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Resilience in Electric Power Systems

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Abstract **– In recent times, there has been a rise in the number of extreme events affecting electric power systems. Power system resilience is the ability to counterattack, adjust to, and rapidly recuperate from such events. As the cognizance of these threating events is rising, the resilience of powers systems has become a highest precedence in the research area of power systems. This paper intends to deliver a summary of basic concepts of resilience in the power system. Definitions and assessment approaches of resilience are discussed. Moreover, strategies to enhance power system resilience are presented. Future challenges, associated with power system resilience, are brought to attention. A case study on the IEEE 14-bus test system is demonstrated to assess resilience.**

Keywords- extreme events; high risks; human attacks; natural disasters; power system resilience

I. INTRODUCTION

Supply of energy is an essential pillar for any society to function. It is important to have reliable energy distribution [1-2]. The electric power systems are generally planned to sustain component outage in accordance with the *(N-1)* security criterion, but lately, various natural disasters have brought forward extraordinary challenges to power systems, stressing the situation that the power system is not adequately planned to cope with disruptive events possessing huge severity, e.g., 11 years ago, in China, a snow storm resulted in over 129 line faults. In 2011, the Great East Japan Earthquake resulted in a power outage for over 4 million homes for about seven days [3]. [4] describes 933 events in the U.S., resulting in outages, from the years 1984 to 2006. The resulting data is presented in Table I [4].

It has been observed that a reliable power system is not necessarily resilient [5]. It has become clear that further deliberations beyond the conventional system reliability analysis are required to completely describe the system. It is expected that the natural disasters, affecting power systems, would continue to rise because of climate alteration and the outdated energy infrastructure [1]. Moreover, man-made errors and cyber-attacks are also a threat to power systems, as outlined in Fig. 1 [6]. In the era of smart grids, machine learning, and artificial intelligence, power system has become more vulnerable. The inherent randomness and outside interferences affect the power system.

Power systems are very susceptible to terrorist attacks as these systems constitute a large cyber-physical entity. For instance, on April 16th, 2013, 17 transformers were damaged by the attack of snipers in Metcalf, California, near the border of San Jose. These damaged transformers required over $15 million worth of repairs. Thus, confronting the rising threats and complexity of the network, incorporating resilience in the power infrastructure is a challenging task. Although, disaster-prone standards should be practiced, an all-inclusive upgradation of the system is very expensive. As a substitute, the notion of resilient electric power system is discussed to deal with the high impact, low probability events [3]. Therefore, recently, various nations are now prioritizing power system resilience considering planning polices of power systems. To understand the concept of power system resilience, the paper reviews some existing works on definition, measurement, and enhancement of resilience in association with power system. Some future challenges are also highlighted

This paper gives an overview of the resilience in electric power system. There are various causes which can reduce the resilience of the system. Caused by power outages. A schematic of some common power outage causes is shown in Fig. 1 [6].

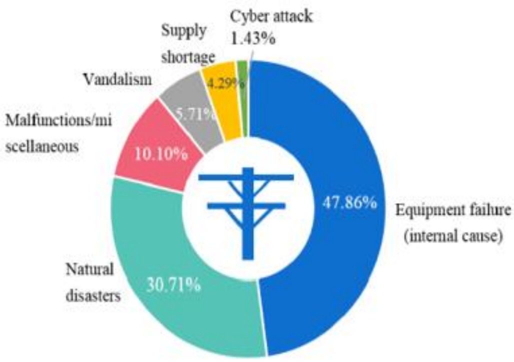

Fig. 1. Common power outage causes

The rest of the paper is organized as follows. Section II introduces the concept of power system resilience. Section III discusses resilience measurement and assessment approach. Section IV suggests some measures to improve resilience. Section V demonstrates assessment of resilience on a standard test system. Section VI discusses future challenges. Finally, the conclusion is presented, along with a future research direction.

TABLE I. CAUSES OF LARGE BLACKOUTS IN THE UNITED STATES [4]

Cause	% of events	Mean size (MW)	Mean size (customers)
Earthquake	0.8	1,408	375,900
Tornado	2.8	367	115,439
Hurricane	4.2	1,309	782,695
Ice storm	5.0	1,152	343,448
Lightning	11.3	270	70,944
Wind/rain	14.8	793	185,199
Other cold weather	5.5	542	150,255
Fire	5.2	431	111,244
Intentional attack	1.6	340	24,572
Supply shortage	5.3	341	138,957
Other external cause	4.8	710	246,071
Equipment failure	29.7	379	57,140
Operation error	10.1	489	105,322
Voltage reduction	7.7	153	212,900

II. Concept of Power System Resilience

The Smart Grid is comprised of three elements that work in cohesion to provide efficient and reliable energy. The complex interconnectivity of communication, computational, and new emerging devices will be discussed in this section. Technological advances and improved monitoring systems help in continuing to improve the electric power grid [2-5].

