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Challenges of Generation and Transmission Expansion Planning Considering Power System Resilience and Provide Solutions

M. Rezaei, M. Tolou-Askari*, M. Amirahmadi, V. Ghods

Department of Electrical and Electronic Engineering, Semnan Branch, Islamic Azad University, Semnan, Iran

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ABSTRACT

Since power systems are susceptible to damages induced by disastrous incidents, the assessment and improvement of system resilience are unavoidable as a new goal of planning and operation. On the other hand, the expansion of generation and transmission grids constitute an essential part of power system planning as it needs a huge budget. So, a primary concern of researchers has always been the optimal planning of power systems. This paper studies the emerging concept of resilience, its criteria, and indicators, how to enhance it, and the identification of its strengths and weaknesses. It also reviews the strategies recommended in the literature to improve power system resilience. The paper briefly reports the models for expansion plan analysis and the generation and transmission expansion planning (GTEP) tools with or without the target of resilience enhancement, which can be instrumental in future research and can be used to estimate the effectiveness of different tools. Furthermore, the paper discusses the planning problems, thereby opening the way for further work in future studies. Finally, the study presents the most eminent challenges of GTEP to accomplish better, resilient, and innovative plans to escalate power system resilience.

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1. INTRODUCTION

Given the growing energy consumption in the contemporary world, the investigation into the development of power systems has become inevitable. A power system refers to a complicated grid composed of instruments to meet consumer needs. These facilities automatically protect the power systems upon detecting a violation of the electrical constraints. In this encoding, the operator separates components from the grid to protect them against any damage given the system evolutions and the implications of a set of predefined events. As load increases, operators should adopt proper strategies for the long-term development of the power systems by systematic planning for the inclusion of grid components. On the other hand, the opt performance results from decisions on precise planning. Various methods have so far been used to provide the best grid expansion design. Accordingly, this paper aims to comprehensively explore generation and transmission expansion planning (GTEP) to improve the resilience of power systems. The study focuses on expanding the power systems in the generation, transmission, and distribution sections. However, investment is more significant in the generation and transmission sections than in the distribution sections. Although GTEP is interdependent, it can be planned separately or concurrently. The GTEP is a complicated problem with nonlinear and binary variables, and time-consuming calculations. Restructured electricity markets exhibit further uncertainties, e.g., random and logical uncertainty, which should consider in the GTEP optimization problem. Power systems constantly expose to perturbations, so it is necessary to enhance system resilience to ensure its capability. Also, rapid fault detection and system recovery to normal conditions in the shortest possible time are significant factors in maintaining the security of a power system. In this case, the static and dynamic effects of hundreds of events should be examined in power systems. Table 1 briefly presents a review of some models with their advantages and disadvantages.

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*Corresponding Author Institutional Email: *m.askari@semnaniau.ac.ir* (M. Tolou Askari)

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TABLE 1. Review of some models with their advantages and disadvantages

Models	Advantages	Disadvantages
1. Topological model	• Power system analysis • Quick detection of unexpected emergency behavior • Consider some basic electrical properties.	• Lack of electrical properties
1.1. Modified topology model	• Provide criteria for combined electrical topology. • Rapid assessment of vulnerability, risk probability, and robustness	
1.2. Maximum flow model	• Use the maximum flow method • Consider the weight of the line and the node	
2. Stochastic simulation model	• Pay attention to the most uncertainties during the waterfall	• Lack of attention to dynamic stability and waterfall details
2.1. Model (practice)	• Introducing single-track and multi-track modes • Adopt an incident tree-based approach	
2.2. Markov China model	• Indicates non-local diffusion	
3. High-level statistical model	• Able to enable risk assessment • Simple and compact	• Ignores all the details of the waterfall
3.1 Cascade model	• The probability of failure is related to the load level	
3.2 Branch process model	• Can be considered as an improved CASCADE model • It considers each component of failure from an early stage through a specific distribution	
4. Dynamic simulation model	• Simulation of most of the dynamic mechanisms in the waterfall • Provides a deeper understanding of cascade failure	• Detailed information on the power system is required • Slow simulation
4.1. model OPA	• Considers the effects of the operation, automation, communications, relay protection, mode of operation, and planning • Tree contact, line failure due to line heating, and UVM model	• The network of this model has a small number of nodes, which is very different from the real system. • In this model, it is assumed that all elements of the system are the same • System control is done with only a small number of parameters • There is no clear relationship between the model parameters and the actual system • The protection system is not modeled • This model cannot cover the self-organized crisis caused by the interactions between the power plant, the operator, and the control system
4.2. Manchester model	• Approve AC power flow • Monte Carlo methods are used for risk assessment	
4.3. COSMIC model	• Considers the mechanism of nonlinear dynamics • Different relay and load models are involved	
4.4. Quasi-dynamic multi-time model	• Uses a quasi-dynamic approach • The approximate time of evolution is considered • Improved reuse simulation	
4.5. ASSESS MODEL	• Optimal AC power flux is provided with security restrictions • Use of quasi-steady state dynamic model simulator • Modeling control in the system through time domain simulator access to statistical tools	
4.6. TRELSS model	• Considers the actions of breakers • Voltage problems are modeled using quasi-steady state AC power flux	
4.7. PRA dynamic model	• Two levels of cascade failure are simulated using two different models • The effect of various changes in the system is simulated	
5. Interdependent models	• Interaction analysis between network connections	• Validation is difficult

5.1. Interconnected models based on complex networks	• The vulnerability of the entire system connection has been investigated and analyzed • Interdependencies are depicted • Computer and cyber risks are considered	• Precise mechanisms are ignored
5.2. Interrelated Markov chain models	• Able to predict system level with tracking details	
5.3. Hierarchical physics-cyber models based on congestion	• Dynamic nodes, PMU, and local cyber-controlled model • Frequency, phase angle, and other related parameters are involved • Control strategies are presented	
6. Other models	• Focuses on specific parts of the mechanism	• It focuses only on parts of the cascade failure mechanisms.
6.1. Potential waterfall model	• The "cluster" approach is used • The goal is to predict possible cascade fractures	
6.2. Hidden error model	• Considers hidden failure and reuse of the generator	
6.3. Models based on historical data	• Accurately reproduce historical events • Complementary models available	

This study provides an up-to-date review of GTEP models and tools and concentrates on the essential role of this scientific discipline in improving power system resilience. Unlike previous studies, this review emphasizes the effect of GTEP models on enhancing the resilience of power systems. Another contribution of the paper is the analysis of the trend of previous studies and the challenges that need new expansion models with/without considering the power system resilience.

