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Power Systems Resilience

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ABSTRACT

Power systems are one of the most important foundations of engineering systems, and the issue of resilience is considered as one of the current scientific topics to improve their function. Resilience has many definitions and features that can be measured and evaluated depending on the type of damage and disturbance in the system. This article will examine this quantity's measurement criteria based on conducted research while it explains the exact and comprehensive concept of the resilience of power systems.

Keywords: Resilience, Engineering Systems, Power Systems.

Introduction

Resilience is defined as the ability to resist threatening effects as well as dealing with its effects and rapid recovery [1]. Vulnerability and resilience will both play a role in how the threat affects society and its assets and how to recover from threats. Resilience is one of the concepts with many applications in various fields, especially psychology and economics, but it is an emerging new concept in power networks. After devastating storms in the United States, the power grid was identified as highly vulnerable equipment.

Engineers have found that the concepts of reliability, risk, security, survival and vulnerability cannot guarantee proper performance in all conditions, especially those with low probability and widespread failure. So even highly reliable systems that are in good condition in terms of risk and vulnerability of equipment are in terms of security and will suffer serious problems and even system collapse.

Resilience in power systems is the ability of the system to withstand events and recover quickly afterwards. Figure (1) shows the resilience structure in a power grid.

Figure 1. Resilience structure in power systems

Definition of Resilience

The word resilience comes from the Latin word "Resilio". It means that something returns to its original state after being exposed to stress (pressure, bending or stretching) [2].

Resilience is examined in the following four areas:

• Organizational
• Social
• Economical
• Engineering

Organizational resilience is defined as the organization's inherent ability to maintain or recover steady state. It enables the organization to continue to function normally after a devastating event or constant stress [3]. In another definition, resilience is defined as the ability of an organization to cope with stress and improve its performance despite a disastrous event [4]. Resilience, from a social perspective, is the resilience of individuals, groups, communities and environments. Social resilience can be expressed as the ability of groups or communities to cope with external disorders and tensions resulting from socio-political and environmental changes [5]. In other words, social resilience is the ability to predict risk, limit adverse consequences, and recover as quickly as possible through withstanding, adaptation, and growth in the face of disruptive change. In the dynamic economics, resilience is the speed at which a system returns from a severe shock to a stable state [6]. In engineering, this term briefly describes a new concept in the electrical industry. Resilience in this area includes a set of capabilities that help the system in difficult situations to overcome unexpected situations with minimal damage, stubbornly withstand stress and pressure and deal with very unfavorable situations to the best of its ability. Once the pressure factor on the network is removed, the most important thing is to get it back to normal state quickly. This concept is in line with the definition defining resilience as the ability of existing networks and systems to predict and adapt an event, and recover quickly from that event [7].

Six factors of resilience improving in power systems are:

• Minimizing of the disturbances
• Limiting of the effects
• Executive methods
• Flexibility
• Controllability
• Early detection

In another definition, resilience is referred to as "4R" [8]:

1. Robustness: The system ability to protect the spread of damage in the damaged system, maintain performance and stability against destructive events and have resistance and stability against events with low probability and high failure.
2. Rapidity: The shortest time the system can return to its previous performance, or at least to acceptable performance.
3. Resourcefulness: system ability to use information, technical, physical and human resources (workers) in response to the event, return to normal state in the shortest possible time after the crisis and have plans for events and emergency operations.
4. Redundancy: This is the amount of availability of components and systems under study with resilience capability. In other words, the amount of equipment that maintains the overall performance of the system in the event of a disturbance or failure.

Review of Literature

Potentially severe weather events can cause multiple outages in electrical systems as well as power outages. Installation of microgrids in suitable places of power systems can be considered as a suitable solution to this problem. This solution is being explored by many US power companies. Considering this issue as well as increasing the number and severity of severe events, Eskanderpour et al. (2016) developed an optimal microgrid placement model that determines the optimal size and location of microgrids in power systems that can maximize system flexibility. This model has been developed with the consideration of outage of multiple components and limited investment budgets. The problem presented in this study is formulated using complex integer linear programming, and its suitability and effectiveness are demonstrated using the IEEE 118-bus standard system [9].

