Power System Resilience Evaluation Framework and Metric Review

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Power System Resilience Evaluation Framework and Metric Review

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Abstract — **Power system resilience has been an emerging hot topic in recent years to investigate the increasing threats of extreme events, such as natural disasters, severe weather, and cyberattacks. Although much research has been done to define, model, and quantify resilience from different aspects, the lack of universally accepted evaluation methods and resilience metrics makes it difficult to assess and compare resilience across different power systems, such as what is typically done in power system reliability studies. In this paper, first, we review the definitions of resilience, and we summarize two core concepts shared by most of the literature. Then, we develop a new framework to assess power system resilience from two perspectives—i.e., pre-event estimation and post-event evaluation—to capture system resilience performance in both general and specific fashions. We conduct a thorough review of existing resilience metrics and categorize them using the proposed framework, where recommendations are also proposed to capture core concepts of resilience.**

Index Terms – **Power system resilience, power system resilience evaluation framework, power system resilience metrics**

I. INTRODUCTION

Major power outages, such as the North America blackout in August 2003, are always among the most critical threats to the power industry. In the past few decades, researchers have established comprehensive concepts, frameworks, models, and algorithms to prevent such major blackouts from happening and to recover the power supply after power outages. These two areas are typically referred to as power system reliability and power system restoration, respectively. Power systems have been operating more reliably in general throughout the years, e.g., with shorter service interruption durations and less frequency. Despite the countless efforts made to strengthen the grid infrastructure and to enhance power supply reliability, we have witnessed an increasing trend in blackouts in recent years, most of which are caused by extreme events, such as disastrous weather [1]. For example, in February 2021, Texas was hit by a severe winter storm, leaving more than 10 million residents in darkness for several days [2]. Hence, it is of great importance to understand, analyze, and deal with such extreme events to minimize the damage to the power grid and electricity service.

Intuitively, we refer to the well-established power system reliability and restoration to see whether extreme events can be incorporated. From the restoration perspective, extreme events will influence the restoration efficiency, but existing models and analyses remain valid; however, it is more challenging to model extreme events using power system reliability frameworks. Unlike traditional power system reliability studies, which rely heavily on probabilistic theory and a large volume of historical data, extreme events are generally high-impact, low-frequency (HILF) events, and they have limited available data to begin with. Therefore, a new terminology—power system resilience—is proposed to capture the performance of the power system in HILF events [3].

Power system resilience has been a hot topic in recent years, and it has attracted much attention from both industry and academia. Although much research has been done in various studies to investigate and implement power system resilience, the definitions of resilience and the metrics and quantification methods to evaluate resilience share little common ground, which is expected when dealing with an emerging, complex topic. Unlike reliability metrics—such as system average interruption duration index and expected energy not supplied, which are widely used to compare reliability performance across different power systems—the variety of resilience metrics and quantification approaches make it difficult to compare the resilience of a given power system with benchmarks and other systems.

In this paper, we review existing work on power system resilience, and we summarize the critical features that should be captured by the power system resilience concept. We develop a new resilience quantification framework that investigates power (include both transmission and distirbution) system resilience from two aspects: pre-event estimation and post-event evaluation. Moreover, among various candidate resilience measures, several representative metrics will be short-listed for resilience evaluation. The rest of this paper is organized as follows. Section II introduces the power system resilience concept and distinguishes resilience from similar concepts. Section III analyzes the resilience evaluation framework, describes existing resilience measures, and reviews a selection of recommended metrics in detail. Section IV concludes the paper.

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II. POWER SYSTEM RESILIENCE

A. *Definition of Resilience*

There are many existing definitions, originating from different fields, that describe concepts concerning resilience [4]. These include safety, reliability, and survivability. Safety is a system property that encompasses the behavior of and interactions among subsystems, software, organizations, and humans. Major investigations during the past decade have pointed to the need for organizations to retool their engineering processes and capabilities to address human and organizational risk factors [5]. Reliability in the engineering domain deals with the ability of the system and its components to perform required functions under stated conditions for a specified period. This reductionist view underlies modeling techniques, such as the traditional form of probabilistic risk assessment [6]. Survivability is the ability of a system to minimize the impact of a finite disturbance on value delivery, achieved through either the satisfaction of a minimally acceptable level of value delivery during and after a finite disturbance or the reduction of the likelihood or magnitude of a disturbance [7].

