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Resilience of the electric distribution systems: concepts, classification, assessment, challenges, and research needs

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Abstract: Distribution system resilience is an emerging topic of interest given an increasing number of extreme events and adverse impacts on the power grid (e.g. Hurricane Maria and Ukraine cyber-attack). The concept of resilience poses serious challenges to the power system research community given varied definitions and multivariate factors affecting resilience. The ability of nature or malicious actors to disrupt critical services is a real threat to the life of our citizens, national assets and the security of a nation. Many examples of such events have been documented over the years. Promising research in this area has been in progress focused on the quantification and in enabling resilience of the distribution system. The objective of this study is to provide a detailed overview of distribution system resilience, the classification, assessment, metrics for measuring resilience, possible methods for enabling resilience, and the associated challenges. A new multi-dimensional and multi-temporal resilience assessment framework is introduced along with a research roadmap outlining the future of resilience to help the reader conceptualise the theories and research gaps in the area of distribution system cyber-physical resilience.

1 Introduction

Enabling distribution system resilience is a multi-step process that begins with the identification of the potential threats to the system, the quantification of the current resilience of the system to the identified threats through the development of resilience metrics, proposing resilience improvements and finally the evaluation of the resilience improvement strategy. This process of enabling resilience requires system-specific research and complex analysis tools. The need for studying this topic stems from the devastating impacts of recent catastrophic events such as the Sandy Super-storm, Hurricane Harvey, Hurricane Irma, Hurricane Maria, and Ukraine cyber-attack [1, 2], to name a few. These low-frequency, high-impact events have caused millions of people to suffer without electricity, but the most significant impact is the loss of service to critical services that have a debilitating impact on national security, national economic security, public health, and safety. The backbone of all critical services is the electrical distribution network that transports power from the substation to the end users. This has been of national importance as directed by the Department of Homeland Security [3]. These critical services are defined as services that are services essential to the minimum operation of the economy, society, and government. Some examples of critical services are telecommunication systems, banking and finance systems, water supply systems, and emergency services (medical, police, fire, and rescue).

The Department of Defence in its Space Policy Directive defines resilience as the ‘ability of an architecture to support the functions necessary for mission success with higher probability, shorter periods of reduced capability, and across a wider range of scenarios, conditions, and threats, in spite of hostile action or adverse conditions’ [4]. Extending to the power distribution system (PDS), resiliency can be defined as the ‘ability of the network to resist discontinuity of power supply to critical loads during stressful operating conditions, and recover from any damages during unfavourable events’. The use of the word ‘threat’ or ‘event’ in this study will always refer to these high-impact, low-probability or high-impact, low-frequency (HILF, a term first used to describe high-impact events in the operations and logistics industry [5]) unfavourable events unless otherwise noted. Some of these events and threats are shown in Table 1. These threats, particularly cyber threats, are common and often have high-occurrence rates. However, from the concept of resilience to these threats, the probability of these cyber threats to create high-impact cyber-physical events are low. This was one of the lessons learnt from the Ukraine cyber-attack.

Table 1 High impact, low probability events

Classification	Examples
physical – manmade	warfare, terrorism, vandalism, and riots
physical – natural	storms, hurricane, earthquake, tsunami, cyclone, snowstorm, avalanche, and solar flares
cyber	eavesdropping, denial of service, bad data injection, data packet modification, man in the middle attack, and day zero vulnerabilities

The PDS is the most vulnerable stage in the electric power delivery mechanism. High-impact events affect the PDS adversely with sometime irrecoverable damages to assets. The radial nature of the distribution system makes the restoration process hard. The PDS by design in most cases lacks redundant paths that can be used as necessary to provide pathways for power delivery. Other factors that impact the inherent resilience of the PDS is increasing frequency of extreme weather events that affect the health of the infrastructure negatively, the general age of the infrastructure and the increased role of cyber components in the PDS for automation, monitoring, and control, which are more susceptible to remote cyber-attacks.

The PDS serves many critical loads such as hospitals, law enforcement centres, and communication lines, whose disruption can cause serious loss of life and property. Even though there are certain building codes and standards in place to ensure the continuous supply of power for life safety purposes, immediate restoration is mandatory. For example, in the case of high-impact disasters such as Hurricane Katrina whose impacts were felt days later, the emergency power provided by diesel generators based on the 96-h fuel capacity of emergency generators, as mandated by NFPA 101 [6] have been exhausted. In addition to this, the loss of power incurs an enormous economic cost to the local population and the US Department of Energy has identified the economic benefits of grid resilience [7].

Irrespective of the type of event affecting the system, the system should have the capability to anticipate and withstand the

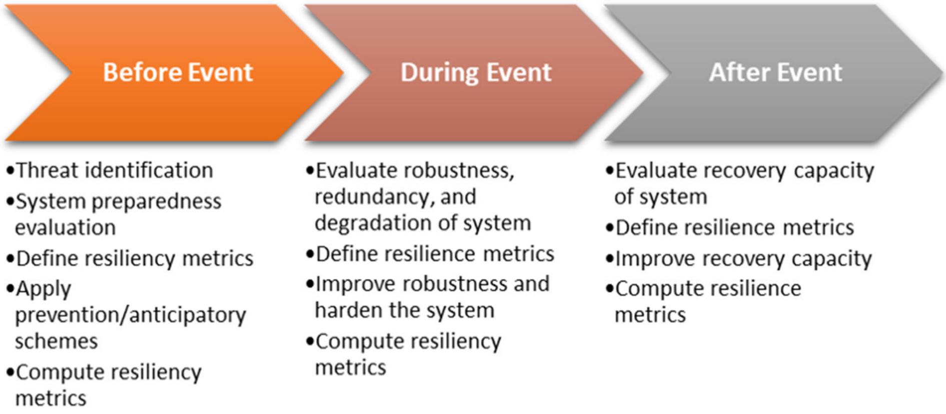

Fig. 1 *Multi-temporal resilience framework*

event while recovering back to its original pre-event state to be defined as a resilient system. With the effects of climate change increasing the frequency of high-impact climate events, it is necessary that pragmatic research is done in this area and the authors believe that this study will provide a primer into resilience metrics. There is multiple published related work for resilience including [8–10].

