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Review of Power System Resilience: Operation Stages, Vulnerabilities, and Modeling Approaches

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Abstract—**Electricity has become a necessity of living to the extent that any outage in electric power could lead to massive disturbances in different life sectors. Natural disasters (flooding, ice storms, etc.) are considered Low Probability High Impact (LPHI) events and may lead to major power outages. Therefore, power systems must be resilient to these events to minimize the impacts of their occurrence. Studies have been presented to emphasize the importance of power system resilience and provide the power utilities and operators with different solutions and strategies to deal with this dilemma. This paper presents a review that classifies some recent power system resilience studies based on different aspects. Such aspects include the operation stages, vulnerable components, and modeling techniques. Several papers have been studied and analyzed and some future research directions have been provided at the end of the paper.**

Keywords—Power System Resilience, Power Outages, Natural Disasters, Hurricanes, LPHI, Resilience Planning, Power Restoration.

I. Introduction

Electricity has become a need for humanity; thus, proactive measures need to be taken for making power systems resilient. According to the U.S. Energy Information Administration (EIA), the latest significant hurricane, Michael, that occurred in October 2018 and over three days period has recorded more than 1,314,000 customer outages, roughly more that 5% of the customers in the affected states [1]. These natural disasters are rarely happening disasters, but their impact is very severe to the electrical grid. Therefore, they are considered as low probability high impact (LPHI) events. In sight of this, modern studies focusing on modeling power systems should consider resiliency as a major factor for more realistic models.

The term resilience impose the show of strength and durability, and for a system to be resilient, the system that encounters a hazard shall have the ability to resist that hazard or absorb it and manage to recover from it efficiently [2]. Therefore, Power System Resilience against natural disasters and extreme whether hazard is the ability of the power system to resist and adapt those changes in order to recover the operational performance rapidly [3]. Considering the climate variability and the unexpected occurrence of extreme weather events, the resiliency of power system is more important than ever. It involves not only the physical hardness of the infrastructure but also the flexibility of the operation and the control systems. Strategies such as grid decentralization, incorporation of renewable energy sources, and advanced grid management technologies have a substantial role in enhancing resiliency.

Moreover, the integration of smart grid technologies, which include advanced sensing, data analytics, and automated control systems, can significantly improve the responsiveness of power systems. These technologies enable real-time monitoring and rapid response to disruptions, thereby minimizing the impact of LPHI events. Furthermore, energy storage systems, such as large-scale batteries and mobile energy storage systems, can play a significant role in balancing supply and demand, especially with the state of availability of renewable energy sources like solar and wind power. Investments in research and development are needed to continually advance our understanding and capabilities in this area. Collaborations between government, industry, and academia can drive innovation in resilient power system design and management. Therefore, as the challenges of an increasingly unpredictable climate events arise, the resilience of the power systems is not just a technical issue but a critical aspect of societal well-being. Ensuring the resilience of these systems in the face of natural disasters is imperative for the safety, economic stability, and quality of life of communities worldwide.

Considering the importance of the subject, recently, different review papers have been published with a focus on the definitions, proactive measures, methodologies, and technologies adapted in the power systems resiliency studies. A definition and review on the metrics used to assess power system resilience are found in [4]. Mohamed et al. in [5] have highlighted the proactive measures needed for enhancing power system resilience against natural disasters, suggesting that prediction and preparation are key to minimize the impacts. Stanković et al. have highlighted the significance of quantifying resilience as a key performance indicator [6]. Additional review papers that focused on the methods of resiliency assessment are found in [7] and [8]. Younesi et al. have presented a comprehensive review on the challenges and opportunities towards evaluating and improving power system resilience [9].

Many articles have been published in the literature in this area. Fig. 1 shows the number of recent papers published in different articles. The highest number of publications are in the IEEE transaction on power systems and IEEE ACCESS; their corresponding numbers are 8 and 7, respectively. On the other hand, Fig. 2 shows the number of published papers from 2014 to 2023. This research only considered the last ten years for this data analysis. The highest number of publications was in 2020, with a slight decrease in the following years.

Since this area of research is rising, it is inevitable to investigate the subject more in-depth. Thus, this paper provides a review from a different perspective by focusing on the main considerations in the power systems resilience studies.

