Review of Sequential Steps to Realize Power System Resilience

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***Abstract*— Natural events have been identified as the major cause of cascading faults on the electricity grid globally. The impact of the events always brings service interruption in all spheres of life with a high loss of revenue. Natural disasters attack on the electric grid has defeated the reliability criterion of N-1 recently. In this case, a more robust resilience measure is needed to prepare and take proactive decisions based on the predictable natural disaster on the power grid to mitigate the impact of natural events (hurricane, cyclone, ice storm, solar geomagnetic storm, etc) and recover fast in case of any contingencies. Achieving resilient electric grid system involves the use of cutting-edge technological approaches such as microgrids, smart-grid, and a wide-area monitoring system, optimal dispatch of repair resources for reduction of restoration time. Considering how important this new concept is, this paper presents a review of the approaches used to realize power system resilience and suggest a future research area to enhance the power system against natural disasters.**

Keywords— ***Natural events, power systems resilience, reliability criterion.***

I. INTRODUCTION

Electricity supply is the main drive of any industrialized and developing nation globally. This very important facility suffers greatly from natural events such as hurricane, cyclone, earthquake, flooding, geomagnetic storm etc. Natural events have been described as a high impact low probability (HILP) events [1] ,due to its stochastic nature. Many nations around the world today are faced with problems of enhancing the resilience of their aging power system networks which were not primarily designed to survive extreme weather events. Extreme weather events have officially been recognized as one of the main causes of electric power outages in the United States [2]. The analysis of the trend of large black out in the United State in 2008 revealed that out of 933 events resulting to power outages from 1984 to 2006, almost 44% were weather related events[3]. The database of grid disturbance with U.S. Department of Energy (DOE) revealed that around 78% of the reported 1333 electric grid supply interdiction from 1992 to 2011 were weather related[4] . In this view, In 2009, the U.S. Department of Energy (DOE), declared that power system resilience ought to be one of the features of smart grid[5]. The two U.S. Presidential Policy Directives, PPD-8, and PPD-21[6], explicitly talked to the national awareness for critical infrastructure, and highlighted that the power systems is exceptionally important because all other critical infrastructures such as medical hospital, transportation, communication, security etc, are driven by electricity and any disruption in the supply of electricity will also lead to their poor service delivery. Natural disaster did not spare the European electricity grid, as it is evidence from the central flood of 2002,2010,and 2013 respectively which made the Europeans to start questioning the reliability security level of their power grid against natural disaster [7]. Asia[8], and Africa [9], to mention few are not spared as well. Global warming have made all continents in the globe to face power supply disruption due to natural events with very huge economic loss [10]. Since the advent of frequent natural hazards or extreme weather attacks on electric grid, the resilience of critical infrastructure, in particular, the power systems grid, had become the focus of utility operators and researchers globally [11]. This is due to its influence on other critical interdependence infrastructures like hospitals, telecoms, transport systems etc. Factually, it is always not possible to resist all extreme events on power systems transmission and distribution lines. Therefore, the system operators need to deploy strategies other than reliability master plan to sustain power supply during extreme events and restore power supply at the very shortest time possible in the advent of contingencies [12]. However, putting cutting-edge technologies in place to realize power system resilience against natural disasters has been an unprecedented mission. If the grid is upgraded with today’s smart grid technologies [13], like distributed energy resources (DER), intentional islanding of microgrids and optimal dispatch of restoration resources and repair team, the power system can be rendered more resilient[14]. A review of the procedural steps to achieve power systems resilience is abstractly presented in this article for pre, mid, and post contingencies [11]. Other sections of this article are arranged as follows: Section II presents the review of power systems resilience concept, section III discuss the review of power system resilience enhancement evaluation, while section IV presents the review of power system resilience enhancement strategies, and V presents the conclusion.

II.OVERVIEW OF POWER SYSTEM RESILIENCE CONCEPT

Power Systems Resilience Defintion and Concept.