2 Assessment of PDS resilience

To impart resilience to a distribution system, the first step is the detailed enumeration of all threats that affect the system. The catalogue of threat obtained from the previous step need to be ranked so that threat that has the highest impact can be earmarked for study and for selective hardening of assets. This step would ensure that the utility that plans on investing in resilience improvements would be able to make a business case to justify the investment. The variation in the threats affecting a particular system also creates the need for a tailor-made solution to enable the resilience of that system. A system that under-grounded its conductors due to wind storms would see a tremendous increase in the system performance in terms of availability but a similar strategy would not work if that main threat to the system is seismic events. Careful consideration of the type of threat is warranted in all cases. Modelling threats and their impact are followed up by examining resilience indicators of the system. Metrics for system resilience are not as well-defined as reliability metrics. The metrics introduced for resilience are detailed in Section 3. Methods for quantifying resilience including capturing system performance as a function of resilience, the use of multi-criteria decision making or the explicit use of resilience indicators such as restoration time, cost of operation and recovery, social expense, and outage duration, are used to derive the resilience status of the distribution system with and without the threats.

2.1 Multi-temporal resilience framework

In terms of enabling resilience to the PDS, the utility will have to look at the temporal nature of the event and the performance of its system to the threat. Therefore, we propose a resilience framework that is novel in its formulation with resilience assessment in each phase of the threat: before, during, and after. Before the threat, the system should be able to accurately predict the threat and its impact, and subsequently, be prepared for the threat. During the threat, the system should effectively withstand the threat by minimising damage to its components and provide continuous service to the critical loads. After the event, the system should be capable of recovering quickly from the damage and revert back to full performance with minimum time. This time frame-based resilience assessment provides researchers or utilities the flexibility to concentrate on the weakness of the system. Robust systems may lack preventative resilience measures. The proposed multi-temporal resilience framework is shown in Fig. 1. A highly automated system may suffer from fragile assets. By separating the impacts, metrics, and strategies temporally, the system can be designed to

- Predict the threat accurately and prevent impact on the system – the system is evaluated for how well it anticipates impending threat, deploys preventative measures, and ensures preparedness.
- Absorb and survive the threat with minimum damage – the system is evaluated for the capacity to withstand the threat, reduce the degradation of the system performance, maximise resilience objective such as minimum loss of critical loads.
- Recover quickly – the system is evaluated for how quickly it can recover with minimum cost and rapidly restore supply to downed critical loads.

The operation of the PDS is an inter-connected, multi-domain, complex system. By only considering power system components, a justifiable level of resilience cannot be specific. Consider a post-hurricane restoration effort, whose completion might be hindered by the flooding of roads, non-availability of replacement equipment or spare parts, crew shortage and the most important of all, money to pay for the repairs. Fig. 2 shows one such system illustrating the multi-domain interconnectedness of the PDS and provides an insight into the interconnectedness of the distribution system. It is imperative to understand the translation of this interconnectedness to the overall resilience of the system.

That being said, a more inclusive method of resilience metrics needs to be included. In this section, we will classify resilience. We begin with the most basic of classification based on if the resilience is imparted, directly or indirectly. Other classifications based on implementation, stage of the event, and non-electrical factors are also discussed. Tables 2 and 3 provide an overview of resilience classification and some examples.

2.2 Passive resilience

Passive resilience is the presence of factors that impart resilience to the PDS by means of strengthening or isolation of intrinsic properties of the system's response to events. It can also be defined as the inherent ability of the PDS to reduce failure. For example, a fully underground distribution system is said to have passive resilience to atmospheric weather events (say tornadoes capable of felling multiple above-grade structures) and an elevated substation is said to have passive resilience to flooding events. In some research articles, it is also referred to as infrastructure resilience where resilience is achieved by hardening the PDS infrastructure or isolating it from extreme events. Similarly, it can also be referred to as planning resilience in some cases, where the effort is planned or designed to impart resilience.

The planning resilience or infrastructure resilience is a dollar-intensive approach to hardening the existing system against the threats [11]. Hardening is defined as 'physically changing the infrastructure to make it less susceptible to damage from extreme wind, flooding, or flying debris' [12]. Hardening existing infrastructure is difficult and expensive than new construction with reduced vulnerabilities to events. The most common hardening

