A Stronger, Bigger or Smarter Grid? Conceptualizing the Resilience of Future Power Infrastructure

Foreword **– Increasing the resilience of critical power infrastructures to high-impact low-probability events, such as extreme weather phenomena driven by climate change, is of key importance for keeping the lights on. However, what does resilience really mean? Should we build a stronger and bigger grid, or a smarter one? This article discusses a conceptual framework of power system resilience, its key features, and potential enhancement measures.**

1. Introduction

The design and operation of the critical power infrastructure has been traditionally driven by the key reliability principles of security and adequacy. These allow dealing with known and credible threats so as to guarantee high quality power supply to end users on a nearly continuous basis, with few interruptions over an extended time period. It cannot be doubted that this has led to the development of one of the most reliable (and complex!) infrastructures of the last century.

However, it is becoming more and more apparent that further considerations beyond the classical reliability-oriented view are needed for keeping the lights on. This is evidenced by several catastrophes that occurred worldwide in the last decade or so. For example, the US northeastern states were struck by Hurricane Sandy in 2012, which destroyed over 100,000 primary electrical wires; in addition, several substation transformers exploded and numerous substations were flooded. This altogether led to the disconnection of approximately 7 million people. Over the 2010-2011 summer, Australia's second largest state, Queensland, was affected by widespread flooding that resulted in significant damage to six zone substations and numerous poles, transformers and overhead wires. Approximately 150,000 customers experienced power disruptions. In 2008, China was hit by a severe ice storm, which resulted in the failure of 2,000 substations and in the collapse of 8,500 towers leading to power interruptions in 13 provinces and 170 cities.

These are only a few examples of the effect of weather-driven high-impact low-probability events that a power infrastructure can experience. These events also illustrate that we need to distinguish blackouts from disasters. A blackout occurs when a large proportion of a power grid is disabled by a combination of unplanned contingencies, which result in a temporary power interruption. A reliable and well-designed power system should be capable of minimizing the amount of power disruption and of recovering very quickly from a blackout. On the other hand, a disaster, which usually includes a blackout, refers to severe and rapidly changing circumstances possibly never before experienced. A disaster can cause the incapacitation of several and often large parts of a power grid, which may last for a long period depending on the extent of the disaster. Hence, a power infrastructure that can maintain high levels of performance under any condition should be *reliable* to the most "common" blackouts, but also *resilient* to much less frequent disasters.

Resilience (or *resiliency*) comes from the Latin word "*resiliō*", which literally refers to the ability of an object to rebound or return to its original shape or position after being stressed (e.g., bent, compressed, stretched, etc.). In the context of power systems, it refers to the ability of a power system to recover quickly following a disaster, or more generally to the ability of anticipating extraordinary and high-impact low probability events, rapidly recovering from these disruptive events, and absorbing lessons for adapting its operation and structure for preventing or mitigating the impact of similar events in the future. Adaptation thus refers to the long-term planning and operational measures taken to reduce the vulnerability to external sudden shocks.

As power engineers, how can we build a network that is both reliable and resilient? The most obvious way is building a bigger and stronger (more redundant and robust) network; however, how cost efficient is this approach? A more cost efficient solution could be investing more into "smart" operational measures, but how robust is this approach? More insights in the concept of resilience can help address this issue.

2. Conceptualizing Power Systems Resilience

C.S. Holling first defined *resilience* in 1973 as a measure of "*the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables*". Since this foundational definition, the concept of resilience has evolved remarkably in several systems, such as safety management, organizational, social-ecological and economic ones. After Holling, numerous interpretations of resilience have been developed, resulting in many different definitions and a lack of a universal understanding of what resilience really is.