In sub-Saharan Africa, electrical infrastructure is growing rapidly. This growth is mainly through the construction of new regional connections and rural electricity supply. Regardless of network flexibility, this growth is not sustainable. It is well established that Mozambique's network needs to improve network reliability. The network does not meet the requirements during periods of adverse weather and peak demand. Buque & Chowdhury (2016) provided an analysis of the challenges and opportunities to improve network resilience in the country. This will happen by identification of the weakest areas of the network and prioritization of regional development through the implementation of micro grids. Analysis of network performance indicators indicates that the northern region of the country offers the greatest need, and at the same time a significant amount of opportunities to improve network flexibility, possibly by integration of solar energy micro grids and distributed generation [10].

In many articles, resilience is usually studied before the moment of event occurrence. In order to overcome a possible event that may not happen for many years, the operating point of the system is placed in the non-optimal working point by some changes, and the load redistribution resources are redistributed and the production of distributed generation units is changed. Therefore, using the concept of resilience in the operation phase may not seem economical. Therefore, with some changes in attitude and implementation of reforms, this concept can be considered in the planning phase of network development and its positive effects can be clearly seen in the operation phase of the system. Chen et al. (2015) presented distribution network development planning with the aim of increasing system resilience to natural disasters and severe storms in two stages of retrofitting and optimal location of distributed generation units. Meteorological information of the region can be used to obtain an approximate pattern of storm movement and to estimate the route and severity of natural disasters such as storms [11]. Yan et al. (2016) analyzed network flexibility to cyber-attacks by formulating random cyber-attacks with different values and number of incorrect data. This study uses a steady-state AC current-based blackout model to simulate system response with post-cyber incorrect information and possible cascade blackouts in transmission networks. Line outage, load shed, and voltage collapse are evaluated in the IEEE 300-bus system. Preliminary results showed that when cyber-attacks are considered as potentially severe threats to the smart grid, a power system can withstand FDI attacks in terms of the risk of blackouts and cascade outages. However, transient voltage stability can be damaged by severe cyber-attacks [12].

Methodology

In this review study, all studies conducted during 2010-2020 were reviewed in a structured manner using the keywords of resilience, engineering systems and power systems collected from Google scholar database and data obtained from selected articles. All foreign and domestic articles were reviewed regardless of location, place of publication and research method. Duplicate and irrelevant articles were removed after reviewing and collecting all searched articles. Then, the obtained articles were reviewed based on the inclusion criteria. This criterion included descriptive-analytic studies that examined the resilience of a power system.

Discussion:

According to studies, it can be said that initially the quantitative indicators must be defined and calculated for the extent of that feature and its components in order to evaluate a feature such as resilience of a power system. The performance index in a power system can be the load provided as the ultimate goal or the value of the remaining loads in the network, the number of healthy and electrified equipment, etc. that may be selected as the system performance index if necessary. For this purpose, appropriate indicators should be identified to evaluate the resilience of the systems. In the following, the indicators used in power systems to assess resilience will be introduced.

1. The Resilience Curve of Power Systems

Most power systems are exposed to unpredictable or uncertain and potentially destructive operating conditions. The change in system performance level over time is represented by P (t). Figure 2 shows the behavior of a resilient system compared to a power system without this feature.

A resilient system can recover its performance level from degradation state to operational state. But in a power system without resilience, its performance may be significantly reduced due to a sudden event. In fact, a power system, depending on the inherent capabilities considered in the design, experiences three situations in the face of destruptive phenomena: resilience, degradation and on the verge of collapse (performance level lower than Pv for the power system) [13].

If the system fails to resolve the problem, it will remain at the degradation level until the system fails or collapses completely. Therefore, considering resilience is very desirable for power systems that are exposed to disruptive events [13].

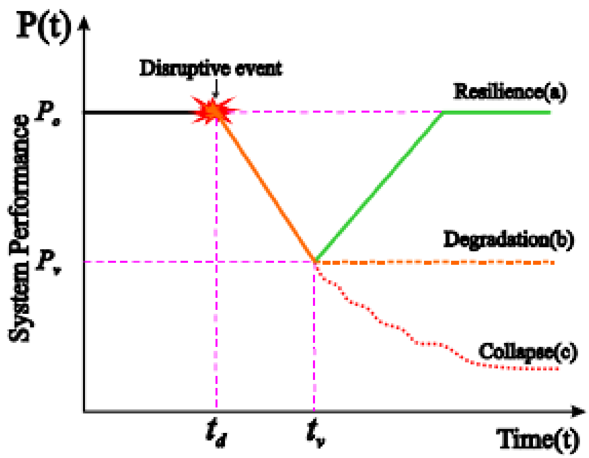

Figure 2. Behavior of power systems in three states: (a) resilience, (b) degradation, (c) non resilience and on the verge of collapse [13].