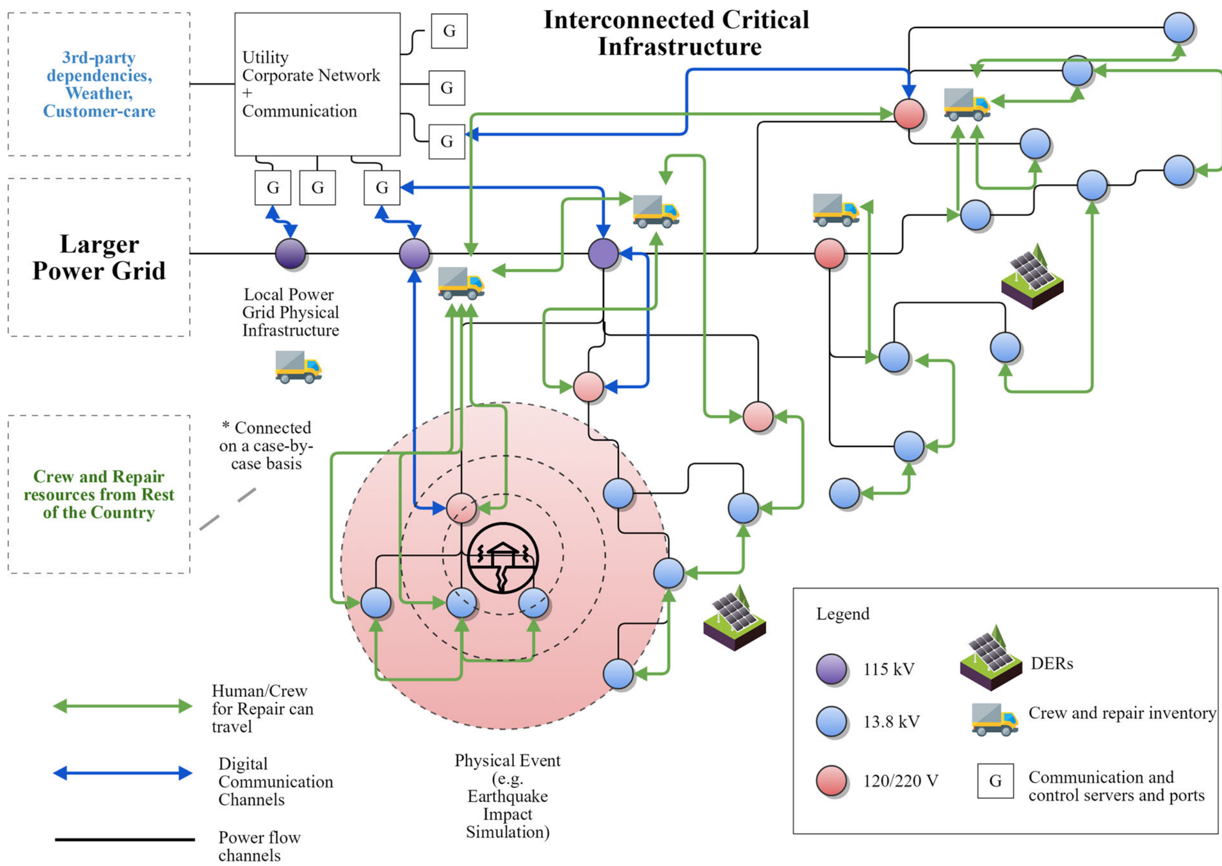

Fig. 2 *Interconnected PDS*

strategy is the 'undergrounding' or the conversion of overhead lines to underground direct-buried or concrete encased conductors. Fluke *et al*. [13] presented a case study of the system modernisation and reliability programme of the Wisconsin public service where overhead lines were replaced with underground lines and distribution automation was installed. As noted earlier, this was done to improve reliability and there is no reason why this would not improve the resilience of the system by removing assets from the threat. The authors of [14,15] provide other methods of infrastructure hardening by elevation of open-air substation structures and equipment. Boggess *et al*. [15] also provide another solution to flood and storm protection of distribution system assets such as an enclosed substation, flooding detection, and waterproofing and provides specifications for the design and construction of such flood and storm-resistant substations. There is some papers that present optimised hardening strategies. In [16], the authors propose an investment minimisation problem, allowing utilities to selectively target their hardening efforts, which are upgrading distribution poles to underground and vegetation management in this case. The authors use a tri-level mixed-integer linear programming approach to optimise the hardening strategy in response to maximum damage with minimal load shedding.

Planning a resilient system is a time and money intensive process, which will depend on the location of the system, its vulnerabilities, and threats. There are other constraints to increasing the passive resilience such as construction schedule limits, permitting issues with authorities having jurisdiction, and the lack of engineering talent to keep up with increased maintenance mandates. The quantification of planning resilience or passive resilience can be extracted from the system characteristics such as graph-theoretic factors such as robustness, betweenness centrality, and path redundancy to supply critical loads. Evaluation of planning resilience is discussed in Section 3.2 and the use of these resilience metrics can provide a baseline and a business case for utilities to prioritise resilience improvements, which increase the passive resilience of the system.

2.3 Active resilience

Active resilience is introducing means and methods to achieve resilience during and after the HILF event has occurred. This is sometimes also referred to as operational resilience. Panteli and Mancarella [17] defined operational as 'considering the effect of the real-time operating conditions that the system experiences.' The review paper [8] has already classified the various methods of operational resilience. Therefore, this study will only introduce the general classification of commonly used active resilience strategies. It should be noted that many of these schemes, such as passive resilience methods, have a basis in increasing the reliability of the distribution system. We further classify active resilience as proactive and reactive resilience. It is apparent that both proactive and reactive resilience depends on the same technology to achieve resilience viz., microgrid formation or islanding. The quantification of active resilience can be performance attributes such as energy not served (ENS) or critical loads not lost, which are derived from the system performance.

2.3.1 Proactive resilience: Proactive resilience is taking preventative actions to improve the resilience of the system. This includes load shedding, islanding, strategic crew deployment and priming of restoration efforts in anticipation of an event. Proactive resilience is sometimes called preventative or defensive resilience. Proactive islanding is discussed in [18–22]. Defensive islanding techniques are predominantly a transmission system strategy, but a similar methodology can be applied to large distribution systems with distributed energy resources (DERs). Self-healing islands are used to describe systems that can detach from the grid to prevent cascading outages while maintaining acceptable steady-state conditions for the continual serving of critical loads. In [18], an optimal islanding solution with minimal load shedding is discussed. Panteli *et al*. [18] provide an example of a transmission system proactive resilience technique that can be applied to large distribution systems with DERs that can operate as islands. In [19], a test system is broken into four islands each served by a DER. Fotuhi-Firuzabad *et al*. [23] propose an optimal switch placement algorithm that is based on a resilience index in which the intensity of the weather impact is the primary variable in the selection of switch locations to serve critical loads. In this scheme, the critical load can be served either by microgrids formed per selected switch placement or by disconnecting non-priority loads to ensure that microgrids have enough capacity.

2.3.2 Reactive resilience: Reactive resilience can be defined as the ability of the system to recover, after a high impact event, with a greatly reduced restoration time with respect to critical loads. This resilience class deals predominantly with distribution system restoration (DSR) and optimised deployment of personnel to repair damaged equipment and feeders. Chen *et al*. [24] propose a resilience-based restoration approach that integrates weather data, field measurements, customer calls, and advanced metering infrastructure (AMI) data to form a DSR decision support tool. DSR optimisation has been proposed using microgrid formation to serve critical loads. In [25], the authors propose a mixed-integer second-order cone programming and in [26], the authors use a maximum coverage problem approach while considering the stability of the microgrid and the dynamic performance of the distributed generators (DGs). During a high-impact event, it is necessary to leverage the use of all available generation sources and reconfiguration schemes and it is a trend that has been noticed in this review paper. Wang *et al*. [27] used a two-stage restoration procedure with the first step being the post restoration topology and the second step being the mixed-integer semi-definite programming to optimise the critical load restoration scheme and the generation output of the multiple generation sources, which in their test case are battery energy storage system (BESS), photovoltaic (PV), and diesel generators. The study shows the usefulness of being able to coordinate multiple energy sources during high-impact events.

Table 2 Classification of power system resilience I

classification of power system resilience	
performance-based resilience	
active resilience: resilience through control and automation. Proactive resilience provides preventative function and reactive resilience provides a restorative function	defensive islanding
	self-healing islanding
	microgrid formation
	optimal switch location
	crew training and response planning
	network restoration
passive resilience: resilience through system attributes	hardening
	network redundancy
	source redundancy
	vegetation management
	asset spares for repair
interdependent systems resilience	
economic resilience	minimising utility loss during an outage
	capital management for HILF threats
	resilience as a service
human resource resilience	optimal crew dispatch for repair and maintenance
	resiliency-oriented operator training
	provisions for emergency supplies for the crew
	threat assessment and response plans
supply chain resilience	inventory control and spares management
	diversification of energy resources, e.g. renewables
	energy markets
	threat informed logistics and supply chain management

2.4 Human resource resilience

PDS resilience is significantly affected by the human factors associated with it. The technical proficiency, training, and availability of the crew along with the response plan to the threat is a crucial factor in PDS resilience.

There are some studies that look into the human element in the resilience quantification and implementation. Tan *et al*. [28] solved the restoration problem through mixed integer linear programming (MILP) and generated an optimal single crew repair sequence. The study also considers the optimal hardening strategy in conjecture with the human element. Crew mobilisation is one of the main steps in post-disaster management. Optimal crew routing and minimising repair times can be crucial in the restoration process. Chen *et al*. [29] used synthetic MILP for restoration and optimal crew dispatch. In [30], the authors have co-optimised the repair crew dispatch with mobile power systems along with scheduling sequence of repairs and mobile power sources (MPS) output, with restoration and load pick-up plans. In [31], the authors co-optimised the repair and restoration of a PDS by using MILP to coordinate DG output, switch position, and repair crew dispatch. This study includes the difference in the performance of the utility workers by assuming that some workers can repair only selected equipment and repair times vary between workers.

