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grid resilience

elasticity is needed when facing catastrophes

ACCORDING TO THE *MERRIAM-Webster Dictionary*, the definition of resilience is as follows:

> 1: the capability of a strained body to recover its size and shape after deformation caused especially by compressive stress and 2: an ability to recover from or adjust easily to misfortune or change.

The first definition implies any physical body, and the second definition obviously refers to human beings. Similar definitions also exist for biology, health, and education. Although we know what key performance indexes (KPIs) such as reliability, efficiency, security, and affordability mean, the term resilience is relatively new. U.S. Presidential Policy Direction 21 defines resilience as "the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions. Resilience includes the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents." More information on this definition is covered in the first article in this issue.

In the recent past, there have been extensive efforts to investigate the importance of resilience as applied to infrastructures in general and electric power and energy networks in particular. Before the resilience concept came to the forefront, some utilities in the United States explored and adopted the "hardening" concept to combat hurricanes. This essentially meant making needed hardware changes. Another concept, self-healing, was also adopted by some other utilities. Now, resilience has also taken on a deeper importance in the wake of recent widespread and major disturbances such hurricane Sandy in the U.S. East Coast; the Fukushima disaster in Japan due to earthquakes and the tsunami, cyclones, and tempests in Asia; and similar catastrophic events in other parts of the world. Some of the articles in this issue describe many of these disturbances.

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These events result in major blackouts, disrupting the electric supply to tens, and even hundreds, of million customers for hours and even days. These outages are not acceptable since they upset the normal life of residential customers, causing significant inconvenience and stress, placing life in danger, and even causing casualties. They also lead to the loss of supply to critical commercial customers such as hospitals and police stations and the loss of revenue for industrial customers. These are recurring events that need to be addressed and the problems fixed to make the electric power networks more resilient against these powerful forces of nature. These solutions should also make the grids elastic for human errors.

We, as coeditors, proposed to dedicate a special issue on grid and microgrid resilience, and the *IEEE Power & Energy Magazine* Editorial Board readily accepted the proposal last summer. So this issue is now a reality and includes six excellent articles about the ongoing efforts around the world to provide resilience to electric power grids that offer potential practical solutions to catastrophic events. As the details of these major events are covered in the articles, they are not covered here. We provide a summary of these articles for your reading pleasure with a sincere hope that you will understand the latest developments and ongoing research and development efforts to improve the resilience of distribution power grids in various parts of the globe.

The Articles in This Issue

The first article, by Dan Ton and Paul Wang, which we consider a must read, outlines the need, justification, and R&D plans of the U.S. Department of Energy (DOE). According to the authors, the key message is as follows: "Due to the increasing frequency and intensity of weather-caused grid outages in recent years, the U.S. DOE has placed an added emphasis of R&D on enhanced climate change and extreme weather resilience. To forge a focused

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national R&D effort on grid resilience, DOE adopts a public/private partnership approach to join with key stakeholders in developing and implementing a resilient grid R&D plan. This article presents the plan development process and key elements of the developed plan, including R&D focus areas and associated priority activities identified as necessary for pursuit of the defined resilience goals. Examples of ongoing projects supported by the DOE in developing resilience metrics and assessment and modeling tools for resilience are provided. Further, the planned activities for out years are outlined."

> This issue includes six excellent articles about the on-going efforts around the world to accord resilience to electric power grid.

The second article, by Strbac et al., focuses on the role of microgrids in enhancing the resilience of the European megagrid. Resiliency needs to be developed to exploit the grid's renewable energy resources to face climate change challenges and enhance its security of energy supply. As shown in studies, a shift from a member-state-centric to an EU-wide approach to decarbonizing the electricity system enabled by an EU megagrid would bring very significant benefits in integrating solar generation in the south and wind generation in the north of Europe. Moreover, this vision should be supported by the application of smart grid concepts and technologies in distribution networks to enhance the cost effectiveness and resilience of the future EU system. "In this context," the authors state, "microgrids, with appropriat enabling technologies, will facilitate the paradigm shift in delivering resilience and security of supply from redundancy in assets and preventive control to more intelligent operation through corrective control actions supported by a range of enabling technologies and ICT." The article describes the control challenges for the effective operation of microgrids both in interconnected and islanded operations, including the effects of communication malfunctions, and focuses on their role in power system restoration. The shift from a centralized to a fully decentralized operation paradigm for enhancing real-time control of microgrids to improve supply resilience and quality of service delivered to end consumers is discussed.

