiple possible resilience metrics and how to find tradeoff to converge on integrated resilience metrics. Thus, this vector can have only few Pareto improvements through multi-objective reconfiguration and optimization [48] till a vector is reached when neither of the metrics can be changed without degrading the resilience of the network overall. The advantage of using the Pareto set in designing or planning resilient distribution systems is that - by restricting focus to the set of choices that are Pareto-efficient, the operator can make tradeoffs within this vector, rather than considering the full range of every resilience metric. As in Eq. (7), the elements of the dominant eigenvector of the adjacency matrix represent the nodes whose functionality is crucial to the resilience of the network.

Though determination of the Pareto set (1) would be a definitive evaluation of the maximum resilience achievable by a particular network configuration, it may not be useful to determine the current state of resilience for a given network configuration. Thus, for such evaluation a traditional weighted summation of the indicator metrics may be used to compute the topological resilience of the network.

Let *V* be the spectrum<sup>3</sup> of a decision matrix  $\overrightarrow{\mathfrak{R}_{\tau}} \overrightarrow{\mathfrak{R}_{\tau}}^{I}$ , which would indicate which resilience metric has the greatest influence upon the overall resilience of the system for a given configuration. Based on the value of the metric, the overall resilience of the system can be ascertained. However if  $\overrightarrow{\mathfrak{R}_{\tau}}$  is Pareto-optimal, any metric will be just as dominating (or non-dominating) as any other and can be used for analysis of resilience of the distribution system. Not all the parameters of  $\overrightarrow{\mathfrak{R}_{\tau}}$  are equally good indicators of resilience. As common in AHP based complex decision making [49], weights are assigned based on a relative interaction between all the resilience indicator metrics using fractions *a* through *u* in the interval (0, 1] (see Eq. (9)). For example,

<sup>&</sup>lt;sup>3</sup> Set of eigenvalues is often referred to as the spectrum



Fig. 3. Adjacency Matrix analysis of a prototypical feeder [43].

algebraic connectivity  $\Delta\lambda$  has  $\frac{1}{e}$  times the influence on the resilience as the critical fraction of the network, and betweenness centrality has *m* times the influence of clustering coefficient. The dominant eigenvector of  $\overrightarrow{\mathfrak{R}_{\tau}} \overrightarrow{\mathfrak{R}_{\tau}}^T$  obtained from (9) can be used as weights accompanying each factor ( $f_c$ , D,  $C_B$ , etc.) that affects topological resilience of the network under consideration.

$$\vec{F}_{c} \quad D \quad C_{B} \quad l_{G} \quad C_{n} \quad \Delta\lambda \quad \lambda_{2}$$

$$f_{c} \quad \begin{pmatrix} 1 & a & b & c & d & e & f \\ 1/a & 1 & g & h & i & j & k \\ 1/b & 1/g & 1 & l & m & n & o \\ 1/c & 1/h & 1/l & 1 & p & q & r \\ 1/d & 1/i & 1/m & 1/p & 1 & s & t \\ 1/e & 1/j & 1/n & 1/q & 1/s & 1 & u \\ 1/f & 1/k & 1/o & 1/r & 1/t & 1/u & 1 \end{pmatrix}$$
(9)

Let  $\rho(i, j)$  be used to represent an element of  $\overrightarrow{\mathfrak{R}_{\tau}} \overrightarrow{\mathfrak{R}_{\tau}}^{T}$ . If  $\rho(i, j)$  undergoes a linear transformation such as

$$\rho(i,j)' = \frac{\rho\left(i,j\right) - \min_{i=1}^{\eta} \left(\rho\left(i,j\right)\right)}{\max_{i=1}^{\eta} \left(\rho\left(i,j\right)\right) - \min_{i=1}^{\eta} \left(\rho\left(i,j\right)\right)}$$
(10)