2.5 Economic resilience

This term is not to be confused with the economics concept of resilience that applies to the economic shock and subsequent recovery during a shock event, in this case, the disruption of power to economic centres. However, it is helpful to note the research on the economic effect of high-impact events, such as [32] that studied the economic resilience characteristic of a hypothetical terrorist attack in Los Angeles, USA. However, it does not emphasise the disruption of power but the interruptions to business activities. Disruption of electricity causes enormous loss in revenue for local businesses and industries.

Resilience research generated initial interest because of the enormous cost of business interruption losses that occurs due to outages in commercial and industrial revenue centres [12]. The effect of HILF events that lead to loss of critical leads can have direct and indirect impacts on both micro-economies. We did not find any research papers that directly dealt with the aforementioned. Therefore, future research into the loss of revenue needs to be introduced as a term of calculating the resilience of the system. Economic analyses such as input–output modelling and computable general equilibrium need to be applied to study the impacts of the loss of critical loads. Metrics need to be developed to evaluate economic costs based on which control and recovery actions can be designed for the most economic resilience.

3 Resilience metrics

Many works have identified Holling's work relating to ecological systems as one of the first definitions of the resilience of a system [33]. With growing interest in enabling resilience of the distribution system, a need for quantifying the resilience of the system has given rise to the development of resilience metrics. Given that the PDS is a complex network with multiple interconnected networks interacting to facilitate a single objective bounded by constraint.

Definition: resilience metrics are the quantification of the resilience of the PDS. This can take the form of a collection of resilience indicators or a multi-domain, multi-dimensional assessment that can accurately capture the ability of the system to continue supplying to critical loads under stressful conditions and recover from the loss of assets during the event. The two main reasons for the need for resilience metrics is to justify the investments in resilience driven upgrades to operations and infrastructure and to evaluate the efficacy of such upgrades or strategies [34].

Table 3 Classification of power system resilience II

classification of power system resilience	
temporality-based resilience	
before threat: the ability of the system to predict, prevent, and mitigate the threat before the threat happens	prediction algorithms to determine an impending threat
	threat models evaluate the expected loss of critical loads during the event
	proactive reconfiguration schemes
	optimal switch and DER placements
	strategic deployment of crew and rationing of fuel resources
during threat: the ability of the system to withstand, absorb, and survive the threat when it happens	withstand capability of the system
	start-up of diesel generators and dispatch of BESS systems
	shedding of non-priority loads to serve critical loads under generation stress
after threat: the ability of the system to recover, restore, reconfigure, and repair itself after the threat	optimal management of recovery and repair
	automatic system reconfiguration
	intentional islanding and microgrid formation
	mobile transformers and gensets
	black-start restoration
implementation-based resilience	
planning phase: resilience by design, system hardening smart investment policies, and implementation	selective hardening of vulnerable assets
	undergrounding conductors
	installation of DERs and BESS
	redundant network paths for serving critical loads
	enhanced communication infrastructure
	implementation of smart sensors and meters
	distribution automation
	resilience-oriented repair crew training
operational phase: resilience by control strategies and policies	network reconfiguration and restoration algorithms
	load curtailment of non-priority loads
	selective dispatch of diesel generators
	proactive charging of BESS for dispatch during threat
	automatic source transfer
event-based resilience	
physical resilience: resilience to man-made and natural physical threats	pole hardening
	inundation risk mitigation such as sump pumps, storm sewer systems, flood monitoring, and elevated construction
	elevated substations
	seismic and wind rated equipment
cyber resilience: resilience to cyber threats	encryption
	access control
	penetration testing of cyber/ communication hardware
	firewall
	redundant communication links

Metrics development has been recognised as one of the outcomes of the Grid Modernisation Lab Consortium Metrics Analysis Project (GMLC 1.1) [35]. It has identified the two categories of resilience metrics

- *Attribute-based metrics* – that identifies power system attributes that affect the resilience of the system. Robustness, resourcefulness, adaptivity, recoverability, and situational awareness are considered resilience attributes. For example, the ratio of underground feeders to overhead feeders' results in increased robustness and in turn, leads to improved resilience of the system to disruptive atmospheric events such as hurricanes.
- *Performance-based metrics* – that can describe system functionality to events. The functionality in resilience terms is the ability to serve critical loads during a disruptive event. Performance-based metrics will use resilience attributes in their calculation but will be described based on function rather than form.

Gao *et al*. [36] identified a set of analytic tools that can be used to calculate the bifurcation point of the resilience of complex natural systems, where beyond the bifurcation point, the system can reach a reduced resilient state or completely collapses. This work proposes that it is indeed possible to determine a universal resilience curve that can be used to quantify the resilience of the multi-dimensional complex system. In the realm of the PDS, a mandated emphasis on metrics for reliability exists and is used extensively by utilities. Liu *et al*. [37] provided a summary of the metrics used in the reliability assessment of cyber-physical distribution systems. However, the criticality of load, nature, and duration of the impact is not considered. Therefore, a comprehensive metric that considers the weather-induced failures and cyber-attacks by malicious actors needs to be developed. This will enable operators to make decisions that will improve resilience with the lowest cost. In terms of classifying the research on resilience metrics, the proposed metrics so far can be classified into three broad categories:

- Performance-based metrics for resilience
- System characteristic-based resilience using resilience impact factors
- Cyber metrics

The cyber metrics developed has been discussed in Section 4.

