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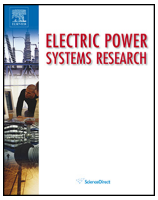

Multi-phase assessment and adaptation of power systems resilience to natural hazards

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ABSTRACT

Extreme weather hazards, as high-impact low-probability events, have catastrophic consequences on critical infrastructures. As a direct impact of climate change, the frequency and severity of some of these events is expected to increase in the future, which highlights the necessity of evaluating their impact and investigating how can systems withstand a major disruption with limited degradation and recover rapidly. This paper first presents a multi-phase resilience assessment framework that can be used to analyze any natural threat that may have a severe single, multiple and/or continuous impact on critical infrastructures, such as electric power systems. Namely, these phases are (i) threat characterization, (ii) vulnerability assessment of the system's components, (iii) system's reaction and (iv) system's restoration. Second, multi-phase adaptation cases, i.e. making the system more robust, redundant and responsive are explained to discuss different strategies to enhance the resilience of the electricity network. To illustrate the above, this time-dependent framework is applied to assess the impact of potential future windstorms and floods on a reduced version of the Great Britain's power network. Finally, the adaptation cases are evaluated to conclude in what situations a stronger, bigger or smarter grid is preferred against the uncertain future.

1. Introduction

Natural disasters around the world, such as floods, ice and windstorms, hurricanes, tsunamis and earthquakes, have had a significant impact on countries' public security and economic prosperity [1]. Furthermore, it is expected that these events may occur more often and with greater severity, mainly because of global warming and climate change [2]. Therefore, it is a necessity to develop techniques for assessing the impact of natural disasters in a comprehensive and systematic way, which will enable the resilience enhancement to these catastrophic events.

Electric power systems, as critical infrastructure, are the backbone of modern societies. It is therefore crucial to design power systems that are resilient to potential high-impact low-probability events that may be driven by natural hazards and related to climate change. Within power systems, the concept *resilience* can be broadly defined as the ability of a power system to withstand the initial shock, rapidly recover from the disruptive event and apply adaptation measures for mitigating the impact of similar events in the future. A comprehensive resilience framework is presented in [3], where five key resilience elements are used to associate the short-term resilience of power systems to an event as well as their long-term resilience, namely: robustness/resistance, resourcefulness, redundancy, response and recovery, and adaptability. These key elements can be seen in the existing research for assessing the impact of earthquakes, hurricanes and windstorms on the electric power systems [4–7].

In [4], a joint effort of European universities analyzes the impact of earthquakes on various cities and different critical infrastructures, including the power system of Sicily. This study includes the use of fragility curves and an object-oriented programming to assess the pre- and post-disaster performance of the network. In [5], the impact of windstorms is analyzed using wind fragility curves, running DC optimal power flows on the IEEE-6 bus reliability test system and comparing different adaptation cases. The resilience of the electric system of Harris County, Texas, US, is evaluated in [6] by running four models: hurricane hazard model, components fragility model, power system response model and

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restoration model. The results are classified in technical, organizational and social dimensions of resilience. In [7], micro-components of the transmission network under seismic stress are modeled to assess the resilience of the power system in Los Angeles, US. The vulnerability is also modeled with fragility curves and, as a result, risk curves are developed. Another notable effort towards practical use that has involved software developments is Hazus, from the Federal Emergency Management Agency [8]. Other governmental programmes, which share the concept of resilience with the present paper, include Ergo-EQ, from Mid-America Earthquake Center [9], Rt, from In Risk—a project funded by Natural Sciences and Engineering Research Council of Canada [10], and the Central American Probabilistic Risk Assessment (CAPRA), a platform developed by Central American Governments [11]. Even though the recent work on the topic has been a huge step towards understanding and measuring resilience, further research in this area remains a concerning issue given the consequences of these and other catastrophic threats to different systems around the world.

The novelty of this paper lies in the formalization of a multi-phase resilience assessment framework along with multi-phase strategic adaptation cases to enhance the resilience of critical infrastructures, with focus on electric power systems and weather hazards. In particular, the main phases of the proposed resilience assessment framework are: (i) *threat characterization*, (ii) *vulnerability of the system*'*s components*, (iii) *system*'*s reaction* and (iv) *system*'*s restoration*, and the *enhancement* or *adaptation* strategies for the second, third and fourth phases are: (i) *normal case*, (ii) *robust case*, (iii) *redundant case* and (iv) *responsive case*, respectively [5,12].