The third article deals with the efforts to improve the resiliency of the power grid in Japan. Chris Marnay and his associates in Japan have been focusing their work in this area for almost a decade. In 2006, Japan took the early lead in focusing work on microgrid research. In the authors' words, "This was driven by four demonstrations funded by NEDO and several notable private sector efforts. These primarily demonstrated high renewable penetration, islanding, reliability, and heterogeneous power quality. Following the great East Japan earthquake of 2011, the major focus shifted from microgrid to resiliency. The objectives of those projects did not include resilience as a high priority; rather they were intended to demonstrate the high penetration of local small-scale renewables, local control of diverse resources, islanding, reliability, and heterogeneous power quality." They further emphasized that "the exceptional performance of the Sendai microgrid compared to the legacy centralized power grid during the 2011 earthquake and tsunami changed perceptions and priorities dramatically. Since that time, microgrid development in Japan has been resiliency focused, and projects have expanded beyond small sites, primarily commercial facilities, to more diverse projects including larger urban demonstrations, as well as small community systems." The article talks about Japan's performance during the 2011 event, the country's microgrid research work, and concludes with the role of resiliency in current research and demonstrations including ongoing projects. This is a fascinating article filled with many details that should capture the attention of all readers.

In the six articles in this issue, the needs for investing in network "smartness" together with reinforcing the network are debated.

The fourth article, by Mathaios Panteli and Pierluigi Mancarella, focuses on the conceptualization of the resilience of the future power infrastructure via a conceptual curve of the resilience level as a function of time associated to a disturbance event. In addition, it considers the long-term adaptation as a key feature for achieving resilience. The aim to boost the grid resilience to high-impact, low-probability events "could be achieved through resilience engineering for enhancing the resilience of the network before and during the event and disaster response and risk management for optimizing the response following the event, which would be the output of the vulnerability/adaptation studies based on previous experiences," according to the authors. "These two resilience goals can be primarily fulfilled through hardening and operational measures. Hardening measures are denoted as infrastructure reinforcement actions for making the power system less susceptible to extreme events. In contrast, operational measures refer to 'smart' control-based actions taken to provide the assets with control capability and resources to effectively deal with the emergency as it unfolds. In particular, the goal of the operational measures is to make the system to 'bend,' rather than 'break,' in the face of a disaster." The authors conclude that "a hybrid network with built-in synergy between hardening and 'smart' measures is likely to achieve a good trade-off between resilience and cost efficiency. This needs to be assessed through a cost-benefit analysis that compares different potential resilience measures and risk-based approaches."

The fifth article, by Mohammad Shahidehpour and other team members, is a welcome addition. The focus of this article is improving the grid resiliency of the Illinois Institute of Technology (IIT) by integrating suitable wireless communication, control, and supervisory control and data acquisition systems. In their words: "Microgrids provide an excellent test bed for implementing emerging smart grid technologies. IIT has recently initiated the Center for Smart Grid Applications, Research, and Technology (CSMART) to develop projects to address the biggest challenges in cyber and physical security of power and energy systems." The authors continue with "The project team developed a software system, based on the OSIsoft PI, and integrated it at the CSMART control room, which allowed the project team to remotely monitor and control the lights at the IIT microgrid. The wireless network implemented with the streetlights provides a myriad of benefits including remote metering, on/off and dimming controls, dimming schedules with sunset/sunrise, event lighting, emergency lighting controls, automated outage detection, and performance data analysis."

Examples of on-going projects in the United States, Europe, and Japan are provided.

In the concluding article, Jesus Varela and his coauthors present the distribution network contribution to resilience, as addressed by smart grid solutions studied within the European research project IGREENGrid. IGREENGrid is focused on identifying the best practices regarding distributed renewable energy source integration issues in a large number of projects and, specifically, in six successful large-scale demonstration projects, in Austria, Italy, Germany, Spain, France, and Greece. Practical implementations of solutions are based on voltage control systems, storage management, generation forecasting, management and curtailment, load/demand management, network reconfiguration, islanding solutions and anti-islanding systems, network state estimation, and network monitoring. An added value of the IGREENGrid analysis is providing KPIs to compare and objectively evaluate different proposals. For example, the voltage quality KPI allows for the comparison of how much of the voltage tolerance range becomes a safety band, and consequently, the KPI is a measurement of resilience.

Concluding Remarks

Recent events have shown that the power infrastructure needs to be reliable not only to known threats but also resilient to the high-impact, low-probability events caused by climate change and extreme weather. In the six articles in this issue, the needs for investing in network "smartness" together with reinforcing the network are debated. Emphasis on R&D to enhance resilience is highlighted, and examples of on-going projects in the United States, Europe, and Japan are provided. The emergence of microgrids has evolved as a key concept and component for improving the reliability of future distribution systems. These are proving to provide resilience in extreme events and able to enhance the resilience of the megagrids (or the whole system).

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