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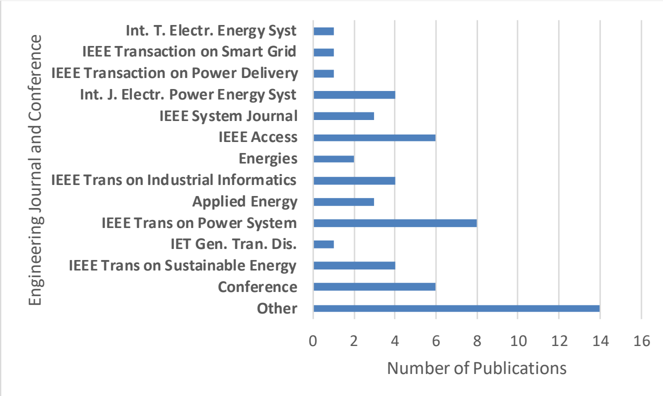

Fig. 1 Number of Publications in Different Journals.

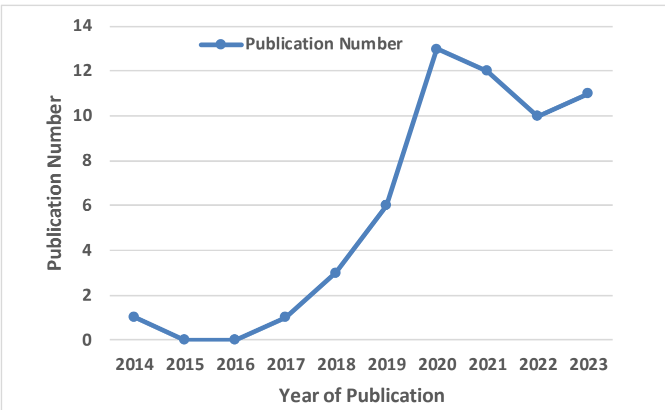

Fig. 2 Number of Publications over the Years.

It addresses some metrics in the literature and classifies the studies based on operations stages, vulnerable components, and modeling techniques. This shall highlight some research gaps for the researchers and suggest some considerations for future studies.

The paper is organized as follows: Section II addresses understanding the power system resilience and the assessment quantification. Section III focuses on classification of the stages of operation, including planning, response, and restoration. Section IV addresses the most vulnerable components and a review classification based on them. Section V highlights the frequently used modeling techniques in the literature. Finally, conclusions and considerations that could be further investigated are presented in Section VI.

II. Understanding the Power System Resilience

In order to classify the existing literature properly, the power system resilience has to be understood thoroughly. According to the definition found in [4], the power system shall have the ability to withstand the LPHI events through minimum outages and fast recovery. This indicates that the system's resiliency is evaluated based on the performance of the system, and therefore, the power system performance has to be analyzed and understood. Normally, the power system performance during a disturbance or a natural disaster degrades with time, the system performance is usually quantified in mega-watthours.

The concept of power system resilience usually adapts a trapezoid performance behavior [3], [4], [5], [7], [9]. Fig. 3 illustrates this trapezoid behavior of the power system. Consider a timeline with 6 timeslots; t_0 to t_6. Between t_0 and t_1, the system is operating normally before a natural disaster occurs at t_1. The system performance degrades between t_1 and t_2 until the disaster event clears. The system operates at degraded state between t_2 and t_3 until the damage is evaluated and the restoration actions are identified. The recovery and restoration actions shall improve the performance gradually between t_3 and t_4, these actions are mainly operational actions that intent to restore the operation at least partially. Once these actions are applied the power system would operate at a 'sub-normal' condition between t_4 and t_5 since some damage may occur on the equipment level. Finally, restoration actions are taken on the equipment level between t_5 and t_6 to lift the performance up to the normal conditions again.

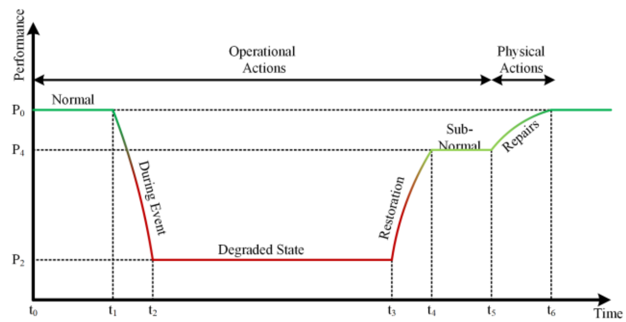

Fig. 3 System Perfromance During Disturbance.