3.1 Performance-based metrics for resilience

Works on resilience metrics have taken various variables into account but can be generally defined as providing a quantifiable means to combine multiple data points such as weather, power system constraints, infrastructure strength, and cyber vulnerabilities. Of the multiple ways in which resilience metrics are developed, we frequently see the use of resilience progression sequences, which show the spatiotemporal impacts of an extreme event on the resilience of the system. A simple definition of resilience as proposed in [38] compares resilience to availability as the ratio of the system up-time to the sum of the system uptime T_u and downtime T_d

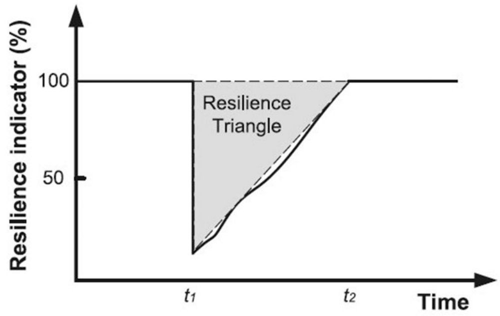

Fig. 3 *Resilience triangle [39]*

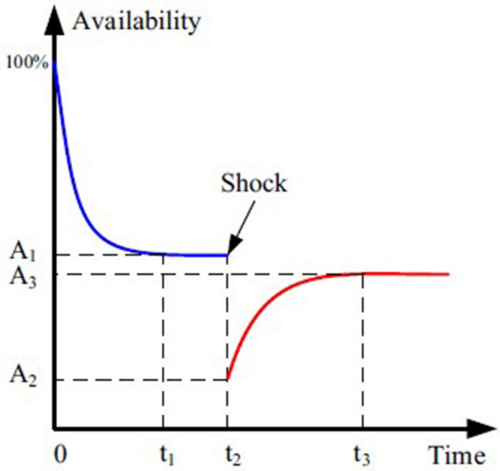

Fig. 4 *Availability as resilience indicator [38]*

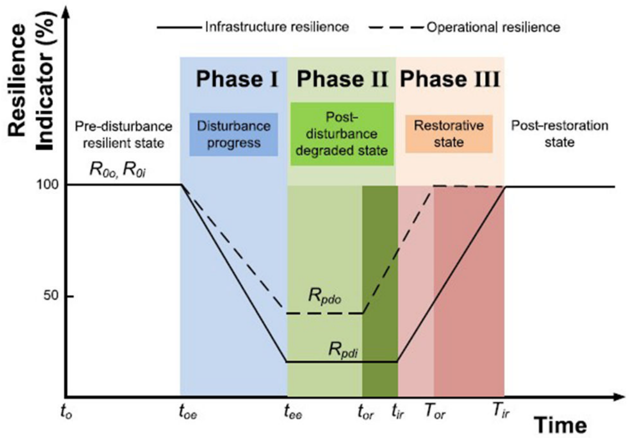

Fig. 5 *Resilience trapezoid [41]*

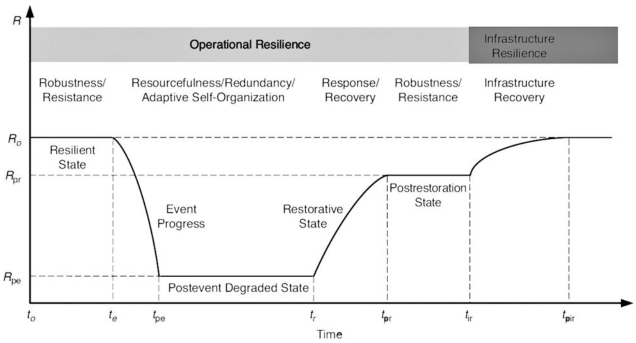

Fig. 6 *Resilience curve [18]*

$$R = T_\mathrm{u}/(T_\mathrm{u} + T_\mathrm{d}) \tag{1}$$

This definition is useful as it takes the availability of the functional performance of the system. However, from a planning and operational point of view, this may be vague to incorporate hardening strategies and control algorithms.

The resilience triangle [39] represents the degradation on the functionality of a particular asset over event time lime as seen in Fig. 3.

Cai *et al*. [38] proposed an availability-based engineering resilience metric. Fig. 4 shows the representation of the availability function of an engineering system, which is the ability of the system to perform the required function under a given time interval. The two temporal events are availability versus shock (blue line) and availability versus degradation (red line). The authors propose a resilience metric that considers the pre- and post-availability (normalised to the natural log of time) shown in Fig. 4 where A is the availability with subscript 1 referring to steady-state availability, subscript 2 the post-shock steady state availability (degraded state), and subscript 3 the post-shock availability (recovery state).

The one-dimensional characteristic of the resilience triangle is not helpful in studying the multi-dimensional nature of power system resilience. There has been some work that quantifies the resilience of a system based on the improvement of social welfare to increased grid resilience as documented in [12]. Najafi *et al*. [40] propose a resilience metric based on the social welfare index during hurricanes that take into account the accessibility of the population to power and water and the interdependency of water and PDS. These one-dimensional analyses are not helpful in evaluating the multi-dimensional nature of power system resilience.

The extension of the triangle is the resilience trapezoid work which considers the presence of corrective actions to the event and post-event degradation state to extend the resilience assessment proposed as the resilience triangle. The authors propose the $\Phi\Lambda E\Pi$ resilience metric system, which measures resilience based on the characteristics of the resilience trapezoid as seen in Fig. 5. The resilience indicators $\Phi\Lambda E\Pi$ are derived from the resilience trapezoid, which is divided into three phases: phase I: disturbance progress; phase II: post disturbance degraded state; and phase III: restorative state [41].

In [18], this trapezoid was evaluated with respect to how the resilience indicators undergo four phases, also referred to as, the '4Rs': robustness, redundancy, resourcefulness, and rapidity as shown in Fig. 6. This conceptual resilience curve has been used to baseline certain resilience enhancement schemes to understand the efficacy of the scheme before and after the event [42, 43]. The resilience metric system as per – Φ denotes the speed of resilience degradation that increases with the intensity of the weather event, Λ denotes the worst case impact of weather impact, E denotes the duration of the post-disturbance degraded state, Π denotes the recovery time. The narrower definition of the resilience of a PDS as the ability to reduce supply discontinuity to critical loads requires the criticality of components in the system. The critical components in most cases are the loads which are typically ranked in the order of priority based on the function performed by the loads such as life safety loads including hospitals, clinics, and care centres, or public safety loads including police stations, fire stations, military bases, and supporting infrastructure such as communication centres, data centres, and water distribution pump houses. Fang *et al*. [44] proposed the use of optimal repair time as a resilience indicator that allows for the categorisation of loads in the order of the priority of restoration. The optimal repair time T_{ij}^{opt} quantifies the priority with a failed component that should be repaired and the authors compute resilience reduction worth RRW_{ij} that quantifies the potential loss in optimal system resilience due to a delay in the repair time. The use of this measure is post-threat and, therefore, deals with the recovery of the system.