when the number of indicators of resilience are  $\eta$ . This number may be different from 7 (as considered in the analysis so far) where there is discrimination or strict dominance, i.e., if one indicator outperforms other indicator metrics against all criteria. A higher value of  $\rho(i, j)'$  means higher performance of a resilience indicator. The most dominant eigenvector has the form

$$V = \begin{bmatrix} A_{f_c} B_D C_{C_B} D_{l_G} E_{C_n} F_{\Delta \lambda} G_{\lambda_2} \end{bmatrix}^T$$
(11)

where A, B, ..., G are the derived weights of importance of the resilience metric in its suffix. Thus the overall topological resilience of the distribution system for a certain configuration is given by

$$\Re_{\tau} = \sum_{j=1}^{\eta} V_j \rho(i,j)'$$
(12)

 $\mathfrak{R}_{\tau}$  in (12) may be considered as a single numeric indicator of the topological resilience of any distribution system. In context of power distribution systems, power flow feasibility and probability of attack are other factors that need to be considered during analysis of resilience of a distribution system. From Eq. (1), a traditional weighted summation of the indicator metrics may be used to compute the topological resilience of the network. This aids the operator to appraise the available network configurations. In this approach, it is important that at least two alternative network configurations exist for the operator to compare and choose. The algorithm creates an "evaluation matrix" of *n* rows and m columns for n feasible network paths available to the operator, and m available alternatives the operator can choose from. As described in [12], based on importance of loads in a distribution system, different network paths can be weighted, and the available options can be reduced to a single value utility score representing the resilience enabled by the decision. The topological resilience metric is considered as a significant factor in a second AHP, alongside information about availability of secondary resources, strength of weather event, or critical load information to compute the composite resilience metric.

#### 4.4. Reconfiguration algorithm

Power system reconfiguration is studied and implemented in practice traditionally as an operator-assisted or automatic mechanism for power rerouting or restoration after or during a system contingency. Reconfiguration in transmission network, called transmission switching, has traditionally been used for routing power across larger geographical areas. In distribution grids which are typically radiallyoperated, power system reconfiguration has been used for rerouting power in by provision to form alternate networks through operable line breakers. The timescale of operation for planned reconfiguration ranges from minutes to hours, while automated restoration is typically in range of seconds to minutes. Most of the research and implementation of reconfiguration algorithms has been done for real-time operation based on operator defined objectives such as loss reduction [22,50,51], with or without other objectives pertaining to reliability, and resilience criteria [52–55]. Integration of DERs and availability of communication



Fig. 4. The analog interconnection between the ViZn Z20 Flow Battery and DRTS for operational control.

assisted sectionalizers and tie-switches has introduced challenges as well as provided enablers to assist development of newer reconfiguration mechanisms. An effort to improve methods both algorithmically or heuristically have been explored as research problems [56–58,54]. Nonetheless, importance and applicability of reconfiguration control algorithms has become evident in the advanced distribution grid functionalities, especially for resilience applications [59]. Hence, reconfiguration emerges as one of the most impactful control in distribution grids and is considered in this work to design the ESS. A depth first search approach is used in this paper [28].

#### 5. Characterization of the flow battery energy storage

At Idaho National Laboratory (INL), we have an experimental setup involving a ViZn Energy flow battery that is connected to RTDS<sup>®</sup> (a commercial DRTS package) via analog connection as shown in Fig. 4. More information about the battery and the Princeton inverters that are connected to the battery are available at [60]. The analog output of the RTDS<sup>®</sup> is provided by the GTAO card (Giga-Transceiver analog output), which utilizes 16-bit D/A converters, allows high accuracy gain, and offset calibration. The analog input of the RTDS<sup>®</sup> is provided by the GTAI card (Giga-Transceiver analog input), which utilizes 16-bit A/D converters, allows high accuracy gain, and offset calibration. Both GTAO and GTAI operates over a maximum range of +/- 10 Vpeak. Digital communications based on Modbus was available to control and characterize the battery as well. Analog communications were used in order to impose dynamic grid conditions (varying voltage and frequency) on the flow battery in real-time due to ease of implementation. Loop delays and response analysis of DER via analog interface with DRTS is straightforward given the lab facilities available for this research.