Since resilience is generally associated with reduced system performance after a disastrous event, then the resilience curve is usually drawn as the performance curve of the P (t) system with respect to time. Evaluation of resilience of distribution network is divided into five stages according to the level of performance, which is the amount of load supplied to consumers [14]:

In the first stage of $t_0 < t < t_d$, the system is in a stable state and its performance level is equal to P (t_0). In this case, the system resilience is high, so that all the desired operating constraints and security margins are within the appropriate range. Also, at this stage, by using a set of hardware measures, the resistance capacity of the distribution network can be increased against disruptive events such as storms, earthquakes, etc. that may occur in the future. This is to prevent system disturbances.

The second stage of $t_d < t < t_{vs}$ is when the system is affected by a disruptive event. In this case, the negative effects of this event appear on the system performance at t_d time. In this state, a significant decrease in power system performance is shown and the system performance level decreases from P (t_0) to P (t_{vs}).

The third stage of $t_{vs} < t < t_{vf}$ is related to the recovery process. At this point the system performance level remains equal to P (t_{vs}). The time required to restore a distribution network following a disruptive event is highly dependent on the rapid and accurate assessment of damage to the system. In the damage assessment process, assessment teams are sent to various parts of the distribution system to inspect all feeders and lines. Then, the assessment teams count and record the number of broken foundations and conductors along with the location of the damaged components. Once completed, the assessment teams are returned and the information is passed on to the operator. The repair crew is then sent to repair the damaged components.

The fourth stage of $t_{vf} < t < t_n$ is the system reconstruction. At this stage, after identifying the damaged parts, they are reconstructed by the repair crew and replaced if necessary. After reconstruction and placing the lines in the circuit, consumers reconnect to the network. In this case, the system performance is returned from P (t_{vs}) to P (t_0).

The fifth stage of $t < t_n$ is to learn from experience. After recovery of the system to normal conditions before the occurrence of disruptive event, limitations , shortcomings and vulnerabilities of the distribution network are identified and evaluated to prevent or reduce the impact of similar events that may occur in the near future.

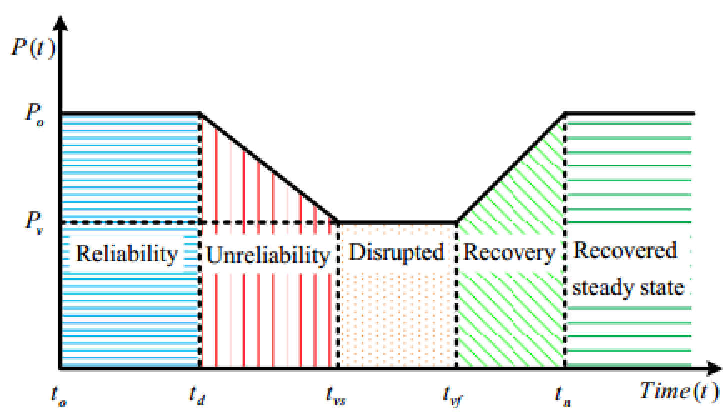

Figure 3. Resilience curve of power systems with five states [14].

Different versions of resilience curves for power systems arise from different perspectives that are considered to show conceptual and qualitative resilience. The reason for these differences is mainly the difference in system status features in unreliability and recovered states as well as the difference in different power systems. For example, a disruptive event differs from another event of this type in intensity and duration, and recovery methods may be different in various cases.

Figure 4 shows some examples of conceptual features that lead to different forms of resilience curves of power systems. In recovery state three states may occur including [15]:

1- Improved (higher than the baseline profile)

2. Stabled (similar to system performance before the occurrence of disruptive event)

3- Weakened (lower than the system performance before the occurrence of disruptive event)

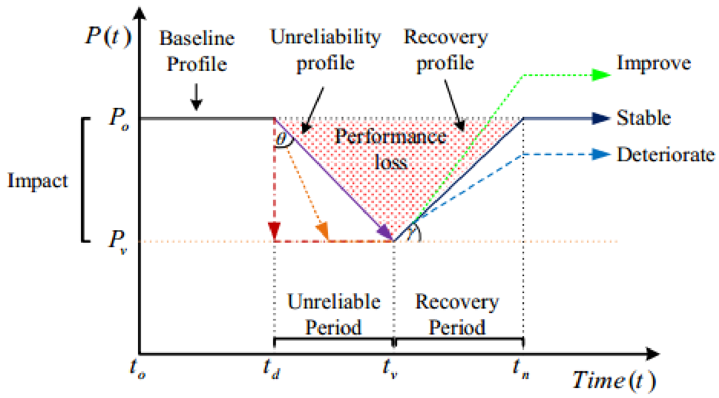

Figure 4. Different types of resilience curves of power systems [15].