The remaining parts of the paper are structured as below. Section 2 reviews resilience concepts, assessment frameworks, and enhancement, as well as its indices. Section 3 deals with models and their applications in expansion planning. Section 4 discusses the literature on the planning of GTEP that aimed at enhancing power system resilience, or did not consider this perspective. Section 5 lists and analyzes the challenges of GTEP. Section 6 finally concludes the paper with some final points.

2. THE CONCEPT OF RESILIENCE

Resilience is a dynamic, complicated, and multidimensional concept in the field of power systems, which has emerged relatively late [1]. Recently, disastrous incidents research has focused on the concept of 'resilience' [2]. Different definitions have been put forth for resilience, but they all have similar natures [3]. The word resilience is rooted in the Latin word resilio, means 'leaping back' as a system feature, and implies the capability of improvement against destructive events. In the simplest sense, power system resilience is defined as the capacity of a grid for the timely management of high-impact, low probability (HILP) incidents, e.g., atmospheric incidents and natural disasters [4]. Arghandeh et al. [5] resilience defines as 'the capability of a system to keep a continuous flow of power to customers by load prioritization.' The UK Energy Research Centre (UKERC) defines resilience as 'the capacity of a power system to tolerate disturbance and continue to deliver affordable energy services to consumers [6].' The US office [7] defines this concept as 'the capacity of grids to anticipate, absorb, adapt to, or/and rapidly recover from a destructive incident'. Also, resilience has been described in terms of the power system consistency and recovery during and after a disaster [8]. According to Presidential Policy Directive (PPD-21), resilience is 'the ability to prepare for or adapt to changing conditions and recover rapidly from disruptions' including 'deliberate attacks, accidents, or naturally occurring threats or incidents' [9]. In 2009, the American Society of Mechanical Engineers (ASME) defined resilience as 'the ability of a system to recover to its normal operating conditions after the occurrence of disruptive events' [10]. In 2011, an effective strategy was proposed for resilience enhancement. In 2013, a paper was published on the economic advantages of a resistant power grid focused on grid resilience during natural incidents [11]. NIAC's description of resilience encompasses robustness (ability to absorb), which implies the ability to absorb shocks and continue to work, defined as the system's resilience against disruption to minimize loss. According to Ouyang and Duenas-Osorio [12], resilience is the ability of the network to withstand damage, continue to work in the event of damage, and recover quickly from blackouts. It also includes adaptability, i.e., the ability to reduce future losses by using learning lessons to reinforce resilience. It refers to the endogeneity of the system and minimizes the consequences by self-organizing. Finally, the reinforcement of any of these four features will strengthen the power system's resilience [13].

Over 70 definitions can be found for the emerging concept of resilience in different papers in different disciplines. These definitions shift between the two features of adaptation and recovery [14]. The term resilience was first introduced in 1973 by Holling [15] to describe how to change perspective on environmental systems and behaviors and to describe different approaches to resource management. Today, however, it has gained more importance in other disciplines [16]. For example, extensive effort has been made to describe and measure the resilience of power systems. In 2011, resilience was defined using the concepts of power system reliability and recovery [17]. In fact, 'the time dimension' distinguishes resilience from reliability. Expansion planning mainly aims to prevent incidents and protect the equipment thoroughly. Recently, research has been conducted on 'timely response and rapid recovery' from destructive incidents. Therefore, attaining arrangements for resilience has become a chief priority, and practical actions should be taken before, during, and after incidents to assist the safe operation of power systems. After planning, system resilience measurement is the main issue [18].

Therefore, a review paper that describes challenges in this field can help the power engineer community to develop standard indices and create a framework for its assessment and reinforcement. This paper tries to shed light on the concept of resilience and its improvement in planning for the expansion of power systems during disastrous incidents, which has become a hot issue today. In this section, we provide a general framework for assessing and reinforcing power system resilience based on a comprehensive review of authentic literature. Due to reinforce system resilience, we first need to determine resilience and a proper method for its measurement. So, this paper provides a literature review on the definitions and measurement of resilience. Then, we discuss them as a tool for enhancing power system resilience with an emphasis on modern technologies.

2. 1. Key Features of Resilience

Since disturbances are unpredictable and may have disastrous impacts on vital infrastructure rapidly, resulting in considerable losses in the system, so it is very complicated and time-consuming to recover the system [1]. An important characteristic of power system resilience is how to recover it. A resilient power system should have the following features. Figure 1 depicts a resilience curve [4]:

1) Before the incident, the system should be consistent and resilient enough, and the operator should estimate the location and severity of the incident to prepare with a series of preventive actions.

2) After the incident, the operator is informed about the situation by advanced information systems, and since the system has entered the destruction phase, the resilience is jeopardized. At this stage, the key features of resilience, including capability, redundancy, and adaptive self-organizing, help reinforce resilience and reduce vulnerability.

3) As the disturbance advances, the system is damaged. At this stage, emergency prioritization, preparation, and coordination adjustment allow the operator to identify the main components for the recovery system as soon as possible and estimate the damages of the incident.

4) As the impact of the incident is minimized ($r_0 - r_b$), the system enters the recovery phase at t_c, and the units are re-installed. Then, the system will enter the post-recovery phase (r_d), at which stage the resilience may no longer be as remarkable as the pre-incident resilience (r_0), i.e., $r_d < r_0$. The recovery duration depends on the incident intensity and the power system's resilience features ($t_f - t_e > t_d - t_c$). So, having the critical resilience features, the power system can predict the following incidents and improve from destruction to the resilient stage. Also, it can adapt its performance and structure to alleviate the impact of the subsequent incidents.

2. 2. Evaluate the Resilience of the Power System

Power system assessment and resilience have dominated research in recent years, but the present methods in the resilience measurement still need development and revision. This subsection discusses power system resilience assessment. Since research on resilience assessment has a multidimensional nature and includes both quantitative and qualitative aspects, they are dealt with below.