These definitions cannot be fully deconflicted because of overlap, and their emphasis tends to be different [4]; however, they share the same two core concepts when approaching resilience:

- The capability of a system to resist, withstand, and adapt to a major disruption, albeit occasionally with reduced performance.
- The capability of a system to bounce back from and recover to a normal state after a major disturbance.

Therefore, in this paper, power system resilience is defined as the capability of a power system to maintain its performance and to speedily recover from damages after a HILF event. The performance of a power system can refer to generation, load, voltage, frequency, or other relevant indicators. For example, bulk power systems might use system generation and the frequency profile as performance indicators, whereas distribution systems could use voltage magnitudes and energy loss to represent performance.

B. *Guidelines of Defining Resilience Metrics*

At a high level, a resilience metric must, at a minimum, consider the following key attributes [8]:

- *Threat*. Definitions of likely disruption scenarios, with associated probabilities where appropriate.
- *Likelihood*. The probability that a disruption scenario could lead to decreased system performance or failure.
- *Consequence*. The impact of system failure given a disruption scenario.

As an example of these properties in the context of the electric power sector, consider the "threat" of disruptive weather to a particular electric utility. It is likely that disruption scenarios can be determined historically and defined in terms of the number and location of grid component failures. The likelihood (and extent) of each disruption scenario can be computed via systems analysis, given knowledge of available alternative generation and transmission/distribution resources and potential system states. The consequence for a disruption scenario can then be expressed in terms of the economic and/or public safety impacts.

C. *Differentiate Resilience from Similar Concepts*

TABLE I COMARISION AMONG RESILIENCE, RELIABILITY, AND ROBUSTNESS

	Reliability	**Robustness**	**Resilience**
Objective disruptions	LIHF	LIHF, HILF	HILF
Analysis on components	Independent	Independent	Correlated
Focus of approaches	Resistance	Resistance	Resistance, Recoverability
Reliance on historical data	Yes	No	No

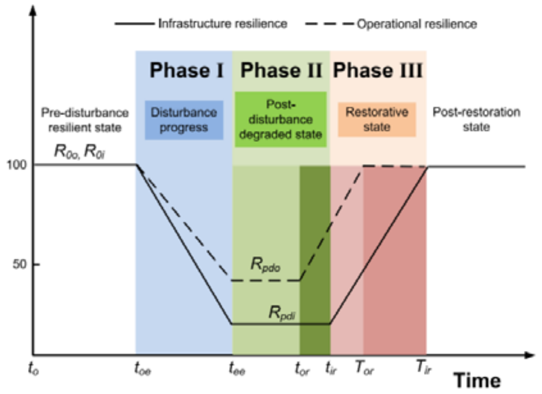

Fig. 1. The multiphase resilience trapezoid [3].

As discussed in Section II.A, power system resilience is a complex framework, and it considers many features that might or might not be modeled by some existing concepts. Reliability is arguably the closest concept to resilience. From the perspective of objects, reliability in the power system domain deals mainly with low-impact, high-frequency (LIHF) events, whereas the focus of resilience is on HILF events (e.g., hurricanes, ice storms, malevolent attacks). From the perspective of analysis, most reliability studies have addressed probabilistic risk-assessment methods, where system components and their behaviors are assumed to be mutually independent. This assumption might be valid on a day-to-day, normal basis. But the major disruptive incidents in resilience analysis often produce coupling among components, which can quickly invalidate this assumption. For example, the failure of a device (e.g., a transformer/line) because of wear and tear is a typical reliability event, whereas the major outage caused by a severe storm should be considered a resilience event. Moreover, the analyses on reliability rely on historical data while the analyses of resilience do not.

Another concept that is commonly confused with resilience is robustness. Robustness denotes the capability of a power system to withstand various types of disturbances; this coincides with the first core resilience concept described in Section II.A. However, robustness does not focus on analyzing HILF events; thus, it can be applied to LIHF or other types of events. Another difference is that robustness cannot model system recovery after a disturbance, which is the second core concept of resilience; thus, it is concluded that resilience and robustness have different focuses, and robustness cannot replace resilience because a key perspective of resilience is missing. Table. I summarize the difference among reliability, robustness, and resilience.