Defining power system resilience is really an issue as demonstrated in [6],[4],[15],[16],[12]. Till now, no consensus definition has been adopted but it is generally accepted that power systems resilience enhancement strategies are set out to achieve power grid network resilience against external disturbance. The adopted definition for this power systems resilience review purpose, can be taken from the perspective of infrastructure and operational resilience as “the ability of an entity to anticipate and prepare, resist and absorb, respond and adapt to, and recover fast from a disturbance” [12]. Authors in [17],[18], present the concept and evaluation, while a review of resilience theory and evaluation, in general, can be found in [12],[17]. The application of smart grid technology for better preparation of power systems grid against power disruption from natural attack is explained in [19],[20]. These papers laid a good foundation for the future development of the concept of power resilience investigation.

A. *Resilience Trapezoid Graph.*

Fig.1, explains the resilience concept using the trapezoid graph. From t_0 near t_1, power systems are sustained by the reliability criterion of N-1. At t_1, natural disaster strikes the grid, t_1 to t_2 showed that a power systems resilience is expected to offer resistance to the power supply disruption better than the conventional reliability system. Right from t_2 to t_3, quick response and adaption to natural disaster strategy is deployed, from t_3 to t_4 advanced restoration strategies which include micro-grid islanding can be deployed promptly to restore the system to near-optimal (t_3 to t_4) performance level while full restoration is achieved from t_4 to t_n upon the deployment of repair crew and optimal repair resources dispatching.

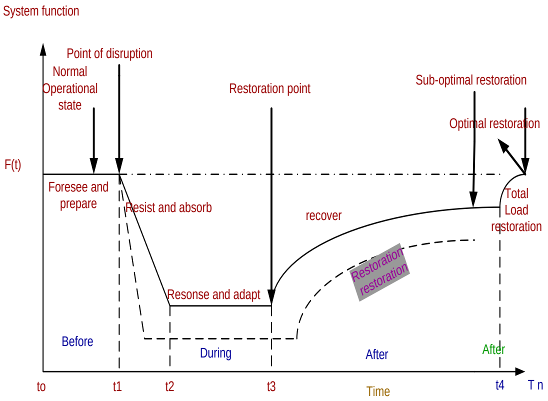

Figure 1: Resilience trapezoid system performance against the time [21].

As it was reported in [12], it is clear that most of the resilience research papers used reliability metrics, such as the system average interruption duration index (SAIDI), the system average interruption frequency index (SAIFI), and the customer average interruption duration index (CAIDI), which always exclude major power outages caused by catastrophic weather attack. Reliability concept of power systems for normal weather condition, may not be able to withstand natural events, therefore standard resilience metrics need to be in place for all possible causes of the extreme weather attack on the critical infrastructure based on enhancement strategies that can be deployed for the three stages, of resilience trapezoid graph in Fig.1.Therefore, having a resilient power system that is capable of effective anticipation of the oncoming contingencies with its impacts on the electricity lines, will enhance the utility operational scheduling, to respond to natural events on the grid and mitigate the effect of such an attack in the future for grid operational enhancement.

III. OVERVIEW OF POWER SYSTEM RESILIENCE EVALUATION CONCEPT

Resilience evaluation or assessment is the first exercise to be done before grid resilience could be achieved. The evaluation methods are qualitative and quantitative methods. Quantitative evaluation approach are of three types which include, analytical method, statistical analysis of historical outage data, and simulation-based method for power systems resilience enhancement against natural attack as reported in [12],[22],[23], The output of power system resilience evaluation brings about hardening and operational measures that help the system operators for operational planning and decision making. The summary of the decision taken for system resilience is shown in Table I. The concept of power system resilience is all-encompassing, from the normal operational stage of Fig.1 to the post-contingencies stage of resilience measures. When natural disasters hit the grid network, the following are the most frequently asked questions that usually provide a lead to the power system resilience solutions.

Question 1**:** What are the problem categories, and **w**hat type of resilience evaluation measure is needed for power system grid assessment in the advent of contingencies? This is the problem category that informs the metrics formulation for resilience enhancement evaluation.

Question 2**:** On which hierarchical stage of the power system did the power flow disruption take place?

Question 3: What type of problem formulation model is most suitable to solve such a problem?

Question 4: What stages (pre, during, and post-contingencies) of power system resilience is to be enhanced?