According to this behavior, to achieve a better operational resilience for the power system, the system performance at the degraded state should be maximized, the timeslot of the degrading state and the restoration phase, i.e., between t_2 and t_3 and between t_3 and t_4 from the figure, should be minimized, and finally, the performance of the sub-normal state should be maximized. These considerations are achieved with different approaches. For instance, to increase the system performance in the degraded state, preparation actions are required, these actions could be physical or operational [2], [3], [5], [7]. To minimize the degraded state and restoration phase period, the system should be evaluated using rapid techniques and algorithms. Finally, to improve the performance at the sub-normal operational state, restoration should be carried out based on optimal strategies. In the following sub-sections, some resilience indices defined in literature are presented and explained.

A. *Resilence Indices based on the Trapazoid Performance*

To ensure that adapting these measures and considerations enhances resiliency. The resiliency of the system is quantified, mainly based on the performance. Different indices are found in the literature. These are utilized in the power system resilience studies as an assessment of resilience. Table I below shows some of the proposed quantifications from the literature with reflection to the timeslots and performance in Fig. 3. This subsection and the one follows is intended to provide a verity of assessment metrics from the literature, pointing out to the ability for researchers to adapt the existing metrics or formulating unique metrics that assess the performance of the power system and its resilience.

TABLE I. RESILIENCE AND PERFORMANCE ASSESSMENT QUANTIFICATION

Ref	Equation	Description
[4], [10], [11], [12]	$R = \int_{t_0}^{t_6} [P_0(t) - P_6(t)]\, dt$	The area difference between the normal performance curve and actual performance curve.
[10]	$R = S_R \cdot \frac{P_6(t)}{P_0(t)} \cdot \frac{P_{1+}(t)}{P_0(t)}$	The speed of recovery by the ratio of the actual performance to the normal performance by the ratio of performance right after the disturbance to the normal performance.
[13]	$R = \sum_{k}^{K} \pi_k \left[\frac{\int_{t_0}^{t_6} P_6(t)dt}{\int_{t_0}^{t_6} P_0(t)dt} \cdot \frac{t_5 - t_1}{t_6 - t_0} \right]$	The sum of the possibility of an event to occur (π_k) by the ratio between the actual performance to the normal performance for the whole period by the ratio of the disturbance period over the whole period.
[14], [15]	$R = \frac{\int_{t_0}^{t_6} P_6(t)dt}{\int_{t_0}^{t_6} P_0(t)dt}$	The ratio between the actual performance and the normal performance for the whole period.
[16]	$\bar{P}(t) = \bar{R}(t) - \bar{O}(t)$	The mean performance is the difference between the mean of cumluative number of resotrations and the mean cumulative number of outages.

B. Other Resilient Indices from the literature

In addition to the indices inspired from the trapezoid performance, other metrics have been presented in the literature. Liu X. et al., [17], have adopted the triangle performance quantifying the resilience as

$$R = \int_{t_0}^{t_1} [Q_0(t) - Q_1(t)]\, dt \tag{1}$$

$$R = \frac{\int_{t_0}^{t_1} Q_1(t)dt}{\int_{t_0}^{t_1} Q_0(t)dt} \tag{2}$$

Where Q_0 and Q_1 are the load supply at normal state and after the event respectively. Hossain et al., [18], have also addressed the triangle performance, the quantified resilience is given as the ratio between the uptime T_u and the total of the uptime and downtime T_d reflecting the system's functional efficiency.

$$R = \frac{T_u}{T_u + T_d} \tag{3}$$

Different probability-based metrics have been presented in the literature. Younesi et al., [19], have measured the resilience based on five metrics including loss of load probability (LOLP), expected demand not supplied (EDNS), line outage Υ, restoration Ψ, and system weakness Λ.