III. RESILIENCE EVALUATION AND METRIC REVIEW

This section reviews existing power system resilience evaluation practices and proposes a new evaluation framework that contains pre-event estimation and post-event evaluation. Existing resilience metrics are reviewed and categorized using the developed framework.

TABLE II RESILIENCE METRICS FOR PRE-EVENT ESTIMATION

	Captured feature	Metric	Description	Reference
1	Stability	Transient stability margin	**Definition**: The region of stability corresponding to the stable equilibrium point of the power system following a simulated event. **Unit example**: N/A	[9]
2	Stability	Applicable protection region	**Definition**: The minimum of the distance relay solution set following a simulated fault clearance. **Unit example**: N/A	[9]
3	Topology	Branch count effect	**Definition**: The ratio of the total number of connected branches for each path combination without loop in a possible network to the number of all critical loads. **Unit example**: N/A	[10]
4	Topology	Overlapping branches	**Definition**: The total number of common branches in each path combination without loop in a possible network. **Unit example**: N/A	[10]
5	Topology	Repetition of sources	**Definition**: The ratio of the number of available sources used to supply all critical loads to the number of all critical loads in each possible network. **Unit example**: N/A	[10], [11]
6	Topology	Path redundancy	**Definition**: The ratio of the total number of paths available for all critical loads connecting to all sources to the total number of critical loads in each possible network. **Unit example**: N/A	[10]
7	Topology	Betweenness centrality	**Definition**: The ratio of the total lengths of all shortest paths passing through a specific node to the total lengths of all shortest paths between all node pairs in the network. **Unit example**: N/A	[10]–[12]
8	Reliability	Critical load supply reserve	**Definition**: The code-based resilience metric evaluates the uninterrupted critical load supply given an event. **Unit example**: N/A	[13]
9	Reliability	Reliability achievement worth	**Definition**: The improvement\decreasement in the reliability indices when line resource is considered 100% reliable\failure on generation resources during the simulations. **Unit example**: %	[14]–[16]

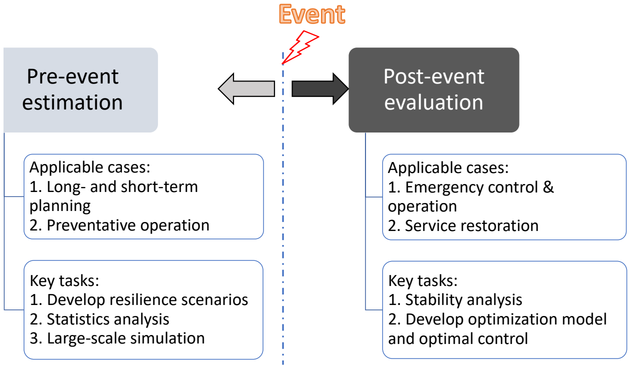

Fig. 2. Pre-event resilience estimation and post-event resilience evaluation.

A. *Resilience Evaluation Framework*

Power system resilience evaluation is a challenging task, given the nature of HILF events. It is challenging to accurately forecast and model HILF events, assess event impact and damage, evaluate power network and apparatus survivability, and predict outages in load supply ahead of time. Therefore, we propose a new resilience evaluation framework to avoid the challenges along with the modeling of HILF events.

A commonly used alternative for power system resilience evaluation is to use the performance data throughout the event period and develop resilience metrics/indicators for further analyses. Fig. 1 [3] shows an example, where the y-axis indicates the resilience indicator, which can be a resilience metric or a system performance measurement (e.g., system generation level). Fig. 1 captures the two core concepts identified in Section II.A, i.e., how the system responds to the HILF event (Phase I and Phase II) and how the system recovers (Phase III).

Although the resilience trapezoid shown in Fig. 1 is suitable for resilience evaluation, constructing such a trapezoid requires accurate information of the studied event, which is rarely available before the event happens, to model the disturbance and analyze recovery. When it comes to planning studies where power systems want to strengthen their grid and implement preventative measures to deal with potential threats, Fig. 1 becomes less helpful since no sufficient reliable data are available to develop the resilience trapezoid. Because it is challenging to provide an accurate forecasting of HILF events in the long planning timeframe, and it is even more complicated to model their damage to the power system elements reasonably.