In the context of power systems as critical infrastructures the picture is even more blur, as the concept of resilience has only emerged in the last decade or so. There have been several attempts by organizations worldwide in the power and energy engineering communities, such as the UK Energy Research Center (UKERC) and the Power Systems Engineering Research Center (PSERC), USA, to define resilience and distinguish it from the concept of reliability. According to the UK Cabinet Office, resilience encompasses reliability and it further includes *resistance*, *redundancy*, *response* and *recovery* as key features. Another pioneer definition comes from the Multidisciplinary and National Center for Earthquake Engineering Research (MCEER), where a generic resilience framework has been developed that is applicable to any critical infrastructure, including power systems. This framework consists of the "4Rs": *robustness*, *redundancy*, *resourcefulness* and *rapidity*.

The list of power system resilience definitions is endless, but the majority of these definitions focus on the ability to anticipate, absorb and rapidly recover from an external, high-impact low-probability shock. Although a full comparison is outside the scope of this work, some key resilience characteristics that differentiate it from the concept of reliability are shown in Table I, which will be discussed in detail throughout this article.

TABLE I
RELIABILITY VS RESILIENCE

Reliability	Resilience
High-probability, low-impact	Low-probability, high-impact
Static	Adaptive, ongoing, short- and long-term
Evaluates the power system states	Evaluates the power system states *and* transition times between states
Concerned with customer interruption time	Concerned with customer interruption time *and* the infrastructure recovery time

2.1. A conceptual resilience curve associated to an event

The illustrative conceptual resilience curve of Fig.1 shows the resilience level as a function of time with respect to a disturbance event. This figure is used here for demonstrating the key resilience features that a power system must possess for coping effectively with the evolving conditions associated to an event, for instance, a heavy storm moving across the system.

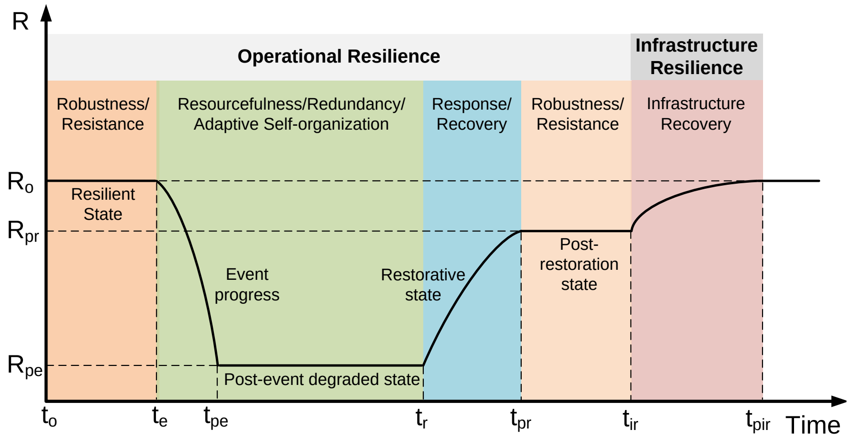

Fig. 1: Conceptual resilience curve associated to an event

Before the event occurs at t_e, a power system must be *robust* and *resistant* to withstand the initial shock. A well-designed and operated power system should demonstrate sufficient resilience (indicated here with R_o, where R is a suitable metric associated to the resilience level of the system – see also further below) to cope with any type of events. The capability of *preventive operational flexibility* is highly critical here, as it provides the operators with the assets to configure the system in a *resilient state*.

Following the event, the system enters the *post-event degraded state*, where the resilience of the system is significantly compromised (R_{pe}). The *resourcefulness*, *redundancy* and *adaptive self-organization* are key resilience features at this stage of the event, as they provide the *corrective operational flexibility* necessary to adapt to and deal with the evolving conditions (that are possibly never experienced before). This helps minimize the impact of the event and the resilience degradation (i.e., R_o - R_{pe}) before the restoration procedure is initiated at t_r.

The system then enters the *restorative state*, where it should demonstrate the *restorative capacity* necessary for enabling the fast *response* and *recovery* to a resilient state as quickly as possible.