2. 2. 1. Qualitatively Evaluating the Resilience of a Power System

The qualitative methods allow investigation of power system resilience from engineering, social, and organizational perspectives. Library work, questionnaires, and personal ratings are used as introduced by Carlson et al. [19] to study resilience. Analytical methods, e.g., the analytic hierarchy process (AHP), can be easily applied in decision-making as employed according to Orencio and Fujii, [20]. The qualitative assessment of the system formulated by Roege et al. [21], and a qualitative evaluation of resilience by events analysis is focused [22].

2. 2. 2. Quantitative Evaluation of Power System Resilience

Quantitative evaluation methods include simulation-based, analytical, and statistical analysis methods, among which simulation-based methods can easily be combined with incident scenarios and allow easy calculation of incident implications. The complicated network model was used by Chanda and Srivastava [23], and outage records are used as Maliszewski and Perrings [24] for data analysis. An analytical method is adopted from Whitson and Ramirez-Marquez [25] to estimate power outage duration, and a statistical model is used as introduced by Nateghi et al. [26]. A quantitative assessment method is proposed by Nan and Sansavini [27] for resilience composed of two

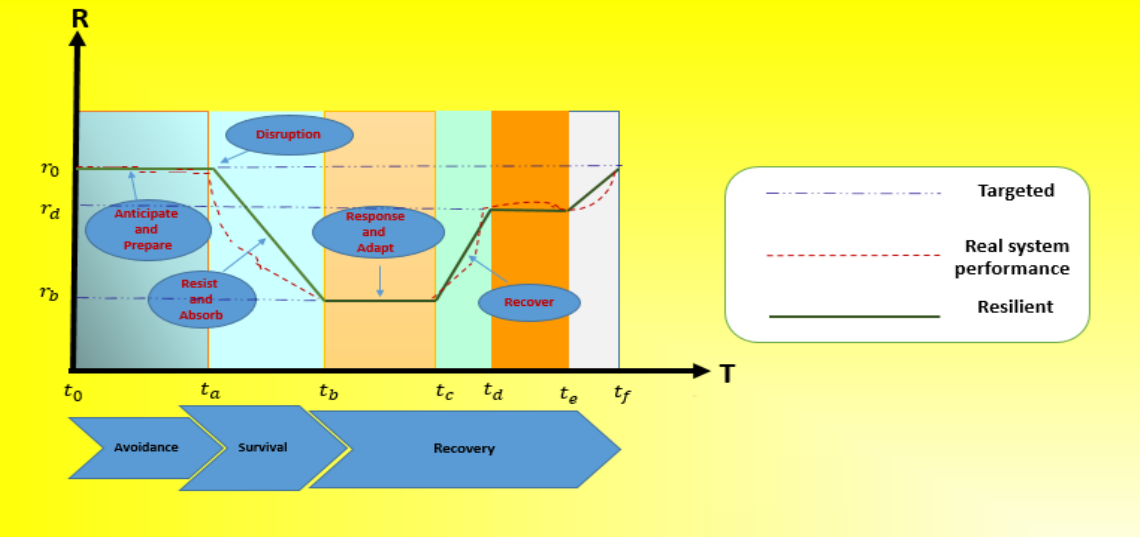


Figure 1. Events-related trapezoidal curve [4]

components an integrated metric to measure resilience and a hybrid model to show the failure behavior of the infrastructural systems.

2. 3. Framework Assessing and Improve Resilience

Research is growing on the assessment and enhancement of power system resilience. However, no unique framework for resilience has been agreed upon, and it still seems necessary to study methodologies and research challenges, formulate resilience reinforcement strategies, and develop definitions and indices. In 2007, the 'resilience triangle' (see Figure 2) was introduced as a guideline for resilience assessment. The resilience of engineering systems is proposed by Ren et al. [28] by using the resilience triangle model developed by MCEER. Panteli et al. [29], indices are presented for resilience quantification in which the resilience triangle is developed into a 'resilient trapezoid'. Francis and Bekera [30] proposed a framework for resilience assessment, which includes identifying and prioritizing the system, defining the system domain, describing main goals of the system, describing physical, chemical, spatial, and social properties, identifying analytical purposes, and analyzing system vulnerability and dynamic behavior. Then, considering the system performance, resilience goals are

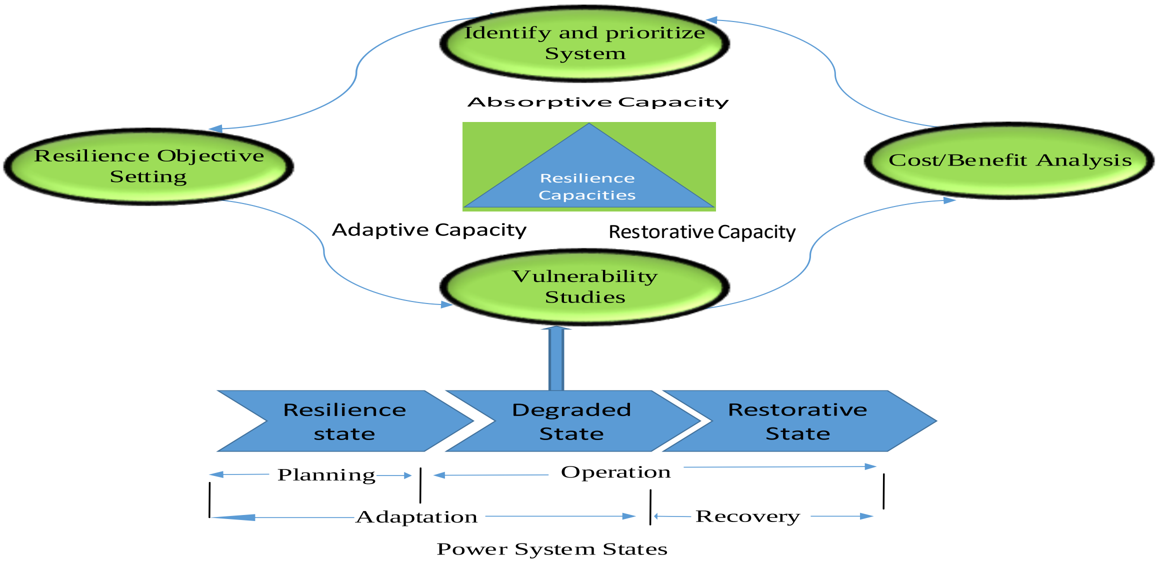


Figure 2. Power system resilience framework

set, and the stakeholders (profit/cost analysis) participate. The last component of the framework is resilience capacities, which encompasses absorption, adaptive, and recovery capacity. Engineering system resilience was explored by Mehrpouyan et al. [31] using the spectral graph approach. Engineering system redundancy, which enables increasing system reliability and decreasing vulnerability, was studied by Wang and Li [32]. A quantitative framework was proposed by Amirioun et al. [33] for the assessment of resilience and the application of microgrids in which destruction index (DI), recovery index (REI), and microgrid resilience index (MRI) are presented for describing the performance of system resilience. As depicted in Figure 3, the assessment of grid resilience, which is employed to assess grid status, compare the grid, and adopt arrangements for its resilience reinforcement, includes risk modeling.