Real Power (P) and Reactive Power (Q) reference inputs to the Princeton Inverters were sent according to the following logic: (1) 5 V equals 0 (zero) power. (2) 0-5 V means negative power, where the battery is charged at a power ranging from 100% to 0%, respectively, of the defined hard limits imposed by the Inverter's operator. (3) 5-10 V means positive power, where the battery is discharged at a power ranging from 0 to 100%, respectively, of the defined hard limits imposed by the Inverter's operator. The interface between RTDS<sup>\*</sup> and the Inverters monitored the control signals and data acquisition to provide the real-time battery behavior and its inclusion in the real-time simulation. Several characterization curves were recorded with analog controls from the simulator to the inverter controls along with the response in real time environment. The characterization curves shown in Fig. 5 provide several control commands (red curve) sent to the master inverter of the flow battery along with the overall response (blue

curve). The response of the flow battery to the analog commands is quite consistent and expected. The approximate time for response by the flow battery is recorded to be 600 ms, whereas a change in mode from charging to discharging is 1300 ms. These are key characterization values recorded as they are needed to ensure requisite responses are ensured from hardware flow battery that can essentially be included as key findings in the resilience framework as explained in the previous sections.

The resilience computation algorithm uses the state variables of the battery to optimally control the charge-discharge cycle of the battery to ensure most resilient operation. A rule-based operation of the battery is implemented in the distribution system controller to start charging or discharging the battery installed in the network. When the network is operating in an islanded mode, the battery is discharged at its rated ramp rate until the lower bound of the depth of discharge is reached. The battery is not charged unless it is connected back to the grid. This is ensured by installation of directional relays at the point of installation of the battery. In the islanded mode, the battery discharge ramp rate is tuned by the distribution management system (or microgrid controller) to match the rate of consumption critical loads. In a grid connected mode, unless a transactive price signal is part of the distribution system operation, the battery is maintained at highest state of charge. However, in some rare but upcoming cases, if a transactive price signal is introduced, the algorithm can be modified to let the battery discharge occasionally to offset operational costs of grid connected mode. The battery discharge due to pricing signal is not a deep discharge, as minimum reserve is maintained for unforeseen contingency at extreme short notice. Thus, the operation of a battery can be formulated as a simple, linear cost minimization problem, with cost of battery operation as a decision variable influencing resilience of the grid.

$$\min C = u_b r_b t_b - c_{cl} t_o + u_g L_{dist.}$$
<sup>(13)</sup>

such that:

$$(\underline{D}_b) \leqslant f(r_b, t_b) \leqslant (\overline{D}_b)$$
$$L_{dist}^{critical} \leqslant L_{dist}$$

where *C* is the operating cost of the distribution network,  $u_b$  is the unit cost of power drawn from the battery, D(b) is the rated depth of discharge of the battery,  $r_b$  is the rate of battery discharge (kW/s),  $t_b$  is time for which the battery is used (s),  $c_{cl}$  is the financial loss due to lack of connectivity of the critical load per second,  $t_o$  is the time of outage (s),  $u_g$  is the price of electricity per unit kWh drawn from the grid, and  $L_{dist}$  is the net real power load in the distribution system network.

The resilience maximization problem can be formulated as a dual of the cost minimization problem proposed in Eq. (13).



Fig. 5. Flow battery characterization using the DRTS. X axis: index of setpoints issued to the flow batter and Y axis: setpoint and response of flow battery in kW.





Fig. 7. Real-time Resilience Computation Workflow.

Fig. 6. Modified networked CERTS microgrid system for resilience simulation.