Once the restoration is completed, the system enters the *post-restoration state*. The post-restoration resilience level R_{pr} may or may not be as high as the pre-event resilience level R_o, i.e. $R_{pr} < R_o$. In particular, while the system may have recovered from the point of view of fully returning to its pre-event operational state (thus showing a certain degree of *operational resilience*), the infrastructure may take longer to fully recover (*infrastructure resilience*), i.e. (t_{pir} - t_{ir}) > (t_{pr} - t_r). This would depend on the severity of the event, as well as on the resilience features that the power system will demonstrate before, during and after the external shock. It is interesting to notice how some measures might make the system more resilient operationally but less from an infrastructure perspective.

For instance, the undergrounding of an overhead corridor might improve the capability of the system to withstand events, but then if the cable is damaged it may take much longer to repair it than an overhead line. This might become a critical issue if a new event were to arrive relatively soon (for instance, settling waves following a major earthquake wave).

It is important to highlight that for a full understanding and assessment of system resilience, which is by definition a multi-dimension concept, both the *resilience levels* of and the *transition times* between the power system states associated to an event are needed. Referring to Fig. 1, in fact, the system resilience is not only characterized by the levels R_o, R_{pe} and R_{pr} associated to different states, but also by the transition time between states (i.e., $t_{pe} – t_e$, $t_{pr} – t_r$, and $t_{pir} – t_{ir}$, respectively). In particular, actions to increase resilience should aim at (i) reducing the resilience level degradation during the event (R_o - R_{pe}); (ii) achieving a relatively "slow" and possibly controlled degradation ($t_{pe} – t_e$), thus also mitigating the degree of cascading; and (iii) reducing the recovery time (both from operational point of view, $t_{pr} – t_r$, and infrastructure point of view, $t_{pir} – t_{ir}$). As also indicated in Table I, this "time dimension" is an important feature that distinguishes resilience from reliability.

2.2. A Conceptual long-term resilience framework

The resilience definition by the National Infrastructure Advisory Council (NIAC), USA, takes the infrastructure resilience framework a step further, as it additionally considers the long-term *adaptation* as a key feature for achieving resilience. This resilience feature refers to the ongoing process of resilience-building using the information and experiences from past events in order to evaluate existing resilience measures and regularly update resilience planning and decision making. Fig. 2 shows the framework for conceptualizing this infinite procedure of evaluating and improving power systems resilience, which is depicted by the *resilience enhancement circle*.

The *adaptation capacity*, which enables the long-term resilience planning, is thus a critical resilience feature as it provides the capacity to deal with unforeseeable and continuously changing conditions. As can be seen in Fig. 2, the first step towards this goal is to perform vulnerability and adaptation studies using the input from past experiences and/or simulations. This would help detect the vulnerabilities of a power system at the different stages associated to an event, i.e. before, during, and after, and develop the adaptation strategies necessary for improving the key resilience features and enhancing the response of the power system to the evolving conditions during a similar event that were to occur in the future.

