Identifying Critical Elements to Enhance the Power Grid Resilience

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***Abstract*—The resilience of a power system refers to its ability to resist and recover from multiple physical failures under extreme operation conditions. In this paper, we study the power grid resilience considering different time scales of recovery strategies and propose a method for identifying critical elements whose physical damage can significantly degrade the resilience of a power system. The maximum power supply (MPS) of the remaining network containing the elements that are not physically damaged is obtained and used to indicate the resilience performance of the system. We identify the critical elements in the grid by iteratively selecting and removing the link with the lowest MPS. We do simulations in the IEEE 118 Bus case to evaluate the grid resilience under various extremes and test the proposed strategy. Simulation results validate the efficacy of our proposed method in the identification of critical elements.**

I. Introduction

The power system is playing a more and more important role in human behaviors with the continual deepening of electrification. The power system's ability to maintain its functions under various conditions has profound influences on society as the interruption of power supplies can make society fall into disorder.

Electric engineers have been making every effort to enhance the security of the power system in the face to disturbances, which mainly lies in the following two aspects: The power between the generators and loads should be real-time balanced; The electrical parameters of the elements should be within their corresponding capacities [1]. Since the birth of the first power grid at Godalming, England in 1881, the operation practices and research efforts in real power systems have accumulated a series of control and protection strategies to ensure the above two aspects [2]. The primary frequency response and the automatic generation control (AGC) are two most classical control technologies used to resist disturbances. The local protection based on protective relays, the remedial action schemes relying on the communication network, and the system splitting techniques are designed for the system protection.

In practice, as the power system broadens its geographical coverage and is exposed to wild environments and weather conditions, it is subject to various disturbances with distinct intensities. For small disturbances, like normal load fluctuations, the failure of a single element, and so on, the system can keep its integrity and operate normally. For example, the power system is required to meet the n-1 criterion, i.e., it should have the ability to withstand the failure of any single element. While, there can occur strong disturbances, under which the power system is unable to retain the complete functioning.

In history, human societies suffered many interruptions of power supplies as the power system was severely damaged by the extremes, including man-made attacks and natural disasters. In 2008, a heavy snow damaged 129 transmission lines in the Southern China Grid, leaving 14.66 million households out of power. In 2011, the Great East Japan Earthquake damaged Japan's power grid and caused power outages for over 4 millions households. The power restoration took more than seven days. In 2012, millions of people in America suffered from power blackouts due to Hurricane Sandy [3]. Due to the limited ability, a portion of power losses are inevitable when the power system is under such extreme operation conditions. In this context, the concept of power grid resilience, which refers to the grid's ability to quickly recover from extremes [4], is put forward and draws much attention from governments, electric industries and academies. The governments of many countries have associated the grid resilience with the national security and launched projects on enhancing the grid resilience [5], [6]. The National Academies of Science, Engineering and Medicine of America published an important report [8] targeting at discussing the resilience enhancement of the nation's grid. The influential journal "Proceedings of the IEEE" arranged a special issue to present the most recent research results on the power grid resilience in 2017 [7].

Compared with the robustness analysis that studies the failure cascade process from initial faults to the final power blackout [9], [10], the power system resilience study focuses more on recovery processes following intensive disturbances. In a conventional power blackout, the protective relays trip the overloaded electrical equipment to protect it from being physically destroyed. Thus, the power restoration by properly switching on circuit breakers and restarting the shutdown elements can be completed quickly. But extremes, like hurricanes, earthquakes or even high-altitude electromagnetic pulses (HEMPs), can physically damage a set of elements in the power system, which greatly prolongs the recovery time. The recovery process after extremes should be carefully modelled by taking into consideration the various repairing strategies and their practical limitations. Though the concept of grid resilience has been widely discussed in recent years, according to our knowledge, the different time scales in recov-

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ery processes have not been distinguished or well considered.

In this paper, we assess the resilience of the power grid and identify the critical elements. A revisit to the power grid resilience is firstly given in Section II. Different from previous related work, we divide the recovery process following the extremes into a succession of periods with different time scales. In Section III, we obtain the maximum power supply (MPS) that can be achieved by fully utilizing the remaining undamaged components and use it as an important indicator for the power grid resilience. Then, based on this model, we identify the set of critical elements by iteratively removing one element that has the lowest MPS in the network in Section IV. Simulation results show that our proposed method can effectively locate the critical elements in the grid, a very small number of which gravely threaten the resilience of the power system. Our work can provide instructions for the power system operation on how to make the best use of the available resources in the face to extremes as well as give useful hints for the power system planning on how to hardening critical elements to effectively enhance the grid resilience.

