RESILIENCE OF DISTRIBUTION GRIDS

WORKING GROUP

Final Report: 31.05.2018

CIRED's point of view

Congrès International des Réseaux Electriques de Distribution

International Conference on Electricity Distribution

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Summary of the Report

The dependence and interdependence between the different economic sectors of society is a current reality effective and concrete. This connection has emerged naturally, accompanying the evolution of technology, globalization and the way we currently interact with society and organizations.

From the Latin *systema* - system - is an ordered set of elements that are interconnected and that interact with each other. Transposing this concept to organizations, where each organization is a system, the question arises in the effectiveness of these links, that is, in what way is interaction and interconnection made. Small failures, deviations or disruptive events of major impact may jeopardize a system if the connections / interconnections to another system or systems are not sufficiently robust and reliable.

"The increasing complexity and interdependence between critical infrastructures and the increasing dependence on the electric energy infrastructure makes the resilience of the energy network a fundamental priority in safeguarding the economic and social growth of modern societies"[1]. And when we reflect on society, on the organizations, we understand that it is a system of interconnected systems that allows us to interact and function in society. The complexity of this aspect increases exponentially. We think that each company is a system endowed with several layers, people, physical infrastructures, technological infrastructures and suppliers.

The ability of Systems and System-of-Systems to be flexible and to adapt to failures, deviations and / or disruptions is widely considered to be defined as Resilience. The organization's ability to adapt, shape and recover from changes, that may arise from different actors, will make the difference between an organization that will prevail in its sector and an organization that does will suffer to maintain its services.

In this complex world of systems, the role of a Distribution System Operator (DSO) is fundamental for the society, both to organizations and to citizens, and the constant search for

[1] WG Resilience of Distribution Grid_Final TOR

equipment, methodologies and techniques that allow to improve the continuity, quality of technical and commercial service provided is today a reality in most DSO.

The work of this WG, over the last two years, demonstrates this effort, commitment and dedication a constant search for innovative processes of improvement in terms of equipment / systems as well as in terms of work organization, allowing DSO to build a higher capability to adapt in the face of disruptive events that may arise.

The main objective of the WG is to present a report that enable to share good practices and promotes the work that different companies and countries are carrying out and have already implemented, through benchmarking and case studies related to the "Resilience of the Distribution Network". Sharing experiences and learning with good practices will serve as a reflection and guidance to improve the efficiency and effectiveness of companies, fostering the opportunity to develop other work that deepens the thematic.

Events and natural disasters such as those that have been experienced in recent times, which have also caused interruptions in the electricity grid, call for this deep dive in the thematic, ending not only in individual solution implementation by each DSO, but also collective ones as, among other, the need to define protocols of mutual assistance between DSO.

It is therefore also necessary that organizations such as CIRED continue to engage experts in distribution networks, allowing them to share their knowledge and experience and thus help organizations move towards resilience.

1. INTRODUCTION

1.1. BACKGROUND AND SCOPE OF THE WORKING GROUP

Resilience is a multi-faceted concept which can be interpreted and defined in several ways by organizations around their world, based on their practices and experiences with extreme events. In the context of distribution systems, resilience can be widely defined with respect to system's ability to withstand rare and extreme events (snow storms, hurricanes, earthquakes, terroristic attacks)[2] and quickly recover to its pre-event resilient state. There is no currently universally definition broad considered to be defined as Resilience, however, considering how different bodies approached this multidimensional concept in order to collectively evaluate which features should be taken into account in the decision-making for building highly resilient distribution networks, Table 1:

Source	Resilience Definition
IEEE Transactions. Power Systems [1]	"Resilience can refer to various functionalities of an organization, ranging from infrastructure robustness to operational resilience and business continuity".
ISO 22301:2012 - Business continuity management systems [2]	"Business continuity management is a holistic management process that identifies potential threats to an organization and the impacts to business operations those threats, if realized, might cause, and which provides a framework for building organizational resilience with the capability of an effective response that safeguards the interests of its key stakeholders, reputation, brand and value-creating activities".
JRC – European Commission [3]	"The term resilience means 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".
RESILENS: Realising European Resilience for Critical Infrastructure [4]	"Resilience is the ability of a system or systems to survive and thrive in the face of a complex, uncertain and ever-changing future. It is a way of thinking about both short-term cycles and long-term trends: minimizing disruptions in the face of shocks and stresses, recovering rapidly when they do occur, and adapting steadily to become better able to thrive as conditions continue to change. Within the context of CI,

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	the resilience process offers a cyclical, proactive and holistic extension of risk management practices".
Energy 2050: Making the Transition to a Secure Low-Carbon Energy System [5]	"Resilience is the capacity of an energy system to tolerate disturbance and to continue to deliver affordable energy services to consumers. A resilient energy system can speedily recover from shocks and can provide alternative means of satisfying energy service needs in the event of changed external circumstances."
Power Systems Engineering Research Centre (PSERC) [6]	"Power grid resilience is defined as the ability to degrade gradually under increasing system stress and then to recover to its pre-disturbance secure state. Also, the degree to which the system can cascade provides a measure of system resilience".

Table 1 - Different Resilience Definition

Concerning the interdependency of the electrical infrastructures that includes all its physical, human and technological domains, resilience for distribution grids is the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions; also includes the capability of an effective response that safeguards the interests of its key stakeholders, reputation, brand and value-creating. It is also highly critical to consider the "long-term adaptation" feature of a resilient distribution grid, in the sense of improving its design, operation and emergency procedures and practices to be better prepared for future events (similar or unforeseen) to mitigate the impact of High Impact and Low Probability (HILP) events on the frequency and severity of power outages. However, in order to enable the effective adaptation and implementation of those strategies for preserving the resilience of a distribution system to extreme events, it is essential to update the policy and regulatory frameworks in order to incorporate resilience-thinking and engineering in the decision-making and planning of future distribution networks, going beyond the traditional reliability planning.

1.2. STRUCTURE OF THE FINAL REPORT

The final report consists of six main chapters that are structured in the same way, where a small introduction is made, present a theoretical framework as well as the state of the art of the themes, which are:

- (i) Impact of different events to the electrical supply system;
- (ii) Interdependence of the electrical infrastructure and others;
- (iii) Evaluation of needs and the existing resilience;

- (iv) Strategies for planning, control and operation;
- (v) Overall strategies for cities in case of an HILP event including crisis strategies of utilities;
- (vi) Role of innovative networks and dispersed generation towards resilience.

In addition, the chapters include several case studies of the companies involved in this work with concrete examples of resilience as well as conclusions and recommendations.
It is understood that the resilience of the distribution network is a much broad topic to present in a single report, so the intended approach to the use of case studies was, on the one hand, to highlight the work that has already been done by companies and in particular by the DSO, given their role in society, and on the other hand to disclose existing good practices because a company will only be effectively resilient the more resilient its stakeholders are.

There have always been concerns about improving the network infrastructure with the goal of minimizing interruption times and monitoring a set of performance indicators, the point being that they were probably not framed under the umbrella of resilience, but it is also the objective of this report to highlight this point of view

1.3. PROCEEDING OF THE WORKING GROUP

The main objective of the report is to address the issue of resilience of the distribution networks, however by analyzing the initial description of the WG proposal, it would be challenging to address all the different issues in a single report, so it was recognized by the participants that it was a very ambitious and comprehensive topic and that some adjustments, to deliver the final report of this working group.

It was therefore decided to direct the efforts to address the issues referred to in the proposal, but limiting the scope and focusing exclusively on the distribution network operators. On the other hand, since there are already several innovation and research initiatives of participating companies but also at international level, for example through European projects under H2020, it seemed a good start to present case studies of concrete situations of the companies involved which clearly contribute to the resilience of the distribution network. This way, this work could contribute to the beginning of a more comprehensive work in this area.

The SharePoint, Figure 1, was a tool used for dissemination and sharing of the information inside the WG.