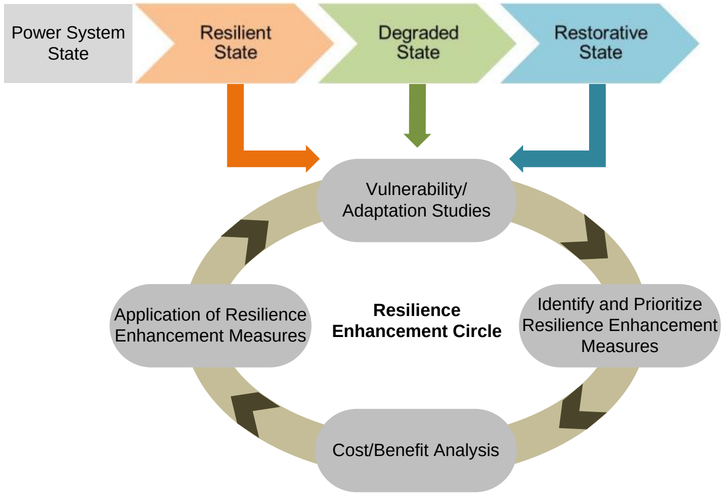

Fig. 2: Conceptual long-term resilience framework

Based on this analysis, the resilience enhancement measures are identified and prioritized depending on the criticality and contribution of each measure for improving resilience. These may refer to operational and/or reinforcement measures, as will be discussed later in this article. However, some of these measures are more resilience-efficient than others, and some measures are more cost-efficient than others. Therefore, a cost/benefit analysis would help gain insights on the benefits of implementing each measure over the cost of realizing the measure. Following this analysis, the resilience actions can be ranked and implemented based on both their resilience- and cost-efficiency indices, which would help build a power infrastructure that satisfies both resilience and cost efficiency requirements.

Based on this discussion, it is clear how *adaptive management*, as a learning procedure that is function of time, is therefore another concept that distinguishes resilience from reliability and is necessary for understanding and building resilience. In fact, the knowledge of a power system and its main resilience threats is often partial and incomplete, as it is almost impossible to accurately and precisely predict the future extreme events that would compromise power system resilience. In this respect, the Intergovernmental Panel on Climate Change (IPCC) defines *adaptive* management as "*A process of iteratively planning, implementing, and modifying strategies for managing resources in the face of uncertainty and change. Adaptive management involves adjusting approaches in response to observations of their effect and changes in the system brought on by resulting feedback effects and other variables*". The adaptive management approach explicitly recognizes the presence of uncertainty and allows decisions to be made and resilience actions to be taken based on new (and possibly incomplete) information, resulting in an infrastructure with *built-in operational and planning flexibility*. At the end of the day, the risk of acting under uncertainty is always lower than the risk of inaction!

There are several examples of adaptive behaviour in power systems for mitigating the impact of catastrophic events. In the UK, for instance, the North Sea storm in December 2013 resulted in the flooding of 2,600 homes, but approximately 800,000 homes had been protected from flooding. By comparison, a similar event in 1953 led to the loss of 307 lives, while 30,000 people evacuated their homes and 24,000 properties were seriously damaged.

2.3. Quantifying resilience

Quantifying resilience is not a straightforward process (quite the opposite, actually, as it may prove the most challenging task within a resilience analysis framework) because, as discussed earlier, resilience is a multi-dimensional, dynamic concept with several intrinsic complexities. However, quantifying resilience is necessary in order to evaluate the effectiveness of the resilience strategies and amend them as necessary. Numerous resilience metrics exist, but they often quantify only one or a few dimensions of resilience. For example, resilience is often quantified based on the degree of robustness to the initial shock, the functionality achieved during the event, or the post-event recovery duration. However, a comprehensive approach for quantifying both the short-term, i.e., before, during and after an event (Fig. 1) and long-term (Fig. 2) features of resilience should be developed in order to get a quantitative understanding of the resilience level of a power system. Both short-term and long-term resilience metrics are needed accordingly (Fig. 3). In addition, as mentioned above, distinction between operational and infrastructure resilience might have to be made within the short-term assessment. This would help establish resilience-building strategies and policies for coping more effectively with the upcoming disaster and also for being better prepared for future disasters.

The resilience assessment methods should be capable of quantifying the frequency and duration of customer disconnections due to severe disasters, and also the number of customers disconnected. They should also provide global resilience indices of the entire power infrastructure, as well as area- and component-specific resilience indices, which would help target resilience enhancement measures. These resilience assessment methodologies need to reflect as realistically as possible the effect of a high-impact low-probability disaster. Finally, the time dimension needs to be incorporated explicitly in the assessment, so as to capture the capability of the system of both slowly