Therefore, we propose evaluating power system resilience from two perspectives: pre-event estimation and post-event evaluation, as shown in Fig. 2. The trapezoid in Fig. 1 fits the post-event evaluation context, where the event data are available to construct the trapezoid for further analyses. Pre-event estimation, on the other hand, investigates the resilience performance of a power system in a more general way. In other words, the pre-event estimation provides a generic resilience assessment, whereas the post-event evaluation is case sensitive and evaluates power system resilience in a specific scenario. The combination of pre- and post-event resilience will provide a more comprehensive resilience assessment.

B. *Resilience Metrics Review and Classification*

Following the resilience evaluation framework discussed in Section III.A, we reviewed existing literature and categorized existing metrics for resilience evaluation into three clusters: pre-event metrics, post-event metrics, and other commonly used metrics. Tables II, III, and IV list the key attributes of these metrics, including their capturing features and definitions.

Table II summarizes the pre-event estimation metrics. The pre-event metrics use system parameters such as protection configuration, network topology, and generation mix to estimate the possible performance when hit by an extreme event. Compared to purely graph theory-based metrics, the metrics listed in Table II already account for power system features, e.g., line parameters such as resistance and reactance are employed to calculate the betweenness centrality (#7 in Table II). Note that none of the metrics listed in Table II rely on event data; thus, the pre-event resilience metrics are case insensitive. Table III summarizes the post-event resilience metrics. Note that most post-event metrics can represent one or multiple features of the resilience trapezoid shown in Fig. 1. As discussed in Section III.A, these post-event metrics quantify the capability of the power system to resist and recover from major disturbances using event data, such as the impact, intensity, and duration of the event. Compared with pre-event metrics, the post-event metrics are generally case-sensitive.

TABLE III RESILIENCE METRICS FOR POST-EVENT EVALUATION

	Captured feature	Metric	Description	Reference
1	Robustness Stability Reliability	Performance drop rate	**Definition**: The total amount of dropped system performance divided by the time that the system performance was dropping. It is defined during the disturbance phase defined in Fig. 1, and it accounts for how fast (the rate/speed of) the resilience/performance drops. **Unit example**: MW/hours; # of lines tripped/hours	[3], [17]
2	Robustness Stability Reliability	Maximum performance drop	**Definition**: The system performance during normal status minus the lowest system performance due to the event. It is defined during the disturbance phase defined in Fig. 1, and it accounts for how low (the lowest/worst of) the resilience/performance drops. **Unit example**: MW; # of lines tripped	[3], [18]
3	Stability Reliability	Degradation intensity	**Definition**: The total time that the system performance is kept at its lowest/worst value due to the event. It is defined during the post-disturbance degraded phase defined in Fig. 1, and it accounts for the intensity (duration) of the post-disturbance degraded state. **Unit example**: Hours	[3], [19], [20]
4	Restorability	Performance recovery rate	**Definition**: The total amount of recovered system performance divided by the time that the system performance was recovering. It is defined during the restorative state phase defined in Fig. 1, and it accounts for how promptly (the rate/speed of) the resilience/performance recovers. **Unit example**: MW/hours; # of lines tripped/hours	[3], [21]
5	Reliability	Uninterrupted service	**Definition**: The area below the resilience/performance curve in Fig. 1 across different phases, accounting for the system service is not interrupted due to the event. **Unit example**: MWh; # of lines tripped × hours	[3], [22], [23]
6	Restorability Robustness	Recovery efficiency	**Definition**: The time that system performance dropped from normal state to the worst state divided by the total time that system was disrupted due to an event and completed recovery. It indicates the recovery efficiency against different levels of disturbances. **Unit example**: %	[21], [24]
7	Restorability Robustness	Grid capacity resilience	**Definition**: The ratio of system disrupted to normal performance times the ratio of system recovered to normal performance and times recovery efficiency. It indicates the grid functionality index that normalizes damage and restored states to its stable state. **Unit example**: N/A	[24], [25]