Resilience was first introduced in 1972 by C.S. Holling in [7] as an idea in ecological systems, which referred to "a measure of the persistence of systems and of their ability to absorb change and disturbances and still maintain the same relationships between populations or state variables" [8]. However, for the power systems, various similar definitions have been proposed, with an emphasis on the ability to deal with disturbing events. According to the U.S. Presidential Policy Directives-21(PPD-21), resilience is "the ability to prepare for and adapt to changing conditions, and withstand, and recover rapidly from disruptions" [9-11]. Although, there is a lack of agreement on the definition of resilience, the spirit of such definitions is usually the same, i.e., resilience is an all-embracing idea that includes the system performance before, during, and after the disrupting events. Thus, resilience can be defined as "the ability of an entity to anticipate, resist, absorb, respond to, adapt to, and recover from a disturbance" [12], as demonstrated in Fig. 2. The resilient system is likely to resist the disruption better than the traditional system (specified by the red dashed line), e.g., from t_o to t_1. From t_1 to t_2, the system can effectively resist the disasters using system hardening; from t_2 to t_3, response and adaption can be attained, and eventually, unconventional refurbishment strategies, will be utilized in an appropriate way to reinstate the system to near-normal performance state (from t_3 to t_4). This modeling approach of system resilience is also known as the "resilience trapezoid".

Some research works have also used the "resilience triangle" [13], as shown in Fig. 3, to present the concept of resilience. The shape of the hypotenuse of triangle can alter, i.e. it can be linear, triangular, or exponential [14], depending on the effectiveness of the adopted recovery strategies.

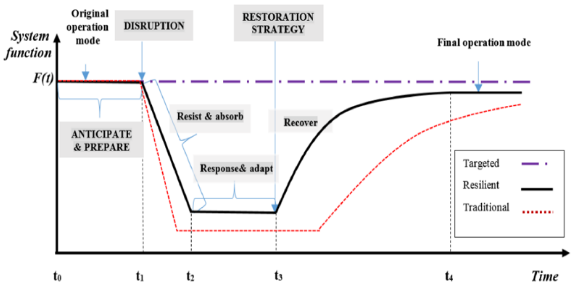

Fig. 2. Process of a resilient power system through disruption

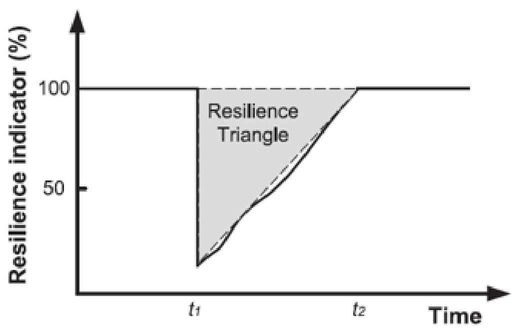

Fig. 3. The resilience triangle

While, this approach can efficiently capture the resilience recovery after an event ($t \in [t_1, t_2]$), it cannot capture other very crucial scopes of resilience that the typical power systems may suffer, e.g., how rapidly the resilience worsens once the event impacts a critical infrastructure or for how much long the substructure stays in post-event tarnished states before restoration process is started. Thus, it is not able to establish a comprehensive depiction of the resilience level during all the phases of a disruptive event [15]. Therefore, "resilience trapezoid" approach is superior than "resilience triangle" approach as it portrays all possible phases that a critical infrastructure can remain in during the disruptive event, including the changeover between these possible states. The "resilience trapezoid" approach is further elaborated in [16] and [17].

III. Resilience Measurement and Assessment

Usually, power system resilience is focused at two different levels: component level, and system level [18]. The former mostly focuses on cyber-physical components [18]. Recent progresses in the design of such components have significantly enhanced their performance, thus, having a satisfactory resilience level [18]. However, to incorporate both physical and cyber interdependencies of these components, power system researchers have made widespread efforts to research the system-level resilience [19]. Defining the suitable system level resilience metrics allows the concerned authorities to accomplish analytical assessments, and perform dissimilar precautionary procedures [20-21]. To measure and assess the resilience in a comprehensive manner, three main features must be considered [22]: measuring the "resilience of what, to what, and under what conditions." Another characteristic that should be considered in formulating a resilience metric is the operating state of the power system, when the disruptive event occurs. Fig. 4 demonstrates a conceptual model for measuring the resilience level of a typical power system [23].