Research around the world has focused on the assessment and reinforcement of the resilience of power systems against disasters [34]. On the other hand, engineers have been challenged by power system complexity and the range of incidents. Ouyang et al. [35], the features of severe incidents are ignored in resilience assessment. The resilience assessment and reinforcement strategies are expressed in details through the CIM method [36]. This part of the paper mentions solutions for resilience reinforcement (see Figure 4). All methods of resilience quantification cannot cover all resilience stages and overlap with other concepts, e.g., robustness and vulnerability [37]. Furthermore, some quantification methods for resilience estimation are inconsistent with the concept of resilience [38]. So, when responding to disturbances, it is necessary to develop a method for infrastructure resilience assessment. Zhang et al. [39] calculated the resilience during an incident within a three-stage framework, and the capacity of grid recovery is evaluated by the Monte Carlo simulation after the incident. The paper proposed an artificial metric system to calculate power system resilience performance. Indeed, contemporary research aims to develop infrastructures or minimize the losses of disastrous incidents [40].

2. 4. Resilience Metrics

Some definitions of resilience indices are provided by Ayyub [41] and discussed in detail by Hosseini et al. [42]. Two indices are provided by Barker et al. [43] for resilience, and one

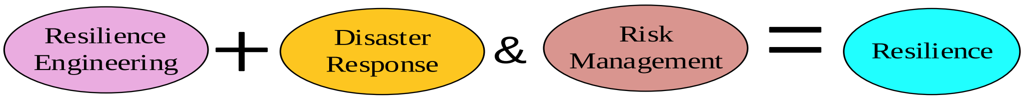
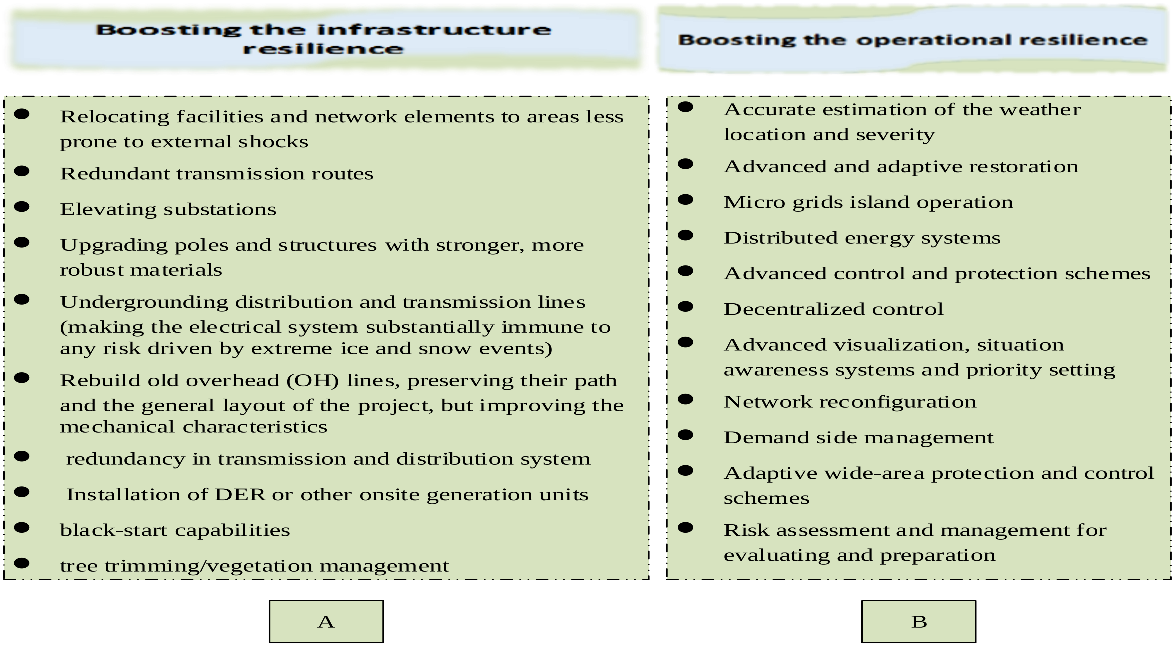


Figure 3. Strengthening the resilience of the power system



Boosting the infrastructure resilience

- Relocating facilities and network elements to areas less prone to external shocks
- Redundant transmission routes
- Elevating substations
- Upgrading poles and structures with stronger, more robust materials
- Undergrounding distribution and transmission lines (making the electrical system substantially immune to any risk driven by extreme ice and snow events)
- Rebuild old overhead (OH) lines, preserving their path and the general layout of the project, but improving the mechanical characteristics
- redundancy in transmission and distribution system
- Installation of DER or other onsite generation units
- black-start capabilities
- tree trimming/vegetation management

A

Boosting the operational resilience

- Accurate estimation of the weather location and severity
- Advanced and adaptive restoration
- Micro grids island operation
- Distributed energy systems
- Advanced control and protection schemes
- Decentralized control
- Advanced visualization, situation awareness systems and priority setting
- Network reconfiguration
- Demand side management
- Adaptive wide-area protection and control schemes
- Risk assessment and management for evaluating and preparation

B

Figure 4. A) The solution to strengthening the resilience of infrastructure. B) The solution to strengthening exploitation resilience [36]

new criterion of resilience was discussed by Hu et al. [44]. A benchmark was proposed by Zhao and Zeng [45] for resilience, considering the impacts of weariness and different vulnerability scenarios. Figure 5 displays resilience indices.