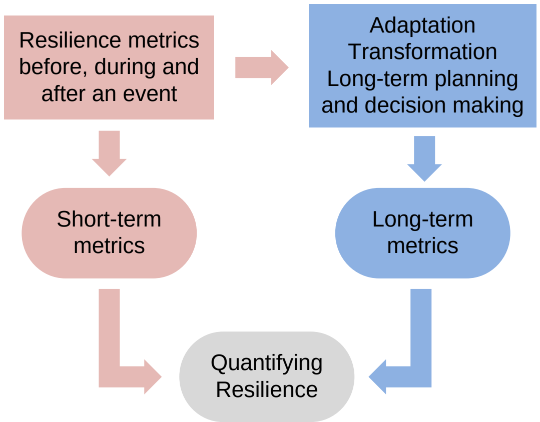

Fig. 3: Quantifying short-term and long-term resilience

degrading from and fast recovering back to the original pre-event state. In order to do so, the spatial-temporal influence of the event on the resilience of the power infrastructure needs to be adequately modelled. If we take the effect of weather events as an example, Fig. 4 demonstrates a procedure of the infinite building-resilience procedure using the concept of *fragility curves*. These curves express the failure probability of power system components as a function of a weather parameter, e.g. wind speed or rain intensity. Similar curves can be developed to relate, for example, the restoration time to the density and duration of the weather event. By mapping the time-series profile (thus considering the event's inter-temporal dimension) of the weather event at different locations of the power system (thus considering the event's inter-spatial dimension) to these fragility curves, the components' weather-related failure probabilities and therefore the resilience implications can be quantified using suitable multi-dimensional metrics (for instance, energy not supplied, duration of interruptions, and time to full infrastructure recovery). Following this, as previously discussed, resilience *enhancement measures* can be applied if necessary. An example of resilience enhancement is shown in the fragility curve of Fig. 4, in which the components are made more robust to higher intensities of the weather event. This procedure needs to be continuously updated for achieving the desired resilience level.

3. Boosting the Resilience of Future Power Systems

The majority of electrical utilities worldwide have recognized the necessity of taking actions to boost the grid resilience to high-impact low-probability events. These efforts mainly aim to achieve *system adaptation*, which refers to the measures taken to reduce the impact of future events, and *system survivability* which refers to the ability to maintain an adequate functionality during and after the event.

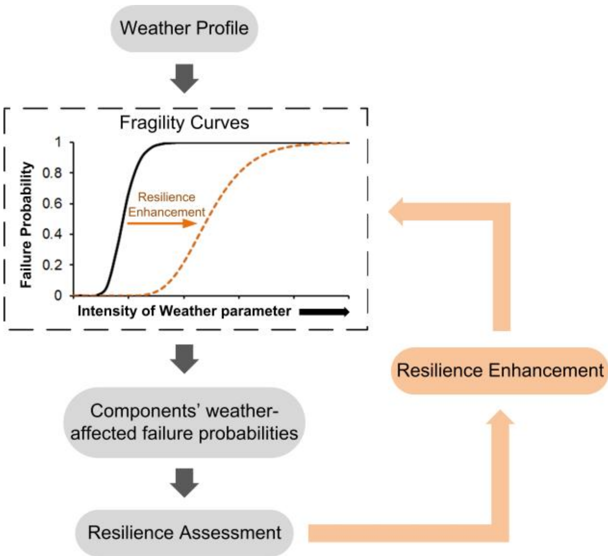

Fig. 4: Evaluating and enhancing resilience to weather events using fragility curves

These aims 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 (Fig. 5), which would be the output of the vulnerability/adaptation studies based on previous experiences (Fig. 2). 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.

Fig. 5: Boosting power systems resilience

A cost versus effectiveness evaluation of these measures can provide the most suitable roadmap for improving power systems resilience. The costs of these resilience actions include capital, operational and maintenance. Fig. 6

illustrates conceptually how hardening measures might (also depending on the resilience metric used) generally be more effective than operational ones, but they are also likely to come at a higher cost. A hybrid approach that allows the development of a stronger and bigger, but also smarter at the same time, system might thus offer the capability to build a more resilient power infrastructure while optimizing the investment in the resilience enhancement measures.