#### 6. Real-time simulations and resilience computation

#### 6.1. Simulation setup

CERTS has made major contributions to the industry adoption of microgrids through the development of a set of advanced microgrid control and integration techniques, known collectively as the CERTS Microgrid Concept. This concept has been further validated via testing at a full-scale microgrid demonstration test bed operated by American Electric Power (AEP), the largest electric utility in the Midwestern United States. The test bed utilized both pre-commercial prototypes and commercial sources commissioned from industry-established vendors of distributed generation equipment [61]. Two proximally located CERTS microgrids [12] (namely MG-1 and MG-2) are used in this paper to demonstrate the efficiency of flow battery technology for enabling microgrid resilience (shown in Fig. 6). The peak load at each of the microgrid is 100 kW, with an average base load of 56.25 kW across the day. 33 kW of the net load (sited at nodes N7, N9, N11 in MG-1 and N17, N19 and N21 in MG-2) have been considered as Critical Loads (CL) and are prioritized by the restoration algorithm. In order to ensure

resilience and redundancy in the network, the two CERTS microgrids are modified by addition of normally open paths shown by tie-lines between N11, N7, N21 and N17. In the base case, diesel-operated generators are connected to nodes N6, N8, N10, N16, N18, N19 and N20 - such that the peak off-grid generation does not exceed 75 kW in both microgrids combined. The ramp-up rate of the diesel generator modeled distributed diesel DERs models were determined to be 2.5 kW/ s, such that system stability is not impacted. This representation is developed in RSCAD (the modeling interface for RTDS<sup>\*</sup>) and the resilience computation and restoration algorithm has been co-simulated using external scripts within the same computer [17,62]. The overall simulation workflow schematic has been represented in Fig. 7.

#### 6.2. Case I - base case

The loads within the microgrid are modeled such that the net energy demand in each of the microgrid follows a typical load profile for a prototypical feeder for the Pacific Northwest region [63] In order to simulate the resilience for the base case, it is assumed that all nodes are subjected to an equal probability of being damaged (p = 0.25), and the damage may be inflicted randomly at any edge such that a 28% (corresponding to the critical fraction of damaged nodes of the network

d=80%



d=95%

d=90%

No DER

Fig. 8. Resilience metric computed for 24 hourly data points considering different secondary energy resources as means of enabling resilience in the distribution system.

[12]) of all edges of the system are consequently damaged. The resilience metric was used to quantify the resilience for 24 data points, corresponding to hourly peak energy demand of a typical day in the prototypical feeder, operating in normal configuration in grid-connected mode. It is shown as blue line, on Fig. 8. The resilience metric, in absence of auxiliary support by means of DERs or reconfiguration algorithms, inversely follows the load profile, where increase in demand corresponds to more stress on the system, and eventually lower resilience. It is important to note that this resilience metric varies by operating conditions, and system configuration.

#### 6.3. Case II - PV battery deployment

The solar data shape file has been obtained for geographic location "46.117 N, -117.812 W" from NREL's solar energy resource [12] for a period of three summer months (May 1 through July 31, 2016). The solar generation data is used to scale the output to a peak production capacity of 75 kW. Compared to the base case, even without implementation of a restoration algorithm, strategic installation of PV-Battery system improves the resilience of the system, as shown by the orange, green<sup>4</sup> and red lines in Fig. 8. Different depths of discharge (d) has been simulated for computation of resilience, namely 95%, 90%, and, 80%. The depth of discharge or maximum energy withdrawn from a battery before recharge is critical while maximizing life cycle and operational efficiency. Typically, Li-ion batteries have recommended lower depths of discharge compared to flow battery. This paper only reports battery simulations up to d = 80%, flow batteries can be operated at higher levels of depths of discharge - contributing to increased resilience, but the approach is generalizable.

#### 6.4. Case III - with flow battery deployment

A scenario is simulated in which a sudden loss of load is inflicted upon the network at node N9, and alternative, off-grid generation resource is required to be brought online. In that event, the resilience metrics drop from 0.77 to 0.63. As described in a previous section, flow battery has extremely fast response times (in milliseconds). Thus, the control system of the network is able to bring all dependent loads online within the next cycle of resilience computation, and the operational resilience of the network was restored to 0.77 within one second. In the base case simulation with traditional DERs characterized by slow rampup rates of 2.5 kW/s, it took the control system to restore all loads and reach original operational levels of resilience after 27 resilience computation cycles, or 27 s with the details as shown in Fig. 9.