For ease of operation, instability and recovery profiles are shown in a straight line in most resilience curves. In power systems, due to uncertainty, the system in non-reliable state and recovery is more likely to show nonlinear behavior. In some cases, convex and concave profiles are also seen [16]. Figure 5 shows five different types of profiles of system performance in recovery and vulnerability states.

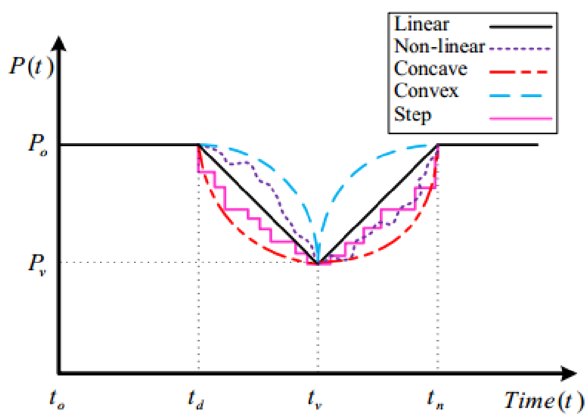

Figure 5. Different profiles related to the reconstruction and vulnerability of power systems [16].

Measurement of resilience of power systems plays an important role in defining the resilience of a system. Although system resilience has been studied in various disciplines of engineering, the resilience assessment criteria of power systems standardization are now very low.

A measurable overall unit that is agreed upon is still one of the challenges in this area. Many different approaches and aspects (including uncertainty) must be considered to measure the resilience of power systems. Resilience measurement criteria can be considered as definite or probabilistic, and static or dynamic. The criteria are grouped as follows. Some criteria can fall into more than one group. There are strengths and weaknesses in each resilience measurement criteria, depending on the purpose of the study and the intended application.

Resilience Measurement Based on the Resilience Curve

The resilience curve is often used to show the resilience behavior of an engineered system under a disruptive event. In the resilience curve, the affected area after the destructive event defines the system performance as shown in Figure 6 with the hatch. If the affected area is surrounded by a non-linear profile, the performance drop can be determined using the integral method.

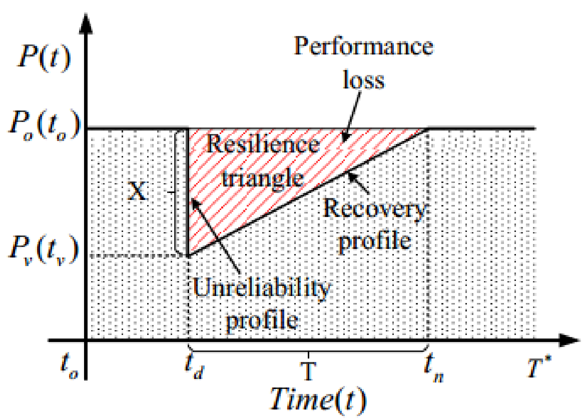

Figure 6. System Performance Drop Estimation in Triangular Resilience [17]

where P_0 (t_0) is the initial performance of the system before occurrence of disruptive event at td time. P (t) is a function of system performance and it is variable with time. The hatched area in Figure 6 has been also presented in the articles as a triangular process. If the system performance is assumed to be at linear recovery stage, the system resilience can also be measured faster and easier using triangle area calculation formula. In some articles, time-dependent operational and infrastructure resilience criteria have been suggested based on different indicators to determine the system resilience.

Figure 7 shows the multi-stage trapezoidal resilience. Operational resilience, as its name implies, refers to the features that provide operational robustness to the power system. For example, we can refer to the ability to guarantee uninterrupted power supply to consumers or available production capacity to deal with disruptive events. Infrastructure resilience refers to the physical strength of power systems infrastructure. Table 1 identifies the key flexibility criteria for trapezoidal resilience [18].