3. MODELS AND THEIR APPLICATIONS IN PLANNINGy

A wide range of studies have addressed the modeling of vulnerability, outage duration during disasters, and post-disaster system restoration, and most proposed methods assess post-incident damages. This section discusses some models used in expansion planning. Various models have been presented for resilience assessment, e.g., the OPA-based DC model [46] and the AC power flux model [47]. The storms damage to a power system is estimated by Guikema et al. [48]. Various methods have so far been proposed for GEP, including mathematical optimization methods, e.g., analytic hierarchy process [49], decision tree [50], dynamic planning [51], decomposition method [52], meta-exploratory optimization methods, e.g., evolutionary planning, ant colony optimization, frog leaping algorithm [53], and PSO [54], and exploratory methods [55]. Furthermore, GEP models are based on robust optimization in which unknown parameters are displayed by an uncertainty set introduced by Mejía-Giraldo and McCalley [56]. In 1997, linear planning was first used by Garver to solve a TEP problem in which transmission losses were ignored, and all constraints were linear [57]. Robust optimization (RO) determines unknown parameters by a set of uncertainties and uses renewable energy resources to describe the unknown nature [58]. RO needs less data than SP [59]. TEP has also been solved by using mathematical optimization techniques, which are harder to use because of nonlinearity and the number of constraints and variables. Branch-dependent method [60] and Benders decomposition techniques [61] have been used too. Two-stage optimization was used by Zhang and Conejo [62] as a framework to address uncertainty in TEP. It is also observed that meta-exploratory optimization methods are employed, such as the honeybee algorithm by Meza et al. [63], the chaos theory by Hedman et al. [64], the evolutionary differential system by Limbu et al. [65], the frog leaping algorithm by Roh et al. [66], smart systems such as genetic algorithms by Rahimzadeh et al. [67], all are useful to find globally optimal solutions but suffer from very slow convergence. In addition to classic methods, the decomposition methods mentioned above have also been employed for analyzing TEP problems. Although the Benders decomposition technique exhibits better performance when analytic methods are used, other methods have also been used to solve TEP problems, such as the internal point method to solve linear and nonlinear problems and the branch and bound method based on the Benders analytic decomposition.