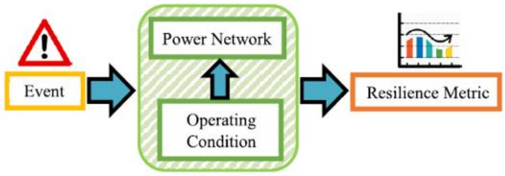

Fig. 4. A model for measuring resilience level for a power system

[23] proposed a seven-stage resilience assessment framework, as shown in Fig. 5. The goal of the first three stages is to define a resilience metric, characterize the disrupting event/threat, and model the potential influences of the event on the power system operation.

During the next three stages, the behavior of the system in response to the chosen disruptive event is simulated. In this aspect, the two decisive points are: 1) simulating the disruptive event and its spatiotemporal impact, and 2) simulating the corrective, and restorative measures that can be taken in response to the event. Consequently, the resilience curve of the system, like Fig. 2, is developed.

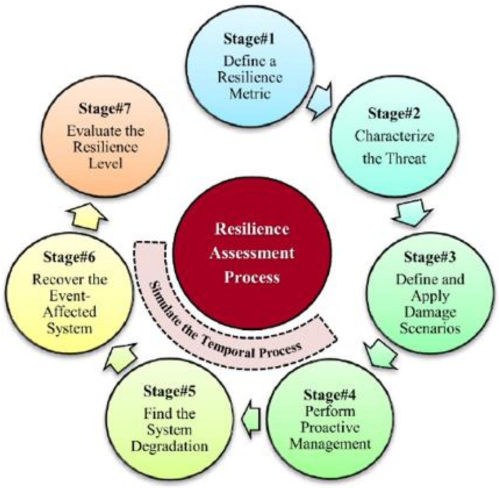

Fig. 5. Resilience assessment process in response to a disruptive event

IV. Resilience Enhancement

As the number of extreme events and their severity is on the rise, power system companies have begun noteworthy infrastructure enhancements. This is a challenging task for policy makers [24]. The primary reason is that measures based on prior disasters do not essentially guarantee protection from unanticipated future disasters. Moreover, the equilibrium between the resilience level and the capital investment is essential to obtain [25-26]. The methods for improving resilience fall in two broad categories: system hardening and use of smart grid technology. System hardening is the process of performing physical changes to the power system infrastructure such that it less vulnerable to catastrophic events. Hardening measures typically require huge capital cost. Some common hardening practices are described below [3,27].

A. Undergrounding the Overhead Power Lines

Undergrounding the overhead lines will result in decreased exposure of the poles and lines from the disruptive weather scenarios. This reduces the extent of the severe weather event.

B. Physical Upgradation and Revitalization

The grid resilience can be enhanced through renaissance of various grid parts. This can be accomplished by replacing the mechanical structure of an old part with the latest available technology. Examples include replacing the power poles with long-lasting materials and devising a new pole design to resist a high-speed wind.

C. Trimming of Trees

Trimming of trees can reduce the airborne debris which may be in contact with the power lines and can cause short circuit faults. It also prevents fallen trees damaging the lines and poles during a high-speed wind instance. Various techniques can be used in this aspect. For instance, Geographic Information System (GIS), can be used to manage the trees in a larger geographical area, and a sonic scanner can be deployed for attaining data from susceptible trees during the storm.

V. RESILIENCE ASSESSMENT: CASE STUDY

An approach based on three-state weather model [28] is used to demonstrate the assessment of resilience on the IEEE 14-bus test system. The single line diagram of the system is shown in Fig. 6.

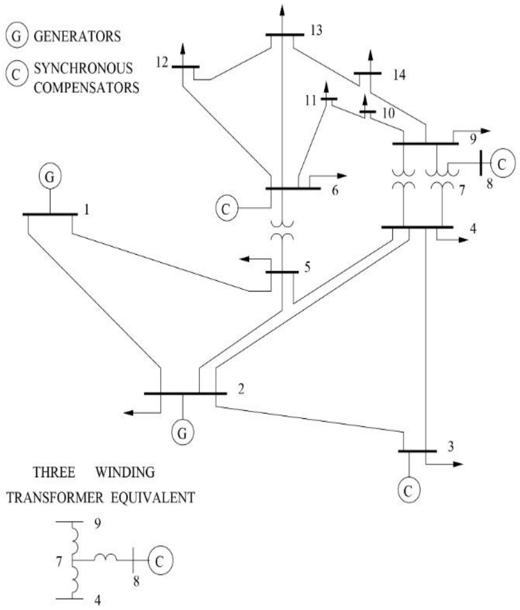

Fig. 6. IEEE 14-bus test system

Fig. 7 shows the three-state weather model used and associated transition rates [28-29]. The values of transition rates (assumed based on historic data) are shown in Table II. In this table, n_a and a_n denote the transition rates from normal to adverse and adverse to normal weather, respectively; m_a and a_m denote the transition rates from major adverse to adverse and adverse to major adverse weather, respectively; n_m and m_n denote the transition rates from normal to major adverse and major adverse to normal weather, respectively.