3.2 System characteristic-based resilience using resilience impact factors

The next evolution of resilience metrics is designed as a multi-objective optimisation problem that takes into account the various

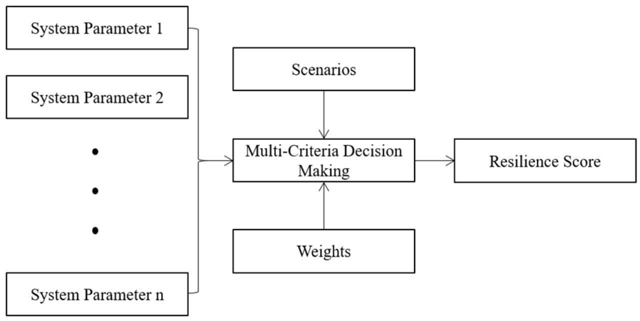

Fig. 7 *Formulation of resilience metrics using MCDM techniques*

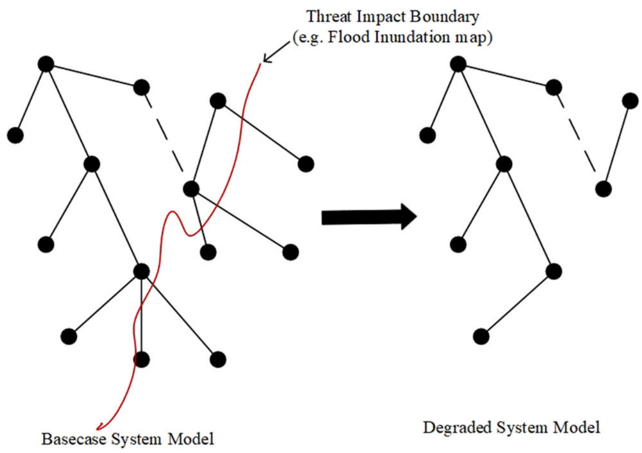

Fig. 8 *Threat modelling using explicit methods*

factors involved in quantifying system resilience. The work on metrics in [45–47] introduces the use of multi-criteria decision-making methods (MCDM) to quantify resilience by taking topological parameters based on graph theory, weather factor, and power system constraints to quantify resilience. A framework for using the MCDM technique for resilience metrics computation is shown in Fig. 7. By selecting system factors that vary during different scenarios and assigning appropriates weights based on their impact on the system resilience, a composite score can be computed. These scenarios can either be the system state during a threat event or after a resilience improvement strategy has been implemented. Careful selection of factors and corresponding weighting based on impact and elicitation with operators and utilities is required.

Graph theory-based assessment of resilience is the best assessment of the topology of the distribution system. The distribution system is modelled as a graph $G = (N, E, W)$, where generators, transformers, substations, sectionalisers, and loads are modelled as nodes (N), feeders are modelled as edges (E), and the critical generators and loads are weighted by (W) indicative of their priority. The work proposed in [48] analyses the graph-theoretic metrics of the Korean power grid. Resilience analysis for error and attack tolerance, cascading failures, and recovery analysis is performed based on node and network metrics of the graph equivalent of the Korean power grid. Graph-theoretic analysis can also be used to evaluate system degradation as a function of geospatial risk as shown in Fig. 8. Chanda and Srivastava [45] proposed a resilience metrics $\mathfrak{R}$ that take the topological resilience of the distribution system, which comprises graph-theoretic factors that include betweenness centrality, algebraic connectivity; system factors that include failure rate of equipment and critical load not lost and impact factor that is described as a weather factor. A decision matrix $\mathfrak{R}\mathfrak{R}^{\mathrm{T}}$ is formed. The relative importance of each term of $\mathfrak{R}\mathfrak{R}^{\mathrm{T}}$ is determined using the analytical hierarchical process and a single resilience metric is calculated through the weighted sum of the individual metric. The effect of the extreme event is usually represented in terms of expected energy not supplied (EENS) so that the fraction of the critical loads that are not supplied can be determined.

Similarly, Espinoza *et al*. [49] proposed the use of the ENS and energy index of unreliability (EIU) to evaluate the resilience of the power system to earthquakes by performing a single-stage temporal assessment of seismic damage to the power system. It should be noted that ENS, EENS, EIU, loss of expected energy (another term similar to ENS and EENS) are still reliability indices but can serve to capture resilience by being applied exclusively to critical loads. This work does not use MCDM techniques but is an example of using existing reliability metrics to quantify resilience. In [46], the authors extend this resilience metric using the analytic hierarchy process by extending the method to include the probability of node damage using percolation theory and also load flow feasibility that will ensure that operational constraints are met, and the power flow converges for the system at normal and reduced operating state. In [47], the authors use Choquet integral, which is an aggregation operator that can be used to quantify the importance of the different resilience criteria and to compute the resilience metric. This work looked at the graph-theoretic analysis of the source to sink paths and created possible networks that comprise nodes between generation, which can be the utility or substation bus and the critical load node. From this set of possible networks, power flow feasibility is performed to filter out infeasible networks and form feasible networks. The MCDM technique, Choquet Integral, is applied to various attributes of the possible networks to calculate the resilience score of each. The one with the highest score is taken as the most resilient network. It should be noted that the factor of time is not used in the previous approach, which is then included in [34]. In this work, the authors are able to formulate an R metric that denotes the system resilience in terms of the time period of outage and magnitude of an outage. This temporal method of resilience evaluation is useful for the operator as it can translate directly into faster and more impactful decisions.

4 Quantifying system resilience to cyber-threats

This section focuses on the non-intersecting research work done understanding the latest development in cybersecurity resilience and lessons learned from recent catastrophic events in Puerto Rico due to hurricanes Maria and Irma and the cyber-intrusions that occurred in Ukraine leading to a blackout. Similar to the introduction sections of many of the research papers dealing with resilience, we would like to begin this section with a definition of cyber-physical resilience of the PDS to put things in perspective. It can be defined as the ability of the power system to keep its cyber-physical functionality intact to an acceptable level in the presence of high impact, low-frequency events (man-made or natural). These threats, such as the ones mentioned in Table 1 may be common occurrences but without any significant cyber-physical effects on the system but when carefully executed by trained actors, such as the Ukraine attack, can be catastrophic. To achieve resilience the system needs to absorb, survive, and recover from such an event [50]. The threats to the cyber-physical system are numerous and some common threats are shown in Table 1. Sridhar *et al*. [51] list cyber vulnerabilities with power system applications.

There have been few papers published that describe the methodology to devise resilience metric framework to quantify cyber-physical resilience. Friedberg *et al*. [50] proposed a resilience metric framework based on a vector of performance measures that can be used to predict the resilience of the system through estimation. The performance measure they used includes load, network delay, error in frequency, and error in phase angle to model the load-generation mismatch and the cyber variables. Clark and Zonouz [52] used a resilience metric that quantifies the cyber-physical intrusion resilience and formulates cyber-defence policies. The intrusion is modelled as a competitive markov decision process and their strategy is to solve the competitive markov decision process to generate an optimal action. Wadhawan *et al*. [53] discussed multiple attacks on various components of smart grids such as fuel distribution systems, DERs, and sensor networks and showed the correlation between the different components and the resilience of the smart grid. Jin *et al*. [54] presented a novel software-defined networking-based communication network

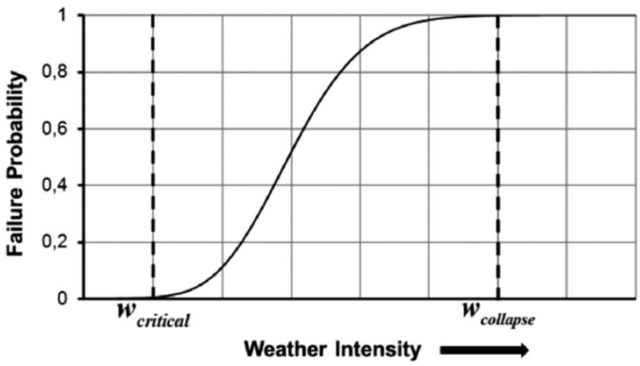

Fig. 9 *Example fragility curve [57]*

architecture to enhance the cybersecurity and resilience of microgrid operations.