These questions are used as research evaluation criteria for power system network resilience enhancement. Fig.2, shows the pictorial view of the responses to the asked questions, to achieve power grid resilience.

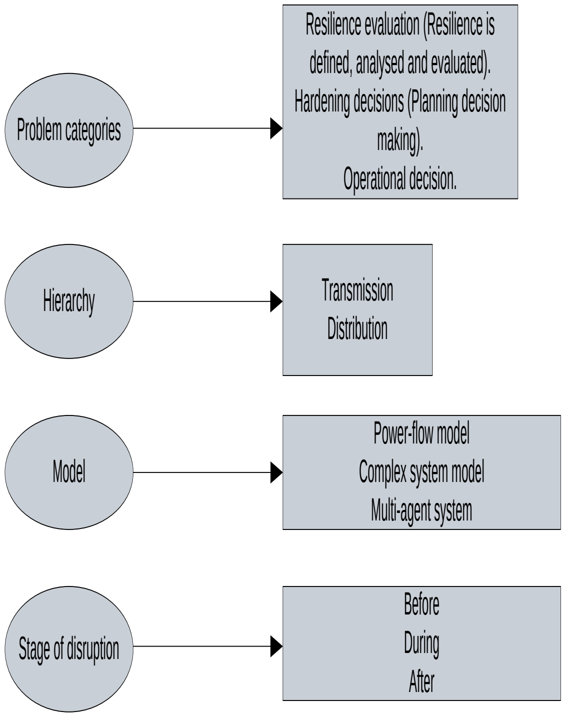

Figure 2: Research evaluation criteria[11].

TABLE I. PLANNING OPERATIONAL MEASURES FOR POWER SYSTEM RESILIENCE[11].

Term	**Planning operational measures for power system resilience.**	
	Hardening measures	***Operational resilience strategies***
Short term	Researve planning	Precise approximation of the weather location and severity
	Black-start capabilities installed	Demand-side management
	Repair crew member mobilization	Fast topology reconfiguration
	Installation of distributed energy generation	Microgrid island operation
	Coordination with adjacent networks and repair crews	Automated protection and control actions: Load and generation rejection, system separation
Long term	Tree trimming / vegetation management	Monitoring: development of situation awareness; advanced visualization and information systems.
	Undergrounding the distribution /transmission lines	Ensure communication functionality
Long term	Upgrading poles and structures with stronger,more robust materials	Microgrids
	Elevating substations and relocating facilities to areas less prone to flooding	Advanced control and protection schemes, such as system integrity protection schemes (SIPS)
	Redundant transmission routes by building additional transmission facilities	Disaster assessment and priority setting. Risk assessment and management for evaluating and preparing for the risk introduced by such events.

Carefully selected relevant research articles that answer the earlier raised questions in this paper are presented in Tab. II.

TABLE II. A DETAILED LIST OF THE SELECTED PAPERS FOR THE RESEARCH OVERVIEW.

Stage of Power supply attack	**A detailed list of the selected papers for the research overview**					
	Problem categories	***Hierarchy***		***Model***		***References***
		Trans. Lines	***Distr. lines***	***Power flow***	***Multi agent***	
Before	Planning	×	×	×		[24] [25] [26] [27] [28] [29] [30] [31] [32] [33] [34]
	Operation	×	×		×	[35] [36]
During	Operation		×			[37]
After	Evaluation		×	×		[12] [38] [9] [39] [40][41] [30][42] [43][44]
		×	×			[45] [46] [47] [48]