II. Revisit to Power Grid Resilience

In this section, we provide a revisit to the life cycle of the grid resilience.Figure 1(a) shows the resilience trapezoid that is widely used by researchers to demonstrate the system evolution after a disaster. It mainly has three stages: In the disturbance progress, the disaster physically damages a set of components in the power network, and part of its function is lost, leading to the decrease of the power supply, denoted by $F(t)$. Then, it gets to the post-disturbance degraded state, where the system operates in the worst state, with $F(t)$ being the minimum; In the third stage, due to the recovering methods applied, the system's power supply gradually restores till fully recovered. Though this sketch map contains the function degradation and restoration procedures, it is unable to realistically reflect the correct time scales of various events in the resilient process.

Though the extremes can physically damage electric elements in a power grid, they normally last for a comparatively short time with most finished within hours. Usually, initial intensive disturbances cause a series of cascading failures under the system control and protection techniques applied. Thus, the power supply can decrease rapidly after the disturbance and the system soon reaches a worst condition.

We should also recognize that the power grid is a typical adaptive complex system. Power engineers will try their best to repair and restore the system to its optimal stage states with available strategies. Among the various recovering methods, the switching on, restarting, and adjusting of tripped elements can be done very quickly, compared with repairing or exchanging the physically damaged elements that can take as long as several months or years. In our model, we assume that the power system will quickly reorganize the available undamaged elements to achieve the maximum power supply. Figure 1(b) is our fixed sketch map for demonstrating the

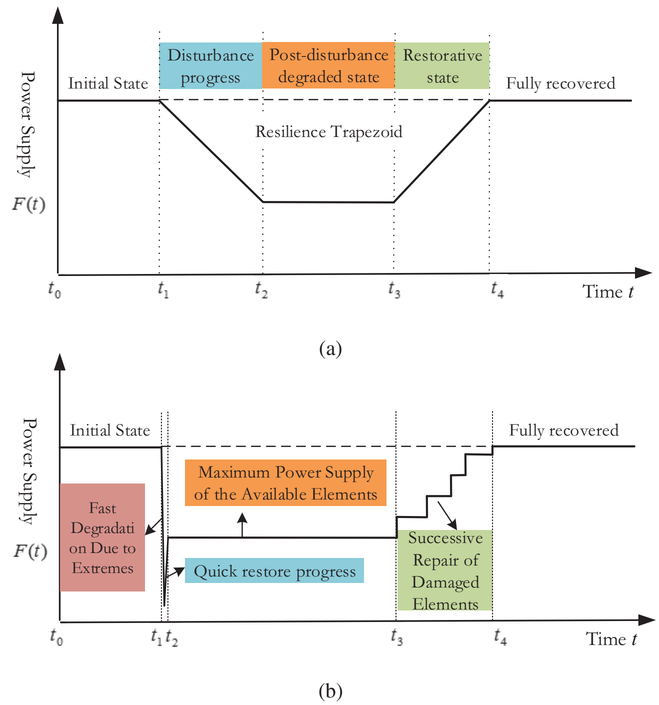

Fig. 1. Sketch maps for illustrating a life cycle of the power grid resilience from the effects of extremes to the fully recovered state: (a) Resilience trapezoid that is widely used in literature; (b) A fixed illustration considering different time scales of repair strategies.

resilience process. The violent functioning degradation and quick restoration complete in period (t_1, t_2).

Then, the power system will operate at this state for a comparatively long period, i.e., (t_2, t_3) in Figure 1(b). With the slow repairs of the physically damaged elements successively finished, the power supply will be restored step by step till fully recovered, as demonstrated in period (t_3, t_4).

Through the above analysis, we classify the recovery procedures by the different time scales. For each recovery procedure, a suitable model should be used for in-depth study.

III. Resilience Assessment of Power Grids

In this section, we assess the resilience of a power grid.

A. Model Description

A power system is a network of interconnected nodes and links, denoted by $G = \{L, N\}$, where L is the set of links and N is the set of nodes (buses). Figure 2 gives an illustration of the power links and nodes in our model. We consider two kinds of nodes in N: the generator node where a connected generator injects power into the grid and the load node where a electric consumer absorbs power from the grid. The transmission lines and transformers that connect the nodes in the power system are represented by links.

For a node $i \in N$, we consider three attributes: C_i represents its operating limits, exceeding which node i will be tripped and removed from the network; f_i describes its nodal dynamics; s_i represents its state. $s_i = 0$ represents that node i can operate normally; $s_i = 1$ represents that node i is tripped and can be

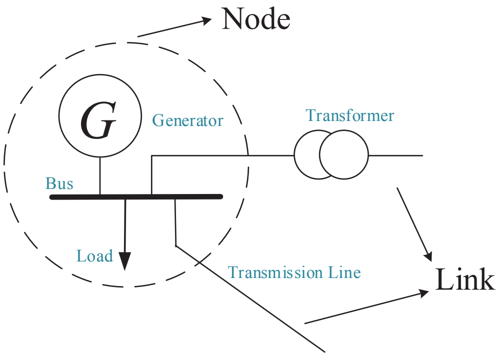

Fig. 2. Illustrations of nodes and links in a power grid.

quickly reconnected; $s_i = 2$ represents that node i is physically damaged and the repair will take a long time.