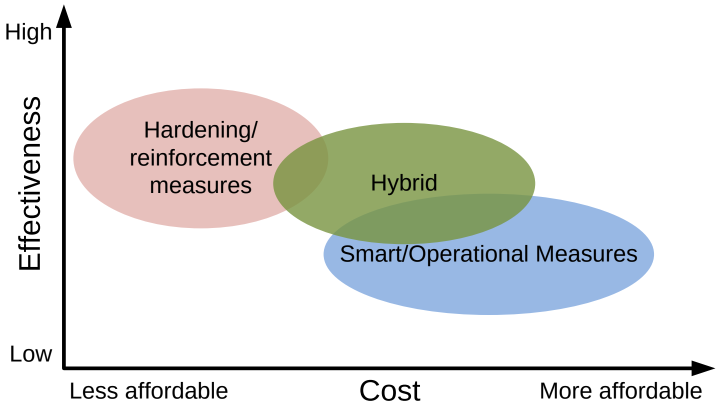

Fig. 6: Cost Vs Effectiveness of resilience engineering approaches – Conceptual comparison

TABLE II
EXAMPLES OF NETWORK AND COMPONENT HARDENING MEASURES

- Undergrounding distribution and transmission lines
- Upgrading poles and structures with stronger, more robust materials
- Elevating substations
- Relocating facilities to areas less prone to extreme weather
- Re-routing transmission lines to areas less affected by weather
- Redundant transmission routes

3.1. Making the Grid Stronger and Bigger

Hardening measures may refer to topology and structural changes in order to make the network less vulnerable to severe events. Table II shows some examples of these measures, some of which with focus mainly on dealing with extreme weather events. These in fact constitute one of the main threats of power systems resilience, as discussed in Section 1, and the uncertainty about the implications of climate change is likely to increase the importance of weather events within the resilience debate.

Undergrounding the transmission and distribution lines is considered one of the most effective measures for reducing the vulnerability to wind damage, lightning and vegetation contact. However, the cost associated with converting overhead systems to underground may make the widespread use of this measure prohibitive. The cost of burying overhead wires ranges from $500,000 to $2million per mile. An additional challenge lies in the restoration time of the buried cables which is significantly higher compared to overhead lines. This is mainly because of the complicated nature of these systems and the inability of the repair crews to visually detect the damaged components. Hence, as mentioned earlier, this action may actually have controversial effects on system resilience, as it enhances the robustness of the network on the one hand, but it affects the response and restoration times following a disaster on the other hand. Targeted or selective undergrounding of overhead lines could thus be a more viable solution than a total conversion, following a proper risk and cost/benefit analysis. Advanced condition monitoring and fault detections techniques would also help tackle these challenges.

Upgrading the components with stronger materials constitute a further primary hardening strategy aimed at making the components more robust to extreme weather phenomena, such as severe winds. For distribution networks, this usually involves the conversion of wooden poles to concrete, steel or any other composite material. For transmission networks, there are several approaches under consideration worldwide, including design and material upgrades. In the UK, for example, National Grid PLC already approved a project of $1.6billion for replacing the traditional steel towers with T-pylons and underground cables while using the existing rights-of-way in the Southwest of England. The T-pylons are shorter than the traditional towers, have less impact on the environment and, more importantly, are considered more robust.

Elevating substations, relocating facilities or re-routing transmission lines to areas less prone to extreme weather help provide protection against flood damage and any other type of damage caused by weather events, for instance tower collapses due to extreme winds and snowfalls. Additional transmission lines help increase the transmission network capacity and they also provide operational flexibility, as they offer the ability to bypass damaged lines, which contributes to the prevention of cascading failures.

3.2. Making the Grid Smarter

As aforementioned, the term "smart" here refers to a broad set of operational actions that can be taken to improve the observability, controllability and operational flexibility of a power system, particularly in response to an extreme event. This is critical in building resilience as it provides the system (and system operators) with monitoring and control assets for dealing with the unfolding disaster in a timely and efficient way. A possible set of smart intervention categories is discussed below.