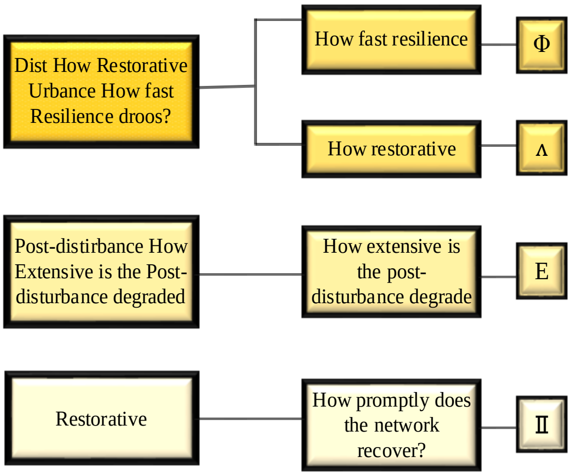


Figure 5. Resilience metrics

3. 1. Planning to Improve, Evaluate, and Resilience

Resilience reinforcement plans are divided into long-term, medium-term, and short-term plans. They are also categorized into single-stage problems (static planning) or multi-stage problems (dynamic planning). In static planning, no time horizon is set, and a plan is developed for a certain year, in which it is assumed that all new lines should be installed in the first year of the planning horizon. But, in dynamic planning, horizon years are studied separately, and new lines are specified for each year. Indeed, power system planning aims to establish resilience in the grid against natural disasters in a more robust manner. Studies have presented different optimization models, from mixed integer programming to quadratic planning and the more complicated stochastic planning, and more robust optimization, to facilitate the decision process. On the other hand, grid resilience should be improved in critical conditions (i.e., its capacity to cope with incidents and rapidly recover after disturbances) by corrective action – to minimize losses and recover the power system to its normal state after an incident – and remedial actions – to lead the power system to its normal state before an incident after load elimination [68]. Resource allocation is another key strategy for resilience planning. To minimize the effects of natural disasters and improve power system resilience, the use of distributed generation (DG) resources was proposed by Wang et al. [1], and the operational strategies that are converted into mixed integer linear programming by the linear scaling method were focused by Wang et al. [69]. As well the failure caused by the incident has been assessed. Defensive islanded schemes are used by Panteli et al. [70] in which the risk severity index, which can record the random and spatial impact, is employed to determine the application of these schemes. Also, the concept of the fragility curve, which expresses the probability of failure as a function of meteorological parameters, has been used. When natural disasters strike, operation strategies consisting of maintenance planning [71] and wide-area control, should adjust in response to communication failures [72] based on the present status of the system and related equipment, as well as the likely future states related to the climatic conditions. A power and natural gas system is suggested by Shao et al. [73] by replacing the underground gas lines to enhance resilience. However, no suggestion has made to eliminate the risk of fire. Gao et al. [74] found that structure, dynamics, and failure mechanisms of a grid determine its resilience. A system of systems (SoS) resilience assessment is proposed by Han et al. [75]. The dominant and analytical Markov chain technique is used by Kwasinski et al. [76] to evaluate and analyze resilience with the availability of fuel, and it used by Song et al. [77] with the availability of photovoltaics. To assess and reinforce the resilience of a three-step system, a metric is defined by Li et al. [78] for resilience and simulated different scenarios to analyze the grid structure against natural incidents. Despite the simplicity of these approaches, the simulation techniques, e.g., the Monte Carlo simulation, used by Arab et al. [79]; results show that they are more appropriate for studies on power system resilience. Panteli et al. [80] used mixed integer programming to evaluate incident effects on power system resilience. A robust optimization model is proposed by Xu et al. [81] to minimize restoration time and improve resilience. Lei et al. [82]presented a scenario-based two-stage stochastic optimization model before a natural disaster. In [83], reliability indices, such as loss of load probability (LOLP) and expected demand not supplied (EDNS) in the presence of microgrids, are employed to reinforce power system resilience. Since modern intelligent network technologies are effective in improving power system resilience and reinforcing power systems against extreme incidents [1], modern systems should be resistant in addition to purposefulness [84]. In research, systems have been hardened by underground electricity lines, vegetation cover management, so on, which also have been effective in resilience enhancement [85]. Wang et al. [86] proposed three-level planning to harden power and natural gas systems against disastrous incidents. A robust defense method is employed. Operation activities to reinforce resilience and to make a comparison for distinguishing system hardening and operating activities are given by Panteli et al. [87], in which frequency load shedding is employed for resilience assessment. Research has also used preventive strategies, e.g., grid topology re-adjustment, to enhance resilience. In [88], using a two-stage integer planning and an analysis-based algorithm, it is concluded that preventive response is preferred to emergency response in terms of resilience enhancement. Resilience can also be increased by topology switching. Other methods used to increase resilience and minimize outage costs include dynamic circuit reconfiguration [89], portable energy storage systems [90], emergency generators in the power grid [91], and back-start unit preparation [92]. Abbasi et al. [93] performed mixed integer nonlinear programming (MINLP) and the post-outage system restoration is discussed with the aim of resilience maximization. Offline restoration planning is performed by Golshani et al. [94] to reinforce grid resilience. The plan formulated is stochastic two-stage mixed integer linear programming with wind energy generation scenarios; the L-shaped integer algorithm is used. It is observed that the optimal wind harnessing strategy can contribute to improving both the restoration process and system resilience. MINLP is performed by Sarkar et al. [95] with a grid restoration approach. Stochastic planning is performed by Su et al. [96] to enhance resilience against disastrous incidents and minimize microgrid costs. Various methods have presented to model restoration and recovery time during natural disasters [97]. Bie et al. [98] proposed resilience assessment methods are explored, and a load restoration method. In [99], five restoration strategies are used for restorating the power and gas grids to analyze resilience. It is revealed that the ‘stochastic restoration’ strategy brings about the lowest resilience for both systems, and the ‘gas aimed’ restoration strategy is related to the highest resilience for the gas system. The estimation of system infrastructure failure and its post-incident restoration was addressed by Marnay et al. [100]. Liang et al. [101], proposed microgrids to enhance resilience in which loss of load reduction is regarded as the most effective resilient source, which has been subject to extensive research. Islanded microgrids were utilized by Pashajavid et al. [102] with centralized and decentralized approaches. A two-level optimization problem was studied by Hussain et al. [103] in the presence of multiple energy carrier microgrids, subjected to power and natural gas grid disturbances. In [104], investment cost and resilience enhancements are considered the constraint and objective function, respectively. However, investment cost and resilience enhancement are the objective functions [105] in which stochastic planning is performed considering the demand response plan and aiming to improve the resilience of microgrids, and solving the model by the constraint ε method. Resilience planning was carried out by He et al. [106] to improve the resilience of an integrated energy system. Recommendations were provided by Chen et al. [107] for solving resilience gaps. Indeed, resilience responses are divided into preventive responses (actions before incident scenarios) and emergency responses (actions taken due to the incident). They play a significant role in reinforcing resilience. In coordinated regional-district operation, an integrated energy system was used by Yan et al. [108] for resilience enhancement. Threat description, vulnerability assessment, recovery, and restoration were addressed by Paredes et al. [109]. In [110], a risk-aversion framework is proposed for more resilient planning and operation. Some studies have also investigated the impacts of critical conditions on power systems [111]. A model called CRISP is presented by Kelly-Gorham et al. [112] to measure power system resilience. In 2012, several parameters of resilience measurement were identified, and the resilience of a transmission grid was assessed for disastrous conditions by Henry and Ramirez-Marquez [113]. In 2017, grid resilience was evaluated under probability scenarios by two-level mixed-integer stochastic programming [114]. Also, two-stage stochastic optimization is proposed by Nagarajan et al. [115], in which the first level is grid investments and the second is the assessment of resilience enhancement related to the grid investment. Three-level optimization is proposed by Ma et al. [116] to minimize investment costs and to lose load. Planning was made by Gholami et al. [117] to enhance resilience in the presence of microgrids using the CVR technique. Power systems caused by cascading failure are analyzed by Xiao and Yeh [118]. Post-earthquake power system restoration planning is performed by Xu et al. [119], and seismic resilience is assessed by Anghel et al. [120]. Two criteria of repair time and resilience reduction are proposed by Fang et al. [121] to evaluate the criticality of power system components from their contribution to the system resilience viewpoint. Also, this method establishes a balance between risk and cost [122]. A mixed integer linear programming model is proposed by Teymouri et al. [123] for closed-loop controlled islanded systems in real-time to enhance resilience. In this paper, AC power flux reinforces resilience, and the recommended method exhibits saving on losing the load. Also, the sensitivity analysis indicates that the total loss of load increases as the delay time increases between line switching and loss of load. In recent decades, as power systems have been exposed to disastrous incidents, it has become imperative to use effective mechanisms for system resilience enhancement. Since most studies have focused on post-disturbance control intending to maximize demand, they are reviewed and analyzed here.

4. EXPANSION PLANNING

Developing goals of resilience, considering different scenarios, and expressing gaps provide opportunities for resilience enhancement, performed in three groups of GTEP and DEP. A comprehensive plan should reduce capacity and location of capacities, initiation time, frequency, severity, and duration of disasters, and improve resilience. The factors that should be considered in stochastic generation and transmission expansion planning are demand rate, availability of existing and candidate resources, and the capacity of the transmission lines.

4. 1. GEP Problem GEP is the most basic model in planning, and the type, location, and time of construction of generators must be determined in a time horizon of 20 or 30 years to meet the demand for projected loads. In generation expansion planning, the goal is to provide adequacy at the lowest cost. In 1955, the first long-term expansion planning was done in French. In 1957, Danzig and Taylor translated it into English, introducing the first linear planning (LP). Anderson, in 1972, showed that the nature of multi-stage generation expansion planning is similar to previous methods in dynamic planning. In 1976, linear expansion planning was to minimize investment and operating costs. Dehghan et al. [58] proposed linear programming of one-step and two-step integers with uncertainty in mind. A multi-stage generation expansion planning considering wind uncertainty has been used. A comprehensive review of generation expansion planning was conducted. Among which, Benders decomposition and Dantzig-Wolfe decomposition are more popular [124]. Also, stochastic optimization models based on scenario generation techniques with different uncertainties have been used [125]. In some studies, exploitation constraints have been included in generation expansion planning [126, 127]. Chen et al. studied GEP [128].

