A State-of-the-Art Literature Survey of Power Distribution System Resilience Assessment

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***Abstract*—With increased threats from frequent natural disasters, power distribution network resilience has been gaining momentum in recent years. In the literature, a variety of methods have been proposed for assessing the resilience level of the power distribution system. This paper conducts a comprehensive review of the state-of-the-art methods on resilience evaluation framework and metrics in the literature. At first, the core conceptions of the resilience are clarified, and different phases before and after the incidents are analyzed. Subsequently, evaluation methods are classified into several categories based on their features and limitations, and reviewed respectively. Finally, challenges and promising topics in this area are discussed and summarized. The value of this paper is to gain a deep insight into this import research area and envision some future works, which can assist the operator/planner to formulate more effective restoration strategies and produce more effective counter-measures to increase the resilience of distribution network.**

***Index Terms*—resilience evaluation, power distribution system**

I. Introduction

Extreme weather and natural disaster can cause significant damage, bringing unprecedented challenges to the electrical power system as well as other interdependent infrastructures. In 2011, 4.4 million homes suffered outages due to Japan Earthquake [1]. Hurricane Sandy in 2012 left 8 million people without power supply across 15 states of the United States [2], [3]. Violent storms and ruthless lightning strikes put entire state of South Australia into an overnight blackout [4]. Recently, even though 36 days after the Category 4 Hurricane Maria made landfall on Puerto Rico, 75% of residents in Puerto Rico are still without electricity, which makes it the largest blackout in U.S. history [5]. Given the mounting severity and inherent uncertainty of extreme incidents, it is impractical to pursue a continuous power supply in such circumstances, and is also prohibitive to merely focus on the enhancement of infrastructures. That is why many efforts are devoted to address the resilience of electrical power system. Power system resilience refers to as the ability of a power system to recover quickly following a disaster or, more generally, to the ability of anticipating extraordinary and high-impact, low-probability events, rapidly recovering from these disruptive events, and absorbing lessons for adapting its operation and structure to be better prepared for similar events in the future [6]-[8].

There are 3 prevalent topics in this area: network structure enhancement in planning stage, in terms of flexibility and robustness; restoration strategies in post-contingency period, aiming to recover loads through control strategy modification and network reconfiguration; and a feasible and objective evaluation framework. Some researchers propose resilience indices from a perspective of a city or a community [8], providing helpful reference and data for governmental institutes and utilities, without adequate consideration of power system features. Many methods have been proposed for resilience assessment, quantitatively or qualitatively, with diversified priorities and various objectives [9]-[18]. However, there are still many important concerns to be addressed, such as lack of adaptability, absence of Microgrids (MG) analysis, inadequate consideration of interdependency among auxiliaries.

In the literature, there has not been a systematical evaluation framework for a power distribution system, which is a keystone for proposing pragmatic and pertinent ameliorations afterward. This paper conducts a state-of-the-art literature survey that discusses innovations and limitations of recent works, and envisions some future research directions. The value of this paper is to provide a deep insight into this area and explore potential research topics, which can assist operators/planners to formulate more effective restoration strategies and produce more effective countermeasures to increase the distribution network resilience. The remainder of this paper is organized as follows: Section II clarifies bewildering conceptions in this area and describes different roles of resilience assessment in various stages. Then a systematical review of the state-of-the-art evaluation framework/metrics reported in the literature is summarized and discussed in Section III. Finally, Section IV concludes the paper with conundrums and suggestions for future research.

II. Re-scrutinization of the Conception of Resilience

A. *Difference between Reliability and Resilience*

Conventionally, the performance of power system is evaluated using reliability indices such as SAIDI, SAIFI, MAIFI [19], which are insufficient to describe the non-stationary faults and restoration process after a natural disaster attack [20]. Furthermore, as designed for low-impact and high probability events, they are inadequate to address emerging challenges like assessing the topological flexibility, identifying the critical infrastructure, cooperation with customers, and potential preventive measure evaluation. However, as metrics of reliability are well-incorporated into practice and fully comprehended by operators and the customers, it is crucial to make resilience metrics comprehensible, instead of conducting a radical shift from number-based indices to coupled implicit