TABLE II. ASSUMED WEATHER TRANSITION RATES

Transition state	Transition rate (per hour)
n_a	1/100
a_n	1/3
m_a	1/3
a_m	1/8760
n_m	1/8760
m_n	1/3

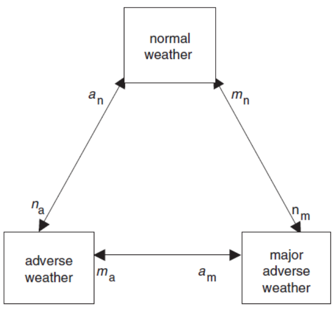

Fig. 7. A typical three-state weather model for power system

Load point reliability indices for four loads i.e. L11, L12, L13, and L14 were used to assess resilience. Expected energy not supplied (EENS) index is used to achieve this. EENS is the amount of energy which is not expected to be met by generation in each calendar year. This index is mathematically given as follows.

$$EENS = \frac{ENS}{\sum C_i} \tag{1}$$

Where C_i denotes number of customers supplied by load point i. In this work, for each load pint, 100 customers are assumed. The value of EENS for each of the four load points is shown in Table III.

TABLE III. EENS FOR FOUR LOAD POINTS

Load Point	EENS (MWh/year)
L11	2.53
L12	3.66
L13	8.98
L14	7.24

As evident from Table III, load point L11 is the most resilient to weather disturbances as value of EENS is the least. This means for weather disturbances; this load has the least probability of losing load. On the contrary, L13 is the least resilient. This approach can be used to compare the resilience of various standard test systems, using different resilience performance criterion.

VI. FUTURE CHALLENGES

A. Modeling of Extreme Events

Conventionally, reliability assessment of power systems has emphasized on the random component faults due to internal reasons. On the contrary, resilience assessment stresses on the external, disruptive extreme events. The faults arising from such events can possess diverse characteristics. For instance, natural disasters faults show both time and spatial correlation; for human attacks, the targeted attack pattern, mode, and approaches may be a theme that many system planners are unacquainted with. As the power system attains more complexity, it is crucial to scrutinize the occurrences of these disruptive events, their impact on the network, and their negative consequences. The intricacy of catastrophic events also signifies the requirement to classify the faults based on their sources. In this aspect, two types of faults are of significance [30]: cascading faults and common-mode faults.

There is some research available on the modeling of faults due to catastrophic events. For instance, [31] provides an outline to model hurricanes in North America; [32] deliberated the cascading faults between the power system and the cyber system. Such researches are valuable references for comprehending the behavior of power system due to faults caused by disruptive events. Moreover, resilience approaches and plans should be deeply inspected to cope with similar faults.

B. Resilience Metrics

Two major challenging questions for implementing power system resilience are: (1) how can system resilience be measured resilience incorporating both the infrastructure and operational aspects? and (2) what resilience metrics can seamlessly incorporate the three relevant characteristics: weather variables, spatiotemporal nonstationary infrastructure failures, and restoration of services for customers? Although, reliability metrics have been used as standards [19], but these metrics are envisioned for daily operations rather than severe catastrophic events. Suitable standard resilience metrics are essential to integrate real-time features.

To sum up, it is of great significance to incorporate resilience in various aspects of power system including planning and operation. Moreover, dealing with correlation amongst various entities for resilience planning, particularly with renewable energy integration and smart grids, is equally important [33-36].

CONCLUSION

Due to large number of extreme events, a solid foundation of the resilient electric power system and the enhancement of resilience have become an unavoidable necessity for the power system. Resilience is, now, documented as an indispensable feature of the power system infrastructure. Although, a huge amount of research is already conducted on resilience, it is still a relatively novel subject in the realm of power systems. The standard definition of resilience in power system stills need to be agreed upon unanimously, as it plays a vital role for thoroughly analyzing power system. This paper reviewed some basic concepts of resilience, along with its assessment methods, and enhancement strategies. There are still various formidable challenges which must be addressed to establish the importance of resilience in power systems. A case study was conducted on IEEE 14-bus test system to assess resilience for various load points. Metrics for power system resilience are still an open area of research. Moreover, optimization assessment of grid resilience enhancement strategies is crucial. The existing research work on resilience is just the tip of the iceberg, and extreme catastrophic events will always be a daunting challenge to mankind. Standard, up-to-date guidelines, and innovative technologies are essential to emphasize the value of resilience in the power system infrastructure.

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