IV. OVERVIEW OF POWER SYSTEMS RESILIENCE ENHANCEMENT STRATEGIES FOR TOTAL LOAD RESTORATION.

A. *Pre-Power System Interruption Stage.*

1) Pre-Power Systems Interruption Stage on Transmission Lines: At this stage, system planners will envision damage scenarios and try to prepare the system for such scenarios. The research problem formulation is usually prepared in two-stages of an optimization problem. The first stage is the hardening of the system components against any foreseeable weather attack while the second stage will assess the network performance gain from the hardening strategies after the conduct of ‘’what if scenarios’’ simulation to identify system vulnerability during contingencies. Details of the methodologies for this stage can be found in these listed literatures[27],[29],[35],[49]. Recently, Ciapessoni et al.[30], moved a step further to perform a risk-based security assessment to enhance power system resilience. The evaluation technique permits the mixing of the hazard/vulnerability analyses in a risk-based security assessment, to use the obtainable data on incumbent threats to anticipate essential system conditions and improve the operators’ preparedness. This approach is mostly deployed at stage 1, of Fig.1. Researchers around the globe are now interested in predicting the riskiest contingency situations and the components most at risk of failure. More of these models can be found in [21],[50],[51],[52].

2) Pre-Power Supply Interdiction on A Distribution Line Units: Authors in [24],[26], applied the defender-attacker-defender (DAD) model on the distribution power network to make hardening decisions for the distribution grid enhancement. The frequent occurrence of natural weather events motivated the development of the maximum attack model in [24]. The model utilizes optimal reconfiguration and distributed energy resources (DER) islanding as a defender technique for system enhancement. Yuan et al. [25], and Ma et al. [26] considered the occurrence of natural disasters from the perspective of line hardening, DER placement, pole undergrounding, vegetation management and implemented resilience-improvement techniques in this regard.

B. *During Power Supply Interdiction Caused By Natural Disasters Stage.*

At this stage, the transmission and distribution power system planners and operators are interested in learning how frequent the attack occurs on the grid and the attacker’s pattern. Knowing fully well that, a good understanding of the severity and the characteristics of the attack is the key to implement sound resilient plan[11]. Therefore, research at this stage is viewed from two broad perspectives of natural events and human attack. The system planners investigate the unique characteristics of natural disasters, such as the influence of natural disasters on component’s failure, e.g. hurricane, earthquake, flood, and provide a model to counter such an attack. Another way to prepare is to determine the worst-case fault scenario for the power system in order to know the most vulnerable grid components under such attack. More details are discussed in the literatures and are reported in [53],[54],[55].

C. Post-Power Supply Interdiction Caused By Natural Disasters Stage.

At this stage, fast restoration of a power system is the most salient feature of resilient enhancement strategy, therefore almost 90% of the major research in the field of post-disruption restoration stage lean towards the power system distribution. Considering the rapid spread of smart-grid technology, power system operators are empowered with diverse strategies to deal with faults nowadays. Current research results have identified three major restoration schemes used to realize optimal load restoration after contingencies are briefly discussed as follow:

*1) Optimal Network Reconfiguration and DG Islanding:*Optimal network topology reconfiguration and DG islanding can be deployed on both transmission and distribution lines during contingencies. This approach have proven to be a reliable measure to prevent and recover from power supply disruption to critical loads during contingencies [24]. In [56], a network reconfiguration algorithm, conceptualizing ‘’electrical betweenness’’ to put the priority of non-black-start generators and critical loads first, for transmission grid fast restoration after natural events was developed. Panteli et al. [57], presented a model established on sequential Monte-Carlo risk assessment framework incorporating a splitting strategy by gapping the transmission line with the least power exchange while ensuring that at least, one black start component is available within each island to guarantees sufficient generation capacity to match the load consumption within each island. This concept is also adopted for the distribution power restoration during contingencies to decrease power loss on the grid, improve renewable energy penetration, and power quality respectively [24]. Network topology reconfiguration and networked DG islanding have proven to be capable, to enhance power system resilience against extreme weather attack by reducing the cascading faults on the lines during natural events by forming microgrids [58]. More details of various methodologies deployed for this task on the distribution power systems can be found in articles [59],[60] for better understanding of an interested readers.