Distributed Energy Systems and Decentralized Control

Decentralized energy systems with large scale deployment of distributed energy resources (and distributed generation and storage, in particular) and decentralized control can play a key role in providing resilience to external shocks. In fact, generating, storing and controlling energy locally without the need of long transmission lines can make the network less vulnerable to disasters and the response to an emergency much faster and more efficient. Restoration times can also be improved in smaller balancing areas. Localized protection and control assets are however required for achieving a more resilient decentralized operation, which is to be considered in the wider picture of smart grid evolution.

Microgrids

A microgrid can be simply defined as the subset of the grid (typically at low voltage and medium voltage levels) that can be islanded and can still supply all or part of their customers during emergencies, thus intrinsically enhancing system resilience. A microgrid requires the smart technologies mentioned above to continue delivering power to the customers in islanded mode. Several projects worldwide aim to develop microgrids, as they are seen as one of the most promising measures for enhancing future power systems resilience during emergencies.

Adaptive Wide-area Protection and Control Schemes

The majority of the existing wide-area protection and control schemes are event-based, which means that they will operate once the pre-determined criteria are fulfilled. For instance, they usually follow the logic of "if A AND B is true, then apply C", where A and B are the electrical events that the scheme is designed to provide protection against and C are the protection and control actions to be implemented. These schemes have so far been very effective in maintaining a high level of security even during stressed conditions. However, the increasing complexity of power systems and uncertainty in the events that might occur call for the development of smarter, more adaptive protection schemes capable to adapt to the evolving system conditions and dynamically determine the best course of actions based on the unfolding events, and not on pre-determined criteria. Nevertheless, adaptive protections have not been widely implemented yet due to concerns about the reliability of these schemes themselves.

It has to be kept in mind though that the use of these wide-area protection schemes does not eliminate completely the need for transmission network expansion, which might be ultimately needed for coping with future operational challenges. In the UK, for example, an operational inter-tripping scheme is in place for controlling the Anglo-Scottish interconnector, but National Grid PLC (within its "Strategic Wider Works") plans to build submarine HVDC links for connecting Scotland to England, as this is considered necessary for the resilience of the future UK transmission network. This practical example points to the direction that "hybrid" measure might be consider optimal to improve resilience, as also elaborated further below.

Advanced Visualization and Situation Awareness Systems

Electrical utilities often have a set of incomplete information on the state of their own network, resulting in delayed and inefficient responses. The development of adequate situation awareness tools that enables the effective and timely decision-making could thus play a key role in preserving resilience during emergencies. For instance, user-friendly visualization technologies including color contours, animated arrows, dynamically sized pie-charts, and 3D representation of the power system could enable transmission and distribution operators to perform more effective system monitoring and develop adequate cognition of evolving conditions during extreme events. In addition, the reliability and functionality of the relevant communication and information systems is critical to enable effective information exchange and coordination between system operators and field/repair crews. It can thus be seen that *human resilience* also plays a key role in preserving power system resilience.

Disaster Response and Risk Management

The smart and operational measures discussed above can improve those emergency and preparedness procedures that enhance disaster response and risk management. This altogether helps mitigate resilience degradation during the event (i.e. R_o - R_{pe}, see Fig. 1), which is critically important in enabling fast recovery and restoration.

This response of the system to a disaster is an additional resilience feature that distinguishes it from reliability, as the focus is not only on impact on customers (e.g., evaluating the duration of interruptions or the energy not supplied), but also on the infrastructure being able to rapidly and effectively recover to its pre-disaster operational state. A resilient network should thus be able to achieve a resilience level that is close or equal to R_o (see Fig. 1) as quickly as possible following the disaster by possessing adequate operational and infrastructure resilience features. In this respect, recovering from a state of degraded performance and resilience (R_{pe}, see Fig. 1) requires an effective post-disaster restoration process. This should describe how the system can “bounce back” to a state similar to the pre-disaster functionality.