5 Challenges and future research needs

5.1 On the definition of resilience

A working consensus on the definition of resilience needs to be attained for the standardisation of the resilience quantification and enabling process. The system level definition of the 'ability of the system to anticipate, resist, respond to, adapt to and recover from a disturbance' is cited in many works [46, 55]. The objective-based resilience definition can be ' the ability of an architecture to support functions necessary for mission success across a wide range of scenarios, conditions, and threats, in spite of hostile actions or adverse conditions' [4]. The objective here can be serving critical loads, minimising loss of loads, restoration time or damage to the system. There are other resilience definitions that are proposed in other disciplines. However, since there is no consensus, researchers often choose the definition that supports their proposed problem statement. Therefore, a control strategy such as non-priority load shedding can be considered to make the system resilient when the definition, in this case, is objectively based but cannot accurately claim to be resilience when the definition is system level based.

5.2 Resilience metrics

As discussed earlier, resilience metrics need to be developed for utilities to justify future investments in resilience improvement strategies and to evaluate the improvement strategy over time. However, a single unified resilience metric that captures all aspects of the distribution cyber-physical system is impractical due to the many reasons. The most obvious reason is the number of disruptive events that threaten the distribution system. Different events demand different response strategies. Consider the hardening strategy of under-grounding conductors, while effective to atmospheric events are not impervious to damage caused by earthquakes and certainly is not a solution to cyber-threats. Therefore, the identification of the hazards that a particular system can face is important. Therefore, the development of resilience metrics that are multi-domain and separated by the event timeline is essentially similar to the framework proposed as per Fig. 1. Evaluating resilience indicators, attributes, and performance of the system before, during, and after requires the multi-dimensional analysis to understand the preparedness, robustness, and recovery potential of the system.

5.3 Threat modelling with multiple infrastructures

A common assumption of most failure or threat analysis of the distribution grid ignores its multiple infrastructure dimension. Wind threats do not affect vaulted transformers and similarly, floods do not affect root-top diesel generation. In this section, some existing research on threat modelling and its challenges are discussed. From Table 1, the degree of modelling required for each of the threats mentioned in Table 1 is different. To model the impact of wind storms on power poles, a sequential Monte–Carlo analysis is performed in [56, 57]. This method uses fragility curves, which map the probability of failure of a component to the magnitude of the threat as shown in Fig. 9. This method can be used for other nodes prone to failure as well. In many works, only a single fragility curve is used. The use of a single fragility curve to compute component failure can lead to some oversimplifications that can swing the threat model because factors such as the age of pole, the material used, and proximity to foliage, may not be taken into account. Statistical tools are employed in [58] to derive node and area probability of failure using historical data. The authors employ rare events logistic regression and mathematical models for the estimation of impact and failure probabilities.

However, many threats that the PDS faces, a more explicit description and impact modelling are used for analysis. This includes inundation plain maps for flood, tsunami, and avalanche risks. In graph theory analysis of the PDS, explicit modelling methods to generate impact as a sub-network provides the degraded PDS to which metrics and resilience improvements can be applied. A simple impact model is constructed using a sample inundation map as shown in Fig. 8. Even though using such a direct threat impact model would create higher accuracy in the prediction of system failure, it is computationally expensive to perform such an analysis for each system. Another issue with the explicit modelling technique would require extensive work by other disciplines such as oceanography, climatology, meteorology, hydrology, geology, and seismology to name a few. The direct application of results from other disciplines to understanding PDS resilience is not well researched. Data-driven techniques such as machine learning can be useful for prediction system failure as shown in [59].

Considering just the impact of the event on the PDS may not be sufficient to compute resilience because of the interconnected nature of the power systems that are dependent on other critical infrastructure for its operation. For example, in a situation where a storm fells power poles and the system is islanded, if the system has pipeline delivered fuel that is also affected or if the roads are flooded to prevent fuel delivery, the resilience of the system is affected significantly. Proper modelling of interdependent systems is required in such conditions for effective threat impact modelling. Other issues to consider while modelling the threat is the penetration of the threats impact in weakening the infrastructure of the PDS that can cause cascading failures in the system and probabilistic models of threat occurrence.

5.4 Resilience with DERs and energy storage

Leveraging energy storage systems for resilience is increasing due to the ease and reduced cost of installation and improvement in control strategies. The most common storage system is the battery-inverter system, which is discussed in several research articles as a resilience resource. In addition, battery technology in plug-in electric vehicles (PeVs) can be used to power the grid during contingencies. Although the business case of installing battery systems under the traditional cost–benefit model might seem uneconomical, the resilience-oriented business case proves effective as demonstrated in [60]. In this work, the authors demonstrated the economic viability of using PV and battery systems taking outage costs into consideration. The state of charge of the BESS at the instant of the outage is vital for the resilient operation of the system and is used as a constraint in the optimal dispatch of storage resources to feed critical loads. In [61], the authors propose a resilience-oriented microgrid scheduling algorithm that schedules the BESS to be fully charged based on predicted islanding contingencies to provide maximum reserve power such that load curtailment is minimised. In [62], a resilience-oriented energy management system (EMS) is proposed that optimises the reserve power during the islanded operation of a microgrid to feed critical loads until the microgrid can operate in connected mode. MPSs, which include electric vehicle fleets, mobile generators, and mobile electric storage systems, present a viable opportunity for system restoration during extreme weather events. Lei *et al*. [63] use optimal resilient routing and scheduling of MPS to enable pre-restoration and increase the survivability of loads. The use of PeVs to enable resilience through restoration strategies depends on the condition of the transportation system, which will also be affected by the threat event in many cases. These effects are pronounced in high-impact physical events such as storms and subsequent flooding, earthquakes, avalanches, and tsunamis among others. It is an important topic of study to analyse the impact of transportation system degradation on resilience enabling strategies such as service restorations, repair and recovery plans by utilities, and the use of mobile restoration strategies such as the use of PeVs and mobile transformers. Zhou *et al*. [64] provide a review of resilient transportation systems and a primer to the resilience metrics, modelling of transportation systems, and resilience enhancement strategies. The impact of HILF events on communication systems heavily burdens communication-assisted control strategies. However, there are some key differences that allow for better survivability of communication networks during such events namely ad-hoc network formation that can establish emergency communications. Chen *et al*. [65] incorporated the communication network failure after a natural disaster and employ a global information discovery algorithm to collect operation parameters of distribution systems for the optimal formation of microgrids to serve critical loads. In [66], the authors employ a multi-agent-based rolling optimisation method for scheduling restoration by allowing agents to identify communication connected parts in the distribution system with distributed communication.