4. 1. 1. Uncertainty in GEP Some prevalent uncertainties in expansion planning include price volatility, reliability of generation units, demand evolution, investment, operating costs, and fuel and electricity prices. Dual uncertainty in the objective and constraint function is also presented by Hu et al. [129]. In GEP, the MCS method is commonly used to deal with uncertainties [130].

4. 2. TEP Problem Recently, transmission expansion planning has become a complex nonlinear optimization problem by determining which, where, and when new lines are to be built at the lowest total cost. In order to develop and strengthen transmission network capacity as well as ensuring future demand and integrating new power units with existing units have been considered by many researchers more than before due to technical/financial constraints along the planning horizon [131] and analysis of two critical issues of network reliability and security modeling [132]. Lumbreras and Ramos [133] presented a literature review up to 2016. Stochastic planning and robust optimization have been used to solve the problem of transmission and storage systems planning [135], for the development of transmission and storage systems, robust optimization reported in literature [134]. A multi-stage random model is used. Conejo et al. [136] presented a model for the simultaneous development of energy transfer and storage with a distinction between long-term and short-term uncertainty in a stochastic planning framework. Zhang and Conejo [137] presented a robust optimization framework that includes random scheduling. A robust optimization model was proposed by Moreira et al. [138] in the possible conditions although the security criterion of the worst-case n-k, and the decomposition algorithm is solved using the column and constraint method [139, 140]. The robust optimization model presented by Chen and Wang [141] identified uncertainties related to the development of future production capacity and the decommissioning of existing generation units. In, The AR-TEP model was presented by Mínguez and García-Bertrand [142] due to the uncertainty of load demand and production capacity. A two-stage AR-TEP model was proposed by Jabr [143], to introduce the uncertainty of loads and renewable energy sources using a decomposition algorithm that finds the optimal investment and minimum cost of fines related to limiting renewable energy loads and sources.

4. 2. 2. Uncertainty in TEP

The problem of TEP is usually with the uncertainty of load forecasting and availability of power system equipment, market uncertainty [144], energy and risk [145], and technology and new forms of production. Based on the results, the researchers found that considering uncertainty leads to better transmission expansion planning. The most common methods for dealing with uncertainties are the mathematical model [146]. The fuzzy approach is used to model uncertainty [147]. The application of DG in transmission development planning has also been investigated.

4. 2. 3 TEP and Improve Resilience

Enhancing resilience and reducing the density of TEP have been increasingly considered by researchers and have been addressed by Zhao et al. [148]. In 2015, transmission network optimization was carried out by Fang ey al. [149] to strengthen the resilience of the power system against cascading errors and minimize investment costs. The impact of fire on transmission development planning was presented by Choobineh et al. [150]. The optimization framework is illustrated by providing the formula of MILP to track the redistribution of power flow DC and the evolution of the theoretical diagram of the network topology during cascade failures and, in the next step, determine the effect of acceleration [151]. Interaction after disruption of system resilience has been suggested to be the worst case of disorder. Whereas some lines are overloaded and some lines have empty capacities after redistribution of power flow due to line interruption, optimal changes in line reactance reduce the flux in overloaded lines and transfer them to lines that have unused capacity. Romero et al. [152] presented the (MIP) model for investment arrangements under terrorist threats. Panteli et al. [153] also presented MCS to evaluate the impact of weather on power system equipment focusing on the effect of wind on transmission lines, using fragility curves that express the probability of equipment failure as a function of wind speed. Arroyo and Galiana [154], Motto et al. [155] used two-level TEP to identify the power system's key elements and to identify the sensitive transmission lines. One of the crucial advantages of transmission expansion planning is its resilience to the worst-case scenarios, which is vital for strengthening the resilience of power system infrastructure.

4. 3. GTEP Problem

GTEP is the most important part of power system planning. Recently, extensive research has addressed concurrent generation and transmission expansion planning (CGTEP) [156], but we are trying to provide a more comprehensive paper. Multi-objective CGTEP was conducted by Tekiner et al. [157] to minimize operational, investment, and emission costs. A three-level model of decentralized GEP and centralized TEP was studied by Javadi and Esmaeel Nezhad [158] using the epsilon method, in which multiple stochastic points are considered along with the load demand uncertainty. A two-level model was presented by Jenabi et al. [159], for the trade between generation and transmission investment and is transformed into a single-level mixed integer linear problem. Probabilistic multi-objective planning was performed by Mavalizadeh et al. [160] to reduce investment costs and adverse environmental impacts. Guerra et al. [161] presented coordinated planning under the constraints on pollutant emissions, storage, and load response programs. Coordinated planning was addressed by Zhang et al. [162] considering load response plans. In the coordinated expansion of power systems and gas grids was planned by Hu et al. [163] under uncertainty and the effect of a wind turbine. Muñoz-Delgado et al. [164] presented a dynamic planning considering grid uncertainty and reliability. Integrated generation and transmission expansion planning models were designed by Baringo and Baringo [165], considering uncertainty. The critical advantage of optimal expansion planning models is the calculation of uncertainty parameters with large dimensions, which does not need probabilistic models or the application of specific probability distributions. Unsihuay-Vila et al. [166] discussed on linear planning of mixed integer coordinated generation and transmission expansion. An exploratory algorithm was used by Alizadeh and Jadid [167] for dynamic

CGTEP in which the power system reliability is assessed within a linear framework. The same method was used by Alizadeh and Jadid [168] in the static form. Interested readers can find more details on GTEP problem-solving [169].

4. 3. 1. GTEP and Improve Resilience To strengthen resilience, a static GTEP was developed by Romero et al. [170] with a scenario-based approach for the analysis of earthquake effects. Studies have dealt with cost reduction, system losses, and increasing grid reliability. However, the alleviating of power system vulnerabilities to deliberate invasions should also be considered [171]. The static model of coordinated planning for GTEP [172], which aims to reduce the side effects of deliberate attacks on the transmission lines and minimize investment and operational costs, can also reduce the power system vulnerability. A scenario-based framework was described by Vaziri et al. [173] in response to seismic incidents. To reduce earthquake-induced power outages, a maintenance plan was studied by Çağnan et al. [174] in which the incident damages are ignored. A four-level planning model was described by Shivaie et al. [175] to reinforce a 400-kV grid in Iran for assessing seismic events. In An instrument was used by Cervigni et al. [176], to investigate the strategies for enhancing infrastructure resilience in Africa against natural disasters. The optimization of integrated GTEP is dealt with in the US in a time frame extending to 2050 [177].