#### 6.5. Case IV - Flow battery with different P/E ratio

The P/E ratio of an installed battery in a microgrid, is a critical aspect of the design with a direct impact on the resilience of the system. The P/E ratio expresses the amount of power that a battery system can supply in real-time compared to its energy capacity. In the experiments for this paper, the nominal power of the flow battery was 22 kW, maximum energy storage capacity 160 kWh, maximum power rating 64 kW and energy at maximum value of 125 kWh. With these design specifications, resilience metrics of the microgrid were computed for a wide range of scenarios at various loading levels of the day, and shown in Fig. 10. It was observed that resilience metrics using flow battery improves resilience from base case by 40.57% during morning hours (6 AM - Noon), 44.15% during afternoon hours (Noon - 6 PM), 38.04% during evenings (6PM - 10 PM), and 8.96% (10 PM - 6 AM) when operating at 0.4 P/E ratio and d = 80% (as shown in Fig. 10). With d remaining constant, 0.2 P/E ratio improves resilience from base case by 18.24% during morning hours, 34.25% during afternoon hours, 19.84% during evenings, and 0.96% during nights, 0.3 P/E ratio improves resilience from base case by 22.77% during morning hours, 33.12% during afternoon hours, 19.13% during evenings, and 7.12% during nights, and 0.4 P/E ratio improves resilience from base case by 38.24% during morning hours, 34.25% during afternoon hours, 22.23% during evenings, and 0.96% during nights. For resilience metric at d = 90.0%and d = 95% is shown in Figs. 11 and 12 respectively.

#### 7. Conclusion

This paper presented resilience-based design approach for flow battery-based energy storage system in advanced distribution grids. AHP is used for decision-making to serve load in order of identified criticality. Various operating scenarios are considered for reconfiguration of the distribution grid, modeled as two interconnected microgrids. Actual hardware-characterized dynamic data is used in simulations to consider exact response of the energy storage. Energy storage interaction is explored by varying P/E ratio in range 0.1 to 0.4, and results

 $<sup>^{\</sup>rm 4}$  For interpretation of color in Fig. 9, the reader is referred to the web version of this article.



Fig. 9. Resilience metric computed with restoration of critical loads using flow battery and diesel generator.



Fig. 10. Resilience metric computed for test system different P/E ratios (0.1-0.4) of flow battery with maximum allowable depth of discharge d = 80.0%.



Fig. 11. Resilience metric computed for test system different P/E ratios (0.1–0.4) of flow battery with maximum allowable depth of discharge d = 90.0%.

show that improvement in power-to-energy ratio almost consistently enables resilience improvement by providing higher power output, under various loading conditions. A couple of exceptions are observed and the decrements in resilience, although very small, may be attributed to higher relative allowable depth of discharge compared to other cases. The ESS with higher depth or state-of-charge aims to maximize resilience by a given reconfiguration, by consistently providing higher power output, thereby lowering available charge for subsequent time periods. Adopting a resilience-based approach, under reconfiguration algorithm to serve critical loads in the distribution grid, can provide optimal results for design of energy storage. Hardware-characterized



Fig. 12. Resilience metric computed for test system different P/E ratios (0.1–0.4) of flow battery with maximum allowable depth of discharge d = 95.0%.

data can be used for other DERs, including other energy storage technologies, for systematic optimal design. Such an analysis provides a comparative assessment between technologies for optimal design of hybrid energy storage systems. The approach presented here can also benefit the distribution system operator by providing an insightful understanding of the absolute threshold of resilience metrics, before implementing the approach in future grid.

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#### Appendix A. Supplementary material

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