5.5 Utilising data from smart devices including micro-phasor measurement unit (μPMU) and AMI

With the advent of distribution level PMU technology, also called μPMU [67], it is possible to obtain high granularity situational awareness in the distribution grid. The μPMU uses a current and voltage sensor to provide a high-sample rate and time synchronised phasor measurements.

The unique problems with the distribution system such as the unbalanced nature of electrical parameters due to single-phase loads and the radial nature of the topology present unique challenges to μPMU placements. An optimal placement algorithm for μPMU placement can be used to locate for maximum observability from resilience stand-point. This would entail the identification of locations that would monitor critical loads, lifeline feeders, and distribution assets. The event detection algorithm applied to the μPMU can forecast impending outages and can prescribe proactive control action to the distribution management system to isolate and heal critical sections of the distribution system. μPMU can be used for the following application and can be extended to resilience improvement measures. von Meier *et al*. [68] introduced the applications of the μPMU and the work needs to extend to resilience building approaches. As part of the GMLC efforts, work is underway in exploring μPMU's role in improving distribution system resilience. In addition to providing increased situational awareness, μPMU is used in high-speed protection system and system reconfiguration design that can greatly improve resilience through faster, proactive control schemes in anticipation of a high-impact event. Two examples of utilising these data as a step towards resilience are listed below.

5.5.1 Real-time monitoring and event detection: The ability of the system to detect phase and ground faults and voltage and frequency violations directly improves the resilience of the system by enabling system operators or control schemes to identify the nature and location of the disturbance events. With the distribution system state estimation technology being developed, this will provide a real-time state of the system. Zhou *et al*. [69] proposed a μPMU-based event detection framework that can include voltage sags and swells, faults, and frequency oscillations.

5.5.2 Topology identification: The connectivity of the distribution system is directly proportional to the resilience of the system. The network topology parameters are important resilience indicators as identified in [45, 70]. Arghandeh *et al*. [71] proposed a voting-based topology detection method that uses high precision μPMU measurements. Cavraro and Arghandeh [72] proposed a time-series verification approach where the measurements are compared against the library of all signature vectors for all feasible topology changes. Zhou *et al*. [69] proposed a machine learning-based event detection method. These works can provide topology changes as an input to the resilience assessment studies that can translate into faster control actions to eliminate degradation of the system resilience.

AMI can improve reactive resilience by validating the outcome of restoration activity through pinging [24]. AMI can be used to determine the outage condition of the system for better situational assessment [73]. The use of AMI for shedding non-critical loads during a threat event can be utilised for the optimal restoration of critical loads during the threat contingencies. Emergency demand response that can be implemented by smart meters can be modified to resilience-based demand response in such cases. In [74], the authors summarise the potential of AMI technologies in demand side management. In particular, the emergency demand response where the customer can opt for responding to emergency signals shows potential as a resilience resource to provide demand response during threat conditions to reduce the stress of the generation in the system. The introduction of AMIs also poses the threat of cyber-vulnerabilities, which are detrimental to resilient grid operations. AMIs as resilience resources are not well-researched and requires further study.

5.6 Co-simulation of interdependent systems

Some of the challenges with the modelling of an interdependent cyber-physical system can be analysed using co-simulation tools. Co-simulation is the analysis framework of running two or more simulators together with simultaneous message transfer and time synchronisation. Most co-simulation software is available as middleware that coordinates the interactions between the simulators. There have been some co-simulation tools and platforms that capture power system and communication system interactions but are exclusively for transmission systems such as GECO [75] and EPOCHS [76]. Some of the tools such as FNCS and HELICS have been developed, which are capable of co-simulating distribution systems and communication networks and can study interactions such as the effects of communication network characteristics on the transmission network and distribution grid performance [77–79]. The capabilities of the co-simulators can be leveraged for numerous resilience use cases. For example, the current iteration of HELICS is capable of modelling the distribution system in Gridlab-D and the communication network in Network Simulator 3.

5.7 Disaster assessment and recovery efforts

Better assessment of post-disaster damage to the distribution system can help optimise the recovery measures of the utility to restore power during an event by (i) identifying damaged equipment and lines and (ii) providing utility workers with knowledge of ground conditions to better improve restoration efforts.

An important development in the assessment of distribution system resilience is the use of unmanned aerial vehicles (UAV or drones) to assess the post-disaster condition. Drone technology has been used to assess disaster zones as early as human effort comes with risks and costs during these events and, therefore, UAV has proved to be useful in understanding the damage to the distribution system post-event. This area of research is still in its infancy and described below are a few published works that can interest some researchers. With the rise of multi-copter style rotary wing drones, the cost of using UAV has decreased dramatically. Image processing techniques applied to drone images can help identify potential failures and mitigate them. A review of drone-based assessment is presented in [80] and can stand as a primer for further research in this area. The combination of drone technology and wireless sensor networks can prove useful in post-event damage assessment and provide useful data for recovery efforts. Lim *et al*. [81] present a mathematical framework for pre-positioning UAVs to optimise power system assessment and increase the estimated time of restoration.

6 Conclusions

This study provides a comprehensive review and discussion based on existing research articles and reports pertaining to the resilience of distribution systems. Methods for evaluating resilience, classification of cyber-physical resilience and future research requirements are discussed. A framework for resilience analysis that captures system resilience through the various stages of the threat is presented. The intent of this work is to provide a basis and direction for future resilience research and a call for consensus in the definition and approach to enabling resilience. Metrics for resilience developed in the literature has been reviewed. Although some metrics have a simple methodology for calculations, the multi-domain nature of distribution system resilience demands a more inclusive, yet separated by function. Metrics need to be developed that can be independent and co-dependent so the different stakeholders (engineers, operators, utility workers, first responders etc.) can come to informed decisions on necessary actions to anticipate, survive, and recover from HILF events. The future of resilience lies in the seamless integration of the various operational and infrastructural upgrades to the smart distribution system along with the co-simulation of interdependent systems, the probabilistic threat modelling, energy storage, improved communication, and sensor data.

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