$$R = [LOLP, EDNS, \Upsilon, \Psi, \Lambda] \tag{4}$$

Zeng Z. et al., [20], have expressed the resilience as the probability that losses L are within a tolerable loss L_{tol}.

$$R(t) = P(L(t) < L_{tol}) \tag{5}$$

Xu T. et al., [21], have addressed the resilience in a coordinated planning model that includes transportation. The adopted deterministic metric is based on the minimal load curtailment (min) for most sever events (max), this has been expressed mathematically as:

$$R = \max_{R,\Delta,Z} \min_{ef,p} \sum_{i,b,t} f_{i,b,t}\left(Lc_{i,b,t}\right) \tag{6}$$

where $f_{i,b,t}()$ is the cost function of load curtailment at bus i, and $Lc_{i,b,t}$ is load curtailment at bus i.

From Table 1 it is anticipated that some metrics, the first equation for instance, are heavily used in the literature for its convenience assessment. However, equations (1) to (6) shows that different metrics are developed to include different aspects.

III. CLASSIFICATION BASED ON STAGES OF OPERATION

As concluded from the previous section, the resilience of the power system can be enhanced by applying some measures or strategies at three different stages of operation, these stages are addressed in the literature as planning, response, and restoration. Some key papers are presented with details in the following sub-sections and Table II highlights other studies that have addressed these stages.

A. Planning Stage

Planning stage is very critical to the resilience of the power system and is considered as normal stage just before extreme event starts. It includes long and short-term actions to prepare the system to withstand the unanticipated events [4], whether these actions are physical or operational actions. Wang H. et al., [22], have presented a framework to create a disaster database extracted from potential disaster scenario. Younesi et al., [23], have presented an assessment for multi-microgrid integrated power systems to assist the power system operators and planners. Ghorani et al., [24], have presented a quantification of the landslide hazard on the power system, this shall assist planners to take suitable reinforcement measures. Cicilio et al., [25], have presented a framework that includes the uncertainty and the DERs availability impact on the resilience and cost-benefits.

B. Response Stage

This stage starts with the occurrence of the event. It includes the evaluation of the system and decision-making for operational measures. Therefore, it requires robust operation to achieve better performance of the system at this stage. Hossain et al., [26], have presented a Bayesian Network-based framework to quantify the system's resilience during disturbing event, this shall offer actions to mitigate the impacts of the event. Sayed et al., [27], have presented a robust two-stage framework that optimize the performance of the system under worst-case conditions through robust decision making.

C. Restoration Stage

At this stage, the event has passed, and the system is usually operating at a degraded state. The system performance at the degraded state is relative to the physical and operational measures taken in the planning stage and during the response stage. Restorations measures are taken to retrieve the normal operation of the system, i.e., fully meeting the consumers' demand. LPHI events are usually destructive; therefore, this stage includes doing repairs and that may take time. Different studies have addressed this issue. Gazijahani et al., [28], have proposed a three-stage framework with a main objective on enhancing the resilience of power system and minimize restoration time by coordinating the repair crew dispatching. Lin Y. et al., [29], have presented a combined repair crew dispatch problem to coordinate the repair of interconnected power and gas system, their results have showed the effectiveness of repair crew coordination in the restoration stage and thus the overall resilience enhancement. Another application used in the restoration stage is the mobile energy storage units where the system can utilize its energy storage resources based on its experience during the event period. Saboori et al., [30], have addressed utilizing the truck-mounted mobile batteries (TMMBs), the study have considered the dispatching of these units taking into account the damage on the transportation routes. Erenoğlu et al., [31], have proposed a real-time optimal allocation strategy for the mobile generation units, electrical vehicles, and mobile energy storage vehicles for load restoration. In addition to the aforementioned studies. Table II highlights other studies that have addressed one or more of these stages. The table shows that a majority of the recent studies focus on the planning stage while few studies have addressed the response stage or considered the three stages.

TABLE II. CLASSIFICATION OF STUDIES IN LITERATURE BASED ON OPERATION STAGE.