TABLE I. Comparison of Reliability and Resilience

Features	Reliability	Resilience
description	frequency and time duration	fragility, survivability, restoration
focus	load and generation	withstand and recover
acceptance	wide-accepted	no wide-accepted or well-defined
situation	computation based on a specific period	dynamic computation or immediately after an event
load	all loads	critical loads oriented
incident types	ignore short time incidents	more extensive scenarios
criterion	universal	situation based
specification	high probability, low impact	high impact, low probability
improvement	capital investment	operation strategy and investment
data source	extensive historical data	lack of field data

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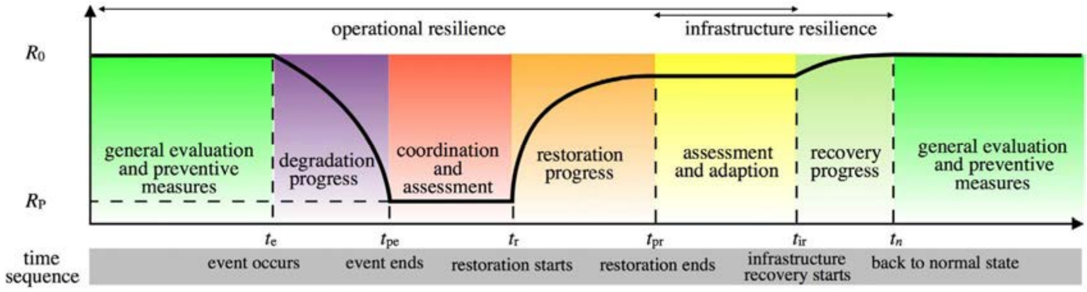

Figure 1. Evolution of Resilience Stage of Power Distribution Systems

ones. Table I summarizes key differences between the two terminologies [21]-[24].

Generally, the conception of resilience, unlike reliability which is more of a consequence and performance evaluation, is a potential capability assessment of a system according to its operational modes. These salient distinctions between them, as listed in Table I, challenge designers and operators of the distribution network with the imperative question of how to develope a holistic objective evaluation system for resilience. And more importantly, such an evaluation system is necessary for a rational discussion of effectiveness of proposed restoration strategies without interferences originated from different background settings and specific presumptions.

B. Resilience Stages and Their Implications

Under an extreme disturbance such as a hurricane, the power system would experience different states, it is thus necessary to define these states for an extensive resilience assessment. Various stage definitions are discussed in the literature for a practical description of evolution progress [15], [25]-[28]. Although these methods are not limited to specific events or network settings, they are generally operation-oriented and lack of details, such as different initial times for various evaluation slots. We extend these classification methods into an evolution curve in Fig. 1, for a better illustration of the overall resilience process, specifying appropriate time points for assessment scenarios. In general, there are 2 resilience categories: 1) *operational resilience* (t_0-t_{ir}), including pre-disturbance state, degradation and coordination process, and post-contingency state, and 2) *infrastructure resilience* (t_{pr}-t_n) for infrastructure recovery and evaluation for enhancements and preventive measures. For a clear clarification of evolution procedures, multiple overlapped disturbances during restoration is not addressed.

1) Operational resilience state

- Pre-contingency phase

The evaluation in this phase aims to assess flexibility and redundancy of available power/human resources and network topology. Specifically, with well-grounded early warning signals, severity of incident and potential affected area can be analyzed for resources preparation needed after the incident and future preventive measures, including active islanding [29], [30], isolating vulnerable facilities and securing critical loads.

- Degradation and coordination progress

The final resilience level (R_p) can be utilized to compare the effectiveness of different preventive measures, and the duration of coordination progress is a vital metric since the system now remains at the bottom in terms of recovered load, resilience level, and topology flexibility.

- Post-contingency phase

Alleviation brought by MGs, the duration of this phase, recovered loads and infrastructures, and other operational metrics can be utilized as resilience indices. Since diversified restorative objectives will complicate the objectivity of the evaluations, the resilience metrics can be adopted as an impartial monitor to ensure that the overall resilience of system is gradually climbing during this phase regardless the specific restorative goals.

2) Infrastructure resilience state

Once all the restoration measures are implemented, the system is entering a stage of post-restoration (t_{pr}-t_{ir}). In this state, resilience assessment contributes to re-evaluate the effective-ness of the MGs since their impact might drop gradually as soon as the infrastructure recovery begins.