5. TRENDS AND CHALLENGES

Since electricity cannot be stored, the operator will be faced to multiple challenges in any planning horizon. Therefore, optimal power system operation needs optimal planning. Since a resilient power system is capable of predicting possible disasters, taking practical actions to reduce losses and damages to the system components, and restoring the system to the pre-incident state, the investigation of its different aspects is crucial for organizing future research. On the other hand, researchers try to transform societies into resilient societies against disasters, in which case the infrastructure will be operated more efficiently. Still, it will result in system vulnerability and cascading errors. As power engineers, we can build reliable and resistant grids. The most obvious way is to build resilient grids, and an economical practice is to make further investments. With more information on the concept of resilience, this problem can be solved. Rezaei et al. [178], have listed the key challenges, constraints of modeling, and resilience enhancement activities. The first step to accomplishing resilience is to study vulnerability. Resilience enhancement activities are first prioritized based on their significance. Some activities are better in terms of resilience, and others are more economical. Eventually, a profit/cost analysis is undertaken. In the next step, the resilience activities can be categorized and fulfilled based on the resilience indices, which will contribute to building power infrastructure and satisfying resilience needs and the need for being economical. When or after a disturbance happens, resilience is analyzed to understand the infrastructure behavior to be more capable of preventing damage. Presently, the deployment of sensors for data collection has opened a new way to understand system resilience reinforcement by data analysis. For instance, machine learning can be used to analyze the collected data. However, there is still a huge gap between big data and significant impacts, while research is rare on it. Factors such as reliability, electricity market [179], uncertainty [180], environment, distributed generation, modeling, line density, reactive power planning, FACTS instruments, and demand-side management (DSM) are effective in resilient planning. On the other hand, the investigation of GTEP challenges in this paper lays the ground for future research. Based on the literature, the presence of distributed generation resources in planning helps develop an optimal plan and reduce costs [181]. As well, reactive power is essential for GTEP, which should be considered by researchers in their attempts to accomplish optimal planning. On the other hand, integrating reactive power planning with GEP will result in more optimal planning, so it is better to consider it in future studies. Research should explore uncertainties and FACTS instruments, e.g., TCSC, SSSC, UPFC, and IPFC, in TEP. Demand management programs, e.g., DSM, are mainly influential in the result of planning, but they have not been adequately studied in research on generation and transmission expansion planning. Microgrids have extensively been used in generation and transmission expansion planning in the studies, which has had good results too, so it has been presented as the most effective way of resilience enhancement. On the other hand, research has shown that energy hubs will be very effective. It is an emerging concept in the issue of power system resilience. This is a contribution of this article, which the authors will address in their future studies. It should be noted that some studies have neglected reliability and security in planning. In contrast the inclusion of reliability contributes to developing a resilient and reliable plan, as many researchers have mentioned as a pressing issue. Almost all studies have considered investment costs to minimize costs or maximize social welfare. However, operational costs are also crucial for a significant planning horizon, so they should also be studied within the model. Therefore, generation and transmission expansion planning are a key factor in long-term power system operation. On the other hand, it has been revealed by the studies that multiple energy supply systems will also help enhance resilience.

6. CONCLUSIONS

Power systems have recently been exposed to disturbances induced by natural disasters, have influenced global security and economic benefits. So, we have to use techniques to assess the effect of these incidents. On the other hand, it is crucial to plan power systems that are resistant to high-impact, low-probability events. Since incidents may have irreparable consequences for power systems and their components, the issue of enhancing system resilience against disasters has become an essential requirement for smart grids. This paper provided resilience definitions and indicators in detail and identified different strategies and technologies for resilience enhancement. Also, the research papers on models were comprehensively reviewed, and the assessment of GTEP separately and concurrently, which is sophisticated and challenges the analysis of the results, was discussed. Finally, the paper mentioned the trends and challenges of the expansion models and my contribution. Indeed, the authors intended to provide a comprehensive review of concurrent GTEP aimed at improving grid resilience and give a general understanding of its effectiveness in improving system performance. In other words, a system is resilient when it can tolerate unexpected disturbances or restore itself rapidly after the incidents. So, it is vital to be able to assess incidents to evaluate and enhance power system resilience against them. This paper is a comprehensive context to find different ideas for future work.

7. REFERENCES

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Persian Abstract

چکیده

از آنجایی که سیستم‌های قدرت در معرض آسیب‌های ناشی از حوادث فاجعه‌بار هستند، ارزیابی و بهبود تاب آوری سیستم به عنوان یک هدف جدید برنامه‌ریزی و عملیات اجتناب‌ناپذیر است. از سوی دیگر، توسعه شبکه‌های تولید و انتقال، بخش مهمی از برنامه‌ریزی سیستم قدرت را تشکیل می‌دهد، زیرا نیاز به بودجه هنگفتی دارد. بنابراین، یکی از دغدغه های اصلی محققان همواره برنامه ریزی بهینه سیستم های قدرت بوده است. این مقاله به بررسی مفهوم نوظهور تاب‌آوری، معیارها و شاخص‌های آن، نحوه ارتقای آن و شناسایی نقاط قوت و ضعف آن می‌پردازد. همچنین استراتژی های توصیه شده در مطالعات برای بهبود تاب آوری سیستم قدرت را بررسی می کند. این مقاله به طور خلاصه مدل‌های تحلیل طرح توسعه و ابزارهای برنامه‌ریزی توسعه تولید و انتقال را با یا بدون هدف تقویت تاب آوری گزارش می‌کند، که می‌تواند در تحقیقات آینده ابزاری باشد و جهت تخمین اثربخشی ابزارهای مختلف استفاده شود. علاوه بر این، این مقاله مشکلات برنامه ریزی را مورد بحث قرار می دهد و در نتیجه راه را برای کار بیشتر در مطالعات آینده باز می کند. در نهایت، این مقاله مهم‌ترین چالش‌های برنامه‌ریزی توسعه تولید و انتقال را برای انجام برنامه‌های بهتر، تاب آور و نوآورانه جهت تقویت تاب آوری سیستم قدرت ارائه می‌کند.