Similarly, a link $ij \in L$ that connects node i and node j has three attributes: C_{ij} represents its power flow limits; a_{ij} represents its admittance; s_{ij} represents its state. $s_{ij} = 0$ represents that link ij can operate normally; $s_{ij} = 1$ represents that link ij is tripped and can be quickly reconnected; $s_{ij} = 2$ represents that link ij is physically damaged and the repair will take a long time.

The power supply of G at time t is denoted by $F\{G(t)\}$. For different recovery periods, different models should be used for the calculation of $F\{G(t)\}$, i.e., different f_i. The system dynamics in the fast process (t_1, t_2) should be described with differential equations and state transition methods. While, for the slow process (t_2, t_4), steady-state power flow models are feasible.

B. Resilience Measures

As the period (t_2, t_3) occupies a large portion of the whole resilience life cycle, the MPS in this period is an important indicator of the grid resilience. In this paper, we fucus on the MPS that can be achieved by the fast restoration techniques, i.e., $F_{\max}\{G(t_2)\}$. In the following, we present the method for obtaining this maximum value.

First, due to the physical damages of elements in G by the extremes, the remaining network can be spit into several interconnected clusters. The total MPS is the sum of MPS of all the clusters.

Second, let G_0 represent one of the interconnected clusters that contain elements with states 0 or 1. $F_{\max}(G_0)$ is the maximum power that G_0 can provide to its loads. We detect all the clusters in $G(t_2)$ and obtain $F_{\max}(G_0)$ for each cluster.

Third, as the period (t_2, t_3) is a slow process, we use a steady-state model, where the active power outputs of the generators and the power demands of loads can be tuned within their corresponding capacities C_i, the power flow across the transmission lines and transformers cannot exceed C_{ij}, and the DC power flow model [1] is used to obtain the power flows.

The acquisition of $F_{\max}(G_0)$ can be suitably converted to an optimization problem, with the objective function being as follows,

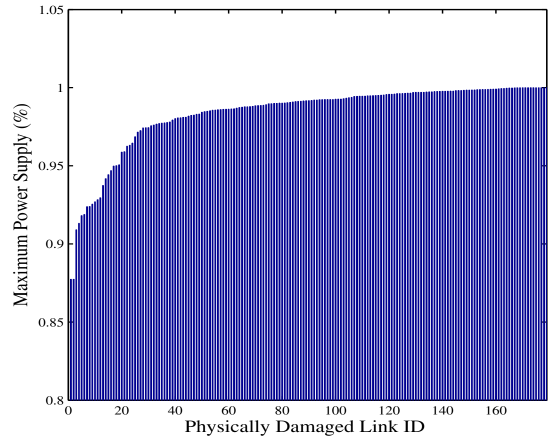

Fig. 3. $F_{\max}\{G(t_2)\}$ after the physical failure of single links in IEEE 118 Bus.

$$F_{\max}(G_0) = -\min \sum P_i, i \in N_l \tag{1}$$

subject to

$$\begin{aligned} &p_{ij} = a_{ij} * (\theta_i - \theta_j), \\ &-C_{ij} \le p_{ij} \le C_{ij}, \\ &\mathbf{A}\theta = \mathbf{P}, \\ &-C_i \le p_i \le 0, i \in N_l, \\ &0 \le p_i \le C_i, i \in N_g. \end{aligned} \tag{2}$$

where N_l contains the load nodes in G_0, and N_g contains the generator nodes in G_0; P_i is the active power injected to the grid through node i, and P_i is positive if $i \in N_g$ while negative if $i \in N_l$; $\mathbf{P}$ is the vector of P_i; θ_i is the phase angle at node i, and θ is the vector of θ_i; $\mathbf{A}$ is the admittance matrix of G_0.

We do simulations in the IEEE 118 Bus test case, the system parameters and the original power flow distribution of the complete case are from Matpower [11]. We set the capacities of the links as 1.2 times of their original power flows, and the capacities of the nodes as their original power injections. Figure 3 shows maximum power supplies of the IEEE 118 Bus after the physical failure of single links. The results are displayed in the ascending order.