- General evaluation phase:

A full restoration from the incident can be expected after the infrastructure recovery (t_{ir}-t_n) is over. Another holistic evaluation of the resilience will provide crucial information to decide operational statuses of planned MGs or newly formulated ones: maintaining the status as islanded MGs, or re-connecting to main grid. Furthermore, the general performance of the preventive measures and restoration strategies, the overall impact of the event, and the unexpected bottlenecks of system during incidents will be thoroughly reviewed and analyzed. It is the practical experience against different external shocks or internal failure/malfunctions that makes the resilience evaluation framework more adaptive and pragmatic.

III. Literature Study

Despite being a significant conception and receiving notable attentions, the detailed quantification of the resilience metrics are relatively limited [12]-[18]. Table III summarizes a general review of the representative state-of-the-art works in the literature within last 4 years. In this paper, we focus on 12 features to present the pros and cons of evaluation methods (as listed in Table II). Researches in this area are generally concentrated on the following aspects: 1) *critical infrastructure*; 2) *system performance*; 3) *redundancy of resources*; 4) *resilience of topology and its flexibility*; 5) *preventive measures*; 6) *communication, and other utility auxiliaries*; 7) *control decisions from operators*. Specifically, this summary focuses on the quantified resilience metrics rather than the qualitative

TABLE II. Features of the Resilience Assessment

Abbr.	Descriptions
A	Incorporation of microgrids
B	All-phase framework
C	Further implementation (comparison of the following optimization or aim to form/improve a strategy rather than simply evaluating)
D	Real-time (on-going)
E	Auxiliaries assessment and interdependency among infrastructures
F	High-adaptability (not event-specific, not network based)
G	Switch allocation
H	Availability and redundancy of resources
I	Consideration of Demand response and reactive power
J	Reliability metrics based
K	Enhancement suggestion (planning stage or post-event analysis)
L	Preventive measures (before and after the post-event analysis)

TABLE III. REVIEW OF STATE-OF-THE-ARTS

Ref	A	B	C	D	E	F	G	H	I	J	K	L	Highlight
12	×	×	√	×	×	√	√	√	×	×	×	×	high adaptability to network structure; switch allocation analysis
13	√	×	×	√	√	×	×	√	×	√	×	×	4 general metrics and consideration of MGs
14	√	×	×	×	×	×	×	×	×	×	√	×	restoration path oriented; variable according to forecast and maintenance.
15	×	×	√	×	×	×	×	√	×	√	×	×	focus on specific natural disaster (hurricane); simulation model based
16	√	×	√	×	×	√	√	√	×	×	×	×	for the most resilient restoration path; low computational burden
17	×	√	×	×	√	√	×	√	×	√	√	×	human factors; all-phase framework; enhancement suggestion; 4 general metrics
18	×	√	×	√	×	√	×	√	×	×	√	√	4 general metrics; all-phase framework

ones because the latter mainly concern about the general but rough pictures of power system and can only serve as a reference for long-term plan decision or policy making. However, qualitative methods incorporate some valuable analysis of influence of auxiliary infrastructures and services, including communication system, transportation system, gas/fuel supply and repair crew response [9]-[11], which are usually attached with little importance in quantified assessment.

A. Resilience Assessment for One Single Stage

A resilience index is defined as "the capacity of the power system to self-recover to a new normal state after experiencing an unanticipated catastrophic event" in [31]. It is extended in [12] into probabilistic presentation and computation of the degree of resilience, a method that explicitly relies on the basic power system equations which makes the proposed indices completely independent of network structures. Regardless of high adaptability in main grid, its limitation is obvious: 1) specific probabilities are relatively easy to decide or confirm in main grid because of its redundancy in terms of network structure and generation capacity, but the characteristics of MGs and distribution network makes the determination of probabilities more prone to fall in a trap of arbitrary; 2) it focus on one stage only rather than all-phases. Another contribution of [12] is the exploration of resilience improvements through recovery optimization, which is not a common objective in the restoration process. Ref. [13] proposes a set of resilience indices, including 2 modified conventional reliability indices (loss of load and expected demand not supplied, for description of the load survivability), a new index for network structure assessment, and one more combined index for recovery difficulty based on a damages severity rating system, which are less general compared with the metrics introduced in [17], [18] and specifically focus on the recovery process of the system.