In brief, given the magnitude and time profile of the weather-hazard, the concept of fragility curves is used, which provides the failure probabilities of the power system's components as a function of a weather parameter (e.g. wind speed) at any given time. By mapping the time-series weather profile to these fragility curves, the weather-dependent failure probabilities are obtained, which are then fed to a Sequential Monte Carlo-based simulation. This altogether allows the stochastic and spatiotemporal modeling of the natural hazards as they move across the system. In order to account for the uncertainty associated with the projected severity of weather events in the future, parametric studies and extreme value theory (which provides different intensities of weather events depending on the chosen return periods) are applied for analyzing a wide range of potential future scenarios. The multi-phase resilience assessment tool presented in this paper provides thus a systematic approach for evaluating the impact of extreme weather events as a direct impact of climate change, as well as investigating different ways for improving the resilience of power systems to such catastrophic events.

The organization of the paper is as follows: in Section 2, the influence of extreme weather and climate change on power systems is described. Then, in Section 3, the four-phase resilience assessment framework is outlined along with enhancement measures and the strategic adaptation cases. Thereafter, in Section 4, the resilience framework and adaptation cases are applied using a reduced version of the Great Britain's power system for assessing the impact of different scenarios of windstorms and floods on the test system. In Section 5, the simulation results are presented. Finally, Section 6 summarizes and concludes the paper.

2. Influence of extreme weather and climate change on electrical power systems

Many natural threats can include not just one single instantaneous impact, but multiple and even continuous impacts. For instance, the windstorms that affected China in 2005 produced more than 60 high voltage transmission towers to collapse, and the ice and snowstorms that devastated a large area in the south of the country lasted for hours [13]. Disasters can even last for days, like the hurricane Sandy in the US, where numerous substations, lines and transformers were damaged resulting in power outages across 16 states [1]. Most recently, two earthquakes hit Nepal in less than 20 days, producing devastating effects [14]. In a similar way, Chile was impacted in 2010 by an earthquake and tsunami followed by a severe replica within two weeks [15]. Therefore, it is imperative to develop a comprehensive analysis combining a suitable period of time and in a time-dependent way. So as to answer questions as: What hazard's intensity can the system withstand? How is the restoration going to be managed and in what time? What happens if a second impact occurs?

2.1. Extreme weather events

A disruptive weather event can be classified into small, moderate, serious, major and extreme based on the number of customers disconnected, the duration and frequency [16]. Great Britain is significantly affected by weather-related electrical faults.

In [17], it is reported that only from April 2008 to March 2009, 211 faults occurred on the transmission network in England and Wales and further 44 in Scotland, of which 23 and 95%, respectively, were caused by weather. For example, several transmission substations and power stations are at high risk of flooding, while high winds can cause transmission lines and towers to collapse. The Climate Change act of 2008 required that the UK electricity industry reported on adaptation measures to deal with the effects of weather and the effect of climate change [18]. This motivates to analyze particularly windstorms and floods in this paper.

2.2. Climate Change and future hazard scenarios

In 1992, the United Nations Framework Convention on Climate Change (UNFCCC) was created with the objective to "stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interface with the climate system" [2]. To achieve this, the Intergovernmental Panel on Climate Change (IPCC) supports UNFCCC producing reports of the scientific, technical and socio-economic aspects of global warming.

According to the IPCC, climate change projections may vary from region to region, but generally it is likely that wet and dry extremes are going to become more severe [2]. In Great Britain, particularly for the variables studied here, reports indicate that while wind has a high uncertainty on how it will change [17], flood risk will escalate because of the potential increase of rainfall volume, intensity and frequency [19]. Unfortunately, existing studies disagree on the quantitative changes of rainfall volume, intensity and frequency [17].

3. Multi-phase resilience assessment and enhancement framework

Reliability aspects, related specifically to security and adequacy, have traditionally driven power system operation and planning. This has helped to build systems designed and operated to be reliable during normal conditions and abnormal but foreseeable contingencies. However, dealing with unexpected and less frequent severe situations still remains a challenge. In this section, the resilience and enhancement framework of Fig. 1 is proposed for evaluating the impact of natural disasters on the resilience of power systems and the effect of possible adaptation strategies.