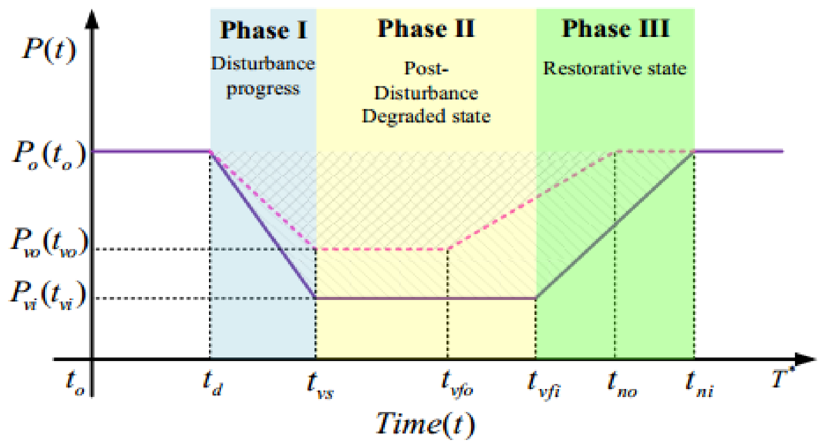

Figure 7. Multi-phase trapezoidal resilience diagram [18].

Table 1. ϕ AEII Evaluation Indicators

Symbol	Measurement Index	Status	Phase
ϕ	At what speed does the system performance reduce?	Vulnerablity	I
^	How much does system performance decrease?	Degradation	II
E	How much does system performance decrease?		
ɳ	How fast does system performance increase?	Recovery	II

Table 2. Mathematical relationships of resilience measurement criteria

Index	Mathematical Expression		Measurement Unit	
	Operational	Infrastructural	Operational	Infrastructural
ϕ	Ψ	$\frac{P_{vi}-P_o}{t_{vs}-t_d}$	$MW/hours$	$Number\ of\ lines\ tripped/hours$
^	P_o-P_{vo}	P_o-P_{vi}	MW	$Number\ of\ lines\ tripped$
E	$t_{vfo}-t_{vs}$	$t_{vfi}-t_{vs}$	$hours$	$hours$
ɳ	$\frac{P_o-P_{vo}}{t_{no}-t_{vfo}}$	$\frac{P_o-P_{vi}}{t_{ni}-t_{vfi}}$	$MW/hours$	$Number\ of\ lines\ restored/hours$

Resilience Measurement Based on the Performance of Power Systems before and After the Event

Resilience of power systems is often related to the loss and reduction of system performance in the event of a disruptive event. Therefore, one of the methods to determine the amount of resilience is the measurement of the extent to which system performance changes. In this state, the resilience criteria can be considered as the ratio of system performance before and after the disruptive event.

In general, the maximum performance drop indicates the worst state which can occur for a system as an impact after a disruptive event occurrence. As shown in Figure 8, the worst state is indicated by p_{max}.

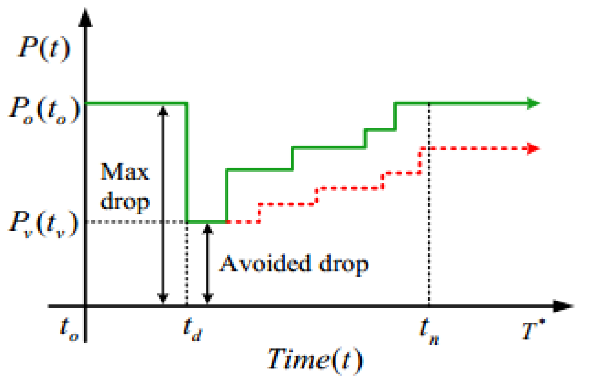

Figure 8. Avoided performance drop and maximum potential performance drop

Conclusion

This paper provides an overview of resilience assessment criteria in power systems while explaining the precise concept of resilience.

Considering the understanding of the probability of disruptive events, a certain level of resilience can be designed to improve the performance of power systems against disruptive events in the system.

To create a high-resilience, low-cost power system, there are two questions about integration of resilience in power systems from a system design perspective:

1- How can resilience measurement criteria be related to system design parameters so that the system resilience can be assessed against various threats?
2- What solutions can be used to design and improve resilience systems?

Therefore, it is very important to determine appropriate indicators in order to answer the raised questions to improve the resilience of power systems. Consequently, useful and practical results will be provided to researchers by the present study.

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