Reference	**Operation**			**Reference**	**Operation**		
	Planning	***Response***	***Restoration***		***Planning***	***Response***	***Restoration***
[32]	✗	✓	✗	[33]	✓	✗	✗
[34]	✓	✗	✓	[19]	✗	✗	✓
[35]	✓	✗	✗	[36]	✓	✗	✗
[37]	✓	✗	✗	[38]	✓	✗	✗
[39]	✓	✗	✗	[40]	✓	✗	✗
[41]	✗	✗	✓	[20]	✓	✗	✗
[42]	✗	✗	✓	[17]	✓	✗	✓
[43]	✓	✗	✗	[14]	✓	✓	✓
[44]	✓	✗	✗	[15]	✓	✓	✓
[45]	✓	✗	✗	[13]	✓	✗	✗
[46]	✓	✗	✗	[47]	✗	✗	✓
[48]	✗	✗	✓	[21]	✓	✗	✗
[49]	✓	✗	✗	[50]	✓	✗	✗
[11]	✓	✗	✗	[51]	✓	✗	✗
[52]	✓	✗	✓	[53]	✓	✗	✓
[54]	✗	✗	✓	[55]	✓	✗	✗

IV. CLASSIFICATION BASED ON VULNERABILITIES ADDRESSED

In some systems, when a disturbance occurs on a system level, it is commonly caused by a disturbance to one or more parts of that system. In power systems, there are different vulnerable parts that could lead to service outages, including power lines, substations, switchgears, power plants, etc. Power lines are considered to be one of the most common vulnerable parts of the power system to natural disaster [56], nevertheless, substations and fuel supplies, e.g., gas lines, are also vulnerable to harsh natural disasters. Therefore, in addressing a power system resilience study, these vulnerabilities are considered a major factor in the problem formulation. Table 3 highlights some of the studies that consider one more of those vulnerabilities. It shows that most studies focus on the power line outages since they are the most vulnerable part of the system. However, the gas lines that supply many power plants are also crucial for the permanence of the operation during natural disaster events and addressing them in future studies shall prevent losing these units from service.

TABLE III. CLASSIFICATION OF STUDIES IN LITERATURE BASED ON VULNERABLE COMPONENT.

Reference	**Component**			**Reference**	**Component**		
	Power Lines	***Substations***	***Fuel Supply***		***Power Lines***	***Substations***	***Fuel Supply***
[32]	✓	✗	✗	[33]	✓	✗	✗
[22]	✓	✓	✓	[23]	✓	✗	✗
[24]	✓	✓	✗	[25]	✓	✗	✗
[34]	✓	✗	✗	[19]	✓	✗	✗
[35]	✗	✓	✗	[36]	✓	✗	✗
[27]	✓	✗	✓	[38]	✓	✗	✗
[37]	✓	✗	✗	[40]	✓	✗	✗
[29]	✓	✗	✓	[17]	✓	✗	✗
[39]	✗	✓	✗	[14]	✓	✓	✗
[41]	✗	✓	✗	[15]	✓	✓	✓
[42]	✓	✓	✗	[13]	✓	✗	✗
[43]	✓	✗	✗	[57]	✗	✓	✗
[44]	✓	✗	✗	[45]	✓	✗	✗
[47]	✓	✓	✗	[28]	✓	✗	✓
[21]	✓	✗	✓	[30]	✓	✗	✗
[51]	✓	✗	✗	[31]	✓	✗	✗
[49]	✓	✗	✓	[53]	✓	✓	✗
[11]	✓	✗	✓	[55]	✓	✗	✗
[52]	✓	✗	✗	[54]	✓	✗	✗

V. CLASSIFICATION BASED ON MODELING APPROACHES

Modeling is a very necessary stage in studying power system resilience since it visualizes the system properties thoroughly. This provides a suitable representation of the system in which scenarios are applied and outcomes are analyzed. Modeling the power system for resiliency implies having different unanticipated events and uncertainties; therefore, probabilistic modeling is the suitable choice for this type of case. Different techniques have been utilized in probabilistic modeling of power system resilience, mainly Monte Carlo Simulation and Bayesian Networks, in addition to other techniques.