TABLE IV OTHER COMMONLY USED RESILIENCE METRICS

	Captured feature	Metric	Description	Reference
1	Robustness Restorability	Economic damage/loss	**Definition**: The load-shedding cost/penalty due to an event. **Unit example**: $	[26]–[28]
2	Robustness Restorability	Real-time capacity recovery index	**Definition**: The ratio of present recovered system performance to the worst performance divided by the total dropped system performance due to an event. It indicates the time-varying uninterrupted grid capacity normalized to its normal capacity. **Unit example**: %	[29]
3	Robustness Restorability	Instantaneous uninterrupted service	**Definition**: The ratio of instantaneous system performance to the target performance during an event. **Unit example**: %	[21], [30]

Table IV lists three commonly used metrics that do not fall into either the pre- or post-event category. The first metric in Table IV is widely used in the existing literature to optimize power system resilience responses. Although this metric is mostly used in the post-event context, it can also be employed in pre-event resilience estimation to guide resilience planning studies. The other two metrics in Table IV target quantifying system performance during the event, so they are more suitable for real-time emergency control decision support.

C. Remarks

Comparing the reviewed metrics and their applications identified in Fig. 2, it is concluded that post-event evaluation is relatively more straightforward than pre-event estimation because the impact of the event is known. A combination of existing post-event metrics in Table III can well capture the featured resilience trapezoid shown in Fig. 1; however, it appears to be more challenging to employ the metrics in Table II to achieve the anticipated objectives shown in Fig. 2. Several remarks are as follows:

- A key missing part of the existing pre-event metrics is the consideration of generation, while generation resources are likely to be scarce in extreme events. Take the topology-based Path redundancy metric (#6 in Table II) for example.

It is possible to have two systems with identical network topology and load/generation resource distribution but with very different load consumption patterns and generation resource mixes. These two systems do not always share the same or similar resilience performances, which cannot be reflected using the topology-based metrics listed in Table II.

- Post-event metrics are well established, but a single metric might cover only a certain feature of the resilience trapezoid. The following metrics/combinations are highlighted: (1) performance drop rate and maximum performance drop (#1 and #2 in Table III), the combination of these two metrics illustrates the robustness of the system against the given event; (2) performance recovery rate (#4 in Table III), this metric captures the capability of the system to restore from the extreme event; (3) economic damage/loss (#1 in Table IV), which models the entire event-affect period and evaluates the overall impact caused by the event. Depending on the emphasis of the analysis, the metrics to evaluate resilience can be selected from the highlighted ones.
- Pre- and post-event metrics are complementary. Assume there are two power systems, *x* and *y*, and *x* has better pre-event resilience than *y*. It is expected that *x* can deal with various unknown extreme events more efficiently than *y*. When it comes to a known threat, such as a specific hurricane event, the post-event resilience of *y* is higher than *x*, meaning that system *y* responds better in that specific or similar hurricane event. Note that for another hurricane event, *y* might still have worse resilience than *x*; therefore, there is no easy answer to which system (*x* or *y*) or which metric (pre- or post-event) is better. For real-world power systems, the objectives should be to improve the pre-event resilience to enhance the capability to deal with all types of events and to identify specific threats in the region to be focused on using post-event performance evaluation.
- Compared to other mature power system indexes, such as reliability, existing resilience metrics fall short in terms of comparability. Post-event metrics deal with specific events, so comparability is outside their scope; however, pre-event metrics should be able to illustrate resilience that is not relevant to a particular system configuration, which cannot be achieved using the metrics summarized in Table II. Hence, more work should be done to develop new pre-event resilience metrics that can be easily compared across different systems to provide sufficient support for power system resilient planning and operation.

IV. CONCLUSIONS

This paper reviews the idea of power system resilience and identifies two core concepts that should be considered in power system resilience analyses. A new resilience evaluation framework is proposed that consists of pre-event estimation, which covers the case-insensitive general resilience performance of power systems; and post-event evaluation, which focuses on system responses against specific events. Existing resilience metrics are categorized and thoroughly reviewed. In addition, we highlight several resilience metrics as candidate metrics that well capture the core concepts of resilience. This paper can help the power industry to identify and develop suitable metrics to evaluate and compare resilience and, eventually, boost the application of resilience in real-world systems to deal with the increasing threats of extreme events and prevent major power outages.

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