2) The Optimal Energy Management Scheme (OEMS): Application of OEMS for load restoration during contingencies do not alter network topology in any form. It only applies an advanced energy management system (EMS) for the network operation optimization after power flow disruption events. OEMS is capable to coordinate the power systems resilience resources components ranging from energy generators and storage devices, demand response, and electrical load to get to an optimal operational point of a microgrid. Energy management algorithm are of two types. These include centralized or decentralized EMS [11]. Centralized energy management schemes are mathematically modelled and executed via numerical simulation. A mixed-integer programming model that can blend with many operating constraints for power supply service restoration as developed in [61], to optimally create a step by step coordinated order for controllable switches, energy storage systems, and dispatchable DGs to help the system operators with operational planning, and decision making. Such a tool’s capability has been proven in [62],[63], to enhance the power system resiliency if considered for the coordination of the networked microgrids in an islanding mode for critical loads survivability during contingencies[62],[63]. In decentralized energy management scheme on the other hand, each of the improvement entity such as DER, microgrid, etc optimizes their operation and exchange information within the local entities independently. In this view, Chen et al.[61], applied second-order conic programming model to control many DGs operational constraints and economic operations in the electricity-market environment. Colson et al. [64], considered managing large power system spanning hundreds of miles with numerous microgrids integration using decentralized multi-agent control measures for distributed microgrids to deal with the complexity of a large power system. The research revealed that the amalgamation of microgrids and multi-agent-based control can enhance power systems resiliency. In [65], it was established that operating multiple microgrids with a distribution system improves the high penetration of distributed energy resources(DERs). A transformative planning for the normal operation and self-healing of networked microgrids connected to a point of common connector bus was discussed and modelled as a two-stages cyber communication network to be controlled by an average concurrence algorithm so as to distribute the needed power among the local entities in case of any emergency power supply operation in [66].A multi-layer of microgrids was deployed for a distribution system using nested EMS to decreases the operation cost of the network[62]. Currently, networked microgrids usage at the distribution power system, has helped the distribution power system to sustain power supply to the critical loads during external attack and render the system more resilient.

3) Optimal Dispatch of Repair Resources and Repair Team: Optimal dispatch of restoration resources and repair crew is the last phase of exercises that help both transmission and distribution system to restore total power supply fast after contingencies because restoration of power supply using optimal network reconfiguration and DG islanding, OEMS are sub-optimal as depicted within t_3-t_4 of Fig.1.Optimal dispatch of repair resources and repair crew take care of the last phase of resilience graph i.e. t_4-t_n. In a reliability evaluation, the faulted components are usually assumed to be restored after a certain period of repair session. However, in a resilience enhancement approach, power supply is best restored quickly via proactive dispatch of repair crew and limited restoration resources[67],[68],[69]. Nowadays, resilience enhancement risk-based assessment, repair crew dispatch, and resource allocation are all parts of the measures to decrease the time taken for an emergency power restoration during extreme events[13]. At this stage, the problem is formulated as a two-stage dispatch scheme that has pre-positioning and real-time allocation and solved using mixed-integer linear programming to achieve optimal dispatch scheduling of repair resources like mobile generators [70].

V. CONCLUSION.

Power system resilience definition, concept, evaluation, and restoration strategies have been discussed in this paper from the perspective of hardening and operational measures for fast total load restoration during contingencies. Power systems resilience study is an emerging area of research and as such, all the three stages, (i.e. pre, mid, and after contingencies) of power systems resilience enhancement against high impact low probability (HILP) natural events still required technological breakthrough approaches. What's more? Extreme events usually caused damage that affect both electric grids and its interdependent critical infrastructures. Therefore, the need to develop a resilience model that can anticipate contingencies, perform risk vulnerability assessment ,and proactively deploy counter-measures (Pre, mid, and post contingencies) to mitigate the impact of natural events on the grid considering the role of other critical interdependence infrastructures like (road, pipeline, telecommunication etc) as it affect the time taken for fast total power supply restoration during contingencies, to enhance grid network[14] is highly needed[71],[72],[69].

Using DERs to boost supply continuity during power supply restoration altered conventional power distribution control schemes. Operators at the distribution systems are saddled with responsibility of voltage and frequency control during contingencies[13],as lower inertia of microgrid usually create a lot of problem for such control schemes to deliver system stability and dynamic performance. Leveraging microgrids to enhance power systems resilience is an interesting aspect that needs to be looked at, detail of the pro and cons can be found in [58], and research and development in these areas are really worthwhile to enhance the power grid resilience against external disturbances.

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