A. Monte Carlo Simulation

Monte Carlo Simulation (MCS) utilizes the stochastic and probability analyses with random sampling to obtain numerical results [58]. This makes it suitable for power system resilience studies as the system has uncertainties that require such type of modeling and simulation. Many power system resilience studies have used Monte Carlo Simulation, Wang Y. et al. [33] have used sequential Monte Carlo in developing a resilience-constrained unit commitment framework. Results have shown the reliable solution of the proposed framework, as the MCS iterations independence indicates the possibility for parallel computation, and therefore lower CPU time. Gautam et al. [34] have utilized non-sequential Monte Carlo framework for probabilistic extreme event model, impact assessment model, and optimal restoration model, where MCS is utilized for better computation efficiency. Johnson et al. [57] have utilized MCS to quantify resilience and compute probability distributions for the not-served demand. Other studies that used MCS are found in [13], [15], [18], [19], [22], [23], [25], [28], [41], [45], [47], [49], [51], [54].

Based on the number of articles utilized it, MCS is a favorable technique for the power system resilence studies. MCS provides a robust statisitcal and probailistic modeling capabilities for systems with uncertainities and interdependencies, allowing researchers to simulate multiple scenarios that mimic the stochastic nature of the power system.

B. *Bayesian Networks*

Bayesian networks (BN) are a type of graph probabilistic modeling that is used for prediction applications and decision making. This makes it useful for power system resilience studies under events such as hurricanes and natural disasters. Moreover, Bayesian Networks have been applied in different systems [36], making it suitable for interdependent systems. Li B. et al. [36] have presented a Bayesian Network-based model to predict outages. Results have shown the BN ability to characterize the causalities of the weather dynamics. Omogoye et al. [45] have presented a comparative study between Bayesian Networks and Fragility-Curve Monte Carlo Simulation, results have shown that Bayesian Networks have the upper hand as an operational planning tool. Other studies that have used BNs are found in [26], [45]. The graphical probabilistic models provided by BN facilitate establishing the interactions of the interdependent entities of the power system and quantifies its uncertainties. Moreover, BN has a dual capability to provide diagnostic and predictive analysis, which support the decision-making process.

C. *Other Techniques*

Event Tree Analysis has also been used as a probabilistic modeling technique in some studies [20], [40]. In addition to the the propabilistic modelig, determiestic modeling is used in these studies for power system modeling and pre-event assessment. Mixed Integer Linear Programming (MILP) seems to be a suitable choice for the application, as many studies have utilized it [4]. Some of the studies the used MILP are found in [35], [43], [44], [45], [46], [47], [48], [54]. MILP has an efficient capability when it is applied for optimal system configuration, including components and resources allocations, and cost-benefit analysis. Table IV shows a summary of the aforementtioned studies and modeling technique used.

TABLE IV. MODELING TECHNIQUES SUMMARY FROM LITERARTURE

Method	References
Monte Carlo Simulation	[13], [15], [17], [18], [19], [22], [23], [25], [28], [33], [34], [41], [45], [47], [49], [51], [54], [57]
Bayesian Networks	[26], [36], [38], [45]
Event Tree Analysis	[20], [40]
Mixed Integer Linear Programming	[35], [43], [44], [45], [46], [47], [48], [54]

VI. CONCLUSIONS AND RECOMMENDATIONS

The importance of power system resilience studies is noticeable by the number of research articles that discuss the subject and the researchers' interests to utilize robust modeling techniques and formulate various assessment metrics to enhance the power system stability. This review paper could be a starting point for the study of power system resilience by organizing the major aspects to be included in the study.

Categorizing the most recent literature on power system resilience based on different aspects has highlighted the most addressed operation stages, vulnerable components, and modeling techniques. At the same time, it has pointed out other concerns that are important to address, such as the response stage, utilizing other modeling techniques that provide efficient framework, such as Bayesian Networks, and including more vulnerable components, such as the fuel supply, in the power system resilience studies. Finally, in addition to the well-known convenient metrics, contemporary efficient assessment metrics are formulated for power system resilience assessment, promoting the possibility to formulate applicable state-of-the-art assessment metrics to enhance the overall resilience.

This review paper aims to guide researchers in defining optimization challenges and effective evaluation criteria to strengthen the operational resilience of power systems. It encourages the use of techniques renowned for their robustness in handling uncertainties, alongside incorporating renewable energy factors. Additionally, it emphasizes the significance of power system resilience to decision-makers and stakeholders by showcasing economic analyses that highlight the balance between planning costs and potential revenue losses.

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