IV. Identification of the Critical Elements

From Figure 3, we can see that the power system is heterogeneous, with the roles of different elements in a power network being distinct. The power grid's functioning can be unaffected by some elements' failure. While, the failure of a few critical elements can significantly decrease the MPS of the remaining network. This set of critical elements are also called the lifeline of the grid. Power engineers always pay close attention to the identification of the grid's lifeline, through hardening which the grid resilience can be efficiently improved. In this section, we compare different strategies for identifying the set of critical elements in a power grid, whose physical damage can degrade the grid resilience drastically.

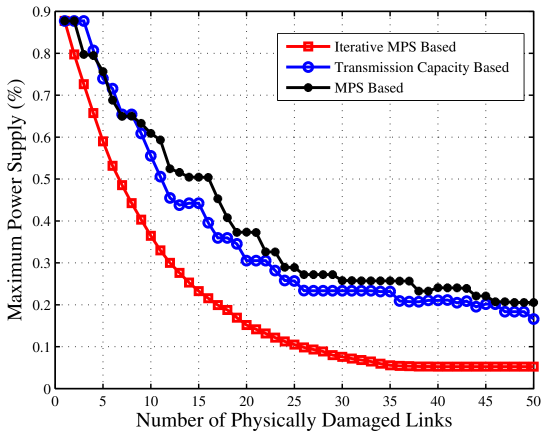

Fig. 4. Comparison of the three strategies for critical element identification.

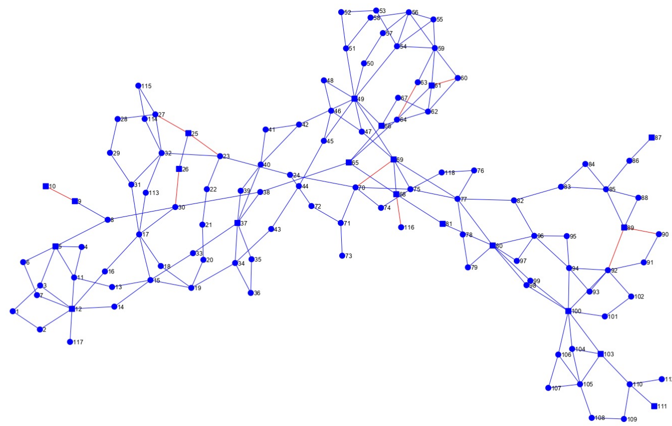

Fig. 5. Graph layout of the IEEE 118 Bus: circles represent load nodes; rectangles represent generator nodes. The ten most critical links identified based on Strategy 3 are colored red; the blue elements are not physically damaged by the extreme.

Intuitively, the links with large power flows or with low MPS as shown in Figure 3 are more likely to be considered as critical elements. Thus, we first examine the following two strategies.

Strategy 1: The links in the power grid are arranged in the descending order of their power flows, and the set of critical elements are generated by selecting a number of the corresponding top-ranked links.

Strategy 2: The MPS of each link is calculated in the IEEE 118 Bus. The links in the power grid are arranged in the ascending order of MPS, and the set of critical elements are generated by selecting a number of the top-ranked links.

We further propose a strategy based on iterative link removals. Strategy 3 is as follows: A specific number of simulation rounds are conducted. In each round, the MPS of each link in the remaining network is obtained. The link with the lowest MPS is selected and removed from the network.

Figure 4 shows the simulation results of the three strategies. We can see that, compared with the two intuitive strategies, our proposed method can more effectively identify the critical elements in a power grid in terms of the grid resilience. The curve derived by Strategy 3 in Figure 4 also shows that the physical damage of only a few critical elements can lead to catastrophic losses of the grid. For example, the physical failure of the ten most critical links in the IEEE 118 Bus (occupying less that 0.6% of the total links) based on our proposed strategy, can make the MPS of the remaining network be lower than 40%. Figure 5 shows the graph layout of the IEEE 118 Bus, where the ten most critical links identified by Strategy 3 are colored red. If these elements are hardened, the resilience of the grid can be effectively as well as economically enhanced.

V. Conclusions

In this paper, we assess the power grid resilience and identify critical elements in the grid. The life cycle of the grid resilience is divided into different periods by considering different time scales of the recovery strategies. We argue that suitable models should be used for depicting system behaviors of different periods. The maximum power supply of the remaining network consisting of the elements that are not physically damaged during the extremes is obtained with optimization methods and further used to indicate the grid's resilience performance. Then, we propose a method to identify the critical elements by iteratively calculating the updated MPS of each remaining link and removing the link with the lowest MPS from the network. Simulation results for the IEEE 118 Bus test case show that our proposed method can effectively identify the critical links in the grid, whose physical failure can lead to catastrophic power losses. Our work can provide useful hints for the power system operation and planning on the resilience enhancement. Future work includes analyzing the characteristics of the critical elements and optimizing the grid topology and the generators' locations.

Acknowledgment

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