Unlike above methods, with a presumption the assessment is within post-contingency stage, Nasiruzzaman adopts a percolation-based approach to analyze the resilience of power system with RESs and explore potential ways for improvement in planning stage [32], [33]. However, authors do not consider unique features of MGs and load priority. For a better quantitative description, ref. [14] extends the previous work into networked-MGs scenarios and proposes a quantitative framework with varied metrics. But as a framework study it needs more analysis and investigation in system dynamics. And, like [32] and [33], it focuses on the problems in planning stage instead of an on-going assessment throughout all stages.

B. Objective-Oriented Resilience Assessment

Another typical resilience evaluation method is focusing on specific natural disasters or serves as a tool for comparison of certain resilience strategies or optimization methods [15], [16], [24], [30], [31]. Ref. [15] introduces a probabilistic model to assess the multi-dimensional hurricane resilience of power systems based on modified traditional reliability metrics and recent resilient studies. However, since the parameters for the models can vary significantly for different geographical locations and be intricate to determine, the method is too specific for a broader implementation. These event-specific assessment methods are vivid reminders of the fact that vulnerability of systems might be varying substantially for different scenarios. A resilience index based on load recovery rate for network-MGs is formulated in [30], but it only serves as an explicit comparison among different EMS management methods instead of an exhaustive performance evaluation of the distribution system. Similarly, with consideration of time duration another metric, based on the curtailed loads, is presented in [24] for effectiveness evaluation of outage management strategies. As for the resilient path optimization, Ref. [16] proposes an algorithm using graph theoretic approach and Choquet integral to determine the most resilient restoration path. However, the introduced metrics mainly concern on the key factors of restoration path rather than a comprehensive framework for resilience assessment.

C. Dimensional Evaluation Framework for All-phase

Several researchers suggest utilizing dimensional and descriptive indices for a more adaptable assessment. Authors in [25] are among the pioneers to explore the area with "4R" metrics: *Rapidity*, *Robustness*, *Resourcefulness*, and *Redundancy*, which, however, are inappropriate for electric engineering implementation for several reasons: concentration on the whole community/city, interdependent and coupled metrics, and lack of basic features regarding the electric power system. Ref. [17] is one of the representative works discussing the resilience evaluation for distribution systems. It presents a quantitative framework for all-phase on 4 dimensional features: withstand capability, restoration speed, preparation/planning capacity and adaptation capability, which are expanded into a set of simple interdependent metrics in different resilient stages and varied time scales. Unlike the qualitative analysis in [35], human factors, such as maintenance policies and repair management, are integrated together quantitatively and interdependency between human and physical system is addressed. Additionally, it provides analytical advisories for the benefits of operation decision making and resource deployment in emergency.

Similarly, ref. [18] exploits 4 simple metrics to describe the resilience quantitatively: how *fast* and how *low* the resilience level drops in the degradation phase, how *extensive* is the coordination and assessment phase, and how *promptly* does the system recovery in the restoration progress. This simplification makes the metric a perfect candidate for online-monitor and real-time analysis, which is favorable for the engineering practice. However, little attention is given to the pre-contingency phase and the post-contingency phase in this paper, and like [17], absence of MGs is an obvious shortcoming here.

D. General Concerns and Promising Topics

Obviously, load restoration should be attached with top priority after a major blackout, but unveiling the driving force and mechanism behind what impedes us from a higher recovery rate is with equivalent importance. In this regard, not only prevailing power quality standards should be reviewed and re-innovated [36]-[37], but other extensive issues should also be covered for an inclusive comprehension of resilience capability, such as reactive power support in islanded mode, DR potentials, critical infrastructures analysis, risk assessment of protection system, communication system review and the evaluation of network reconfiguration. Apart from references [13], [17], which present some auxiliaries analysis, authors in [38] also present a potential method to conduct risk assessment of protection system during emergency. Besides, switches pair [39] and optimal allocation [40] in planning stage are also valuable efforts to evaluate reconfiguration potentiality and conflicts during the restoration. For instance, redundancy of switches leads to higher resilience, but their frequent operations are detrimental to the system during emergency. "Criticality Indices" are introduced for a better assessment of reconfiguration [41], incorporating less favored factors like weather conditions, repair rates and common outages. DR potentials investigation, instead of concentrating on meeting demands solely, is also crucial during critical period [42], [43], which distinguishes a MG with higher load flexibility from other MGs with lower resilient capability.