There are mainly two aspects that drive the development of this procedure: the time required to restore each of the damaged components and the criticality of each component in restoring resilience. The former is strongly related to the infrastructure resilience and depends on several factors, such as availability of backup components, accessibility to the affected areas, and number and location of repair crews. The latter refers to the contribution of each component to restoring operational resilience under different operational scenarios. However, the influence of these two aspects on the decision-making is not independent, but it is in contrast strongly correlated. For example, if a component is ranked first of the most critical components in restoring operational resilience, but under specific circumstances it may be very difficult or lengthy to restore, then it might not be highly ranked in the priority list. Other components, possibly less “operationally” critical, may be restored first.

3.3. Hybrid Grids: Stronger, Bigger and Smarter

It can be clearly seen from the discussions in the previous sections that understanding and enhancing grid resilience is a very open challenge. Hardening/reinforcement schemes may come at a significantly higher cost than the smart/operational measures. On the other hand, operational measures without sufficient strengthening of the network may not be enough for keeping the lights on in the face of a disaster. In addition, some of these actions, such as undergrounding overhead lines or making use on adaptive protections that may not be sufficiently reliable, may have controversial effects on the key features of resilience.

A hybrid network might be the solution for boosting the resilience of future power systems in an economically feasible way. The term “hybrid” can be interpreted here in two different, but related, ways. The first refers to the combination of hardening and smart measures for meeting the resilience and cost efficiency targets. The second refers to the co-existence of large, interconnected traditional grids (with centralized control) and smaller balancing areas (with distributed and decentralized control) that in case could be operated as microgrids. Such a hybrid system would thus offer the advantages of both bigger and more robust networks as well as more operational flexibility and security.

4. CONCLUSIONS

Building a power infrastructure that is reliable to known and credible threats, but also resilient to the high-impact low-probability events is very challenging. In order to achieve this, we need first to get a good understanding of what resilience is. Resilience is not a static concept, but it is a dynamic, ongoing procedure for adapting (and possibly transforming) the structure and operation of power systems to be better prepared to external, unforeseeable shocks. A resilient network must thus be robust and operational flexible, but must also possess the adaptation capacity to plan, facilitate and implement the actions and measures required for preparing to similar or new events in the future.

In general reinforcing the network (i.e. making it "bigger" or "stronger") may not always have the desired effect, while it usually requires a significant investment. A hybrid network with built-in synergy between hardening and "smart" measures is thus likely to achieve a good trade-off between resilience and cost efficiency. This needs to be assessed through cost/benefit analysis that compares different potential resilience measures and risk-based approaches. In this respect, from this work several research questions emerge that are only now starting being addressed, including how smart grid measures can cost-effectively and reliably enhance resilience when compared to hardening and reinforcement actions, what metrics should be used to assess the multiple dimensions of resilience, and what type of tools are appropriate to make resilience-related cost-effective decisions taking into account the relevant uncertainties and risks.

Further Readings

M. Panteli and P. Mancarella, "Modelling and Evaluating the Resilience of Critical Electrical Power Infrastructure to Extreme Weather Events", *IEEE Systems Journal*, in press.

M. Panteli and P. Mancarella, "Influence of Extreme Weather and Climate Change on the Resilience of Power Systems: Impacts and Possible Mitigation Strategies", *Electric Power Systems Research*, in press.

National Infrastructure Advisory Council, "A Framework for Establishing Critical Infrastructure Resilience Goals", USA, October 2010.

UK Energy Research Centre (UKERC), "Building a Resilient UK Energy System", April 2011.

Cabinet Office, "Keeping the Country Running: Natural Hazards and Infrastructure", UK, October 2011

Executive Office of the President, “Economic Benefits of Increasing Electric Grid Resilience to Weather Outages”, The White House Office of Science and Technology, USA, August 2013.

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