Although as an effective way to boost the robustness of the system, an important bridge between restoration strategy and infrastructure recovery, and a reserve for coming disruptions, [18] is the only work reported, as illustrated in Table III, that conducts some preliminary research on the preventive measures for resilience. The success of preventive measures, including but not limited to active/defensive islanding, pre-deployment of human/infrastructure/energy resources, and preventive generation re-dispatch, substantially depend on the accuracy of information about the coming incidents, especially for natural disasters. On the other hand, early warning signals [44] are also helpful to identify the indication of catastrophic incidents caused by accumulative stress in power infrastructures, which is critical and rudimental for preventive measures.

IV. Summary and Outlook

Generally, preventive measures, integration of DGs and MGs, network topology analysis, adaptability, interdependency among infrastructures, and assessment of alleviation from the reactive power source and DR, are the major challenges in this field. How to implement these features into an extensive resilience assessment framework and combine qualitative and quantitative metrics for specific scenarios is still a pending question, of which obstacles can be described as follows:

1) Interdependency Intricacy

Unlike common failures in power system, natural disasters will have profound impacts on utility infrastructures, such as transportation, gas/water/oil supply, communication system, which in turn may lead to delayed repair crews, inadequate fuels for DGs, and deficiency of rudimental data for the restoration. On the other hand, while interdependency among various utility facilities is vital, interdependency within power system itself is also significant. For instance, during restoration the redundancy of the energy capacity is strongly correlated to the available power lines capacity in this area, and the robustness brought by the underground cable will be counterbalanced by difficulty of time-consuming recovery.

2) Quantification Concerns

It is beneficial to have a quantitative evaluation framework since a qualitative one is inappropriate for engineering practice. But on the other hand, there are many open questions in the domain of quantitative metrics: 1) how to define weights of different parts in the system; 2) higher adaptability vs event/topology-specified; 3) balance between simplification of metrics for pragmatic reasons and inclusion of adequate considerations in various aspects. In fact, specifications of an engineering system in term of higher resilience and its vulnerability to other scenarios are in inverse proportion [45], for instance, a highly resilient system to natural disasters might be deemed as vulnerable to human-triggered incidents.

3) Regulatory and Policy Challenges

Although DGs and MGs have been demonstrated as effective tools to boost resilience during emergent scenarios, electricity utilities are still reluctant to employ them for the restoration process, partly because of the regulatory criterions, such as DG units must be disconnected from the main grid after a major blackout. And the stereotyped perspective of MGs as a self-autonomic power distribution system is impeding the efforts of encouraging more participation. That is why a relaxed regulatory is needed for emergencies. Moreover, from the customer's view, there is no compensation for owners of DGs for providing extra energy or even reactive power during restoration. Inclusion of these features in evaluation can motivate the government to re-examine the balance between capital investment in power facilities and incentives for achieving a distributed collective effort.

4) Data Deficiency

Common outages, due to man-made faults, maloperation, or facility malfunction, are inherently distinct from natural triggered contingencies. Inadequate historical data (difficulties in collection process during emergency and ignorance from the administrative level) made the assessment and future restorative strategies based on it less convincing. To utilize the simulation models is an effective alternative, but the adaptability and the efficiency may be the concern.

5) Support from DR and Reactive Power Resources

An inclusive investigation of customers' inclination to participate in DR should be incorporated into resilience evaluation, such as price incentives, violation penalties and guiding policy, presenting the potential cons and pros of the energy management during restoration. DGs, instead of being regarded as constant factors in restoration like traditional power sources, should be evaluated in an approach that not only consider the inherent uncertainty and flexibility associated with them, but also pay an attention to the vulnerable physical features during high impact natural disasters and limited capacity in islanded mode in terms of voltage regulation and dynamic response. An index for reactive power reservoir can be formulated according to different priorities of the operators of MGs: appreciation of longer overall service time or pursuing higher load recovery percentage.

6) Weather Forecast and Geographical Features Analysis

Weather forecast accuracy is groundwork of effective preventive measures. A close examination on error distribution study and historical data analysis could give the operators more leverages during extreme events, such as defensive/active islanding scheme and isolation of the vulnerable components before strikes hit the grid. On the other hand, geographical features, like distance between power sources and loads, DG unit distribution and vulnerability of infrastructures in different scenarios, confer the MGs distinct characteristics that can develops into unexpected impediment during restoration. These inherent features could produce valuable feedbacks and advices for the planning stage of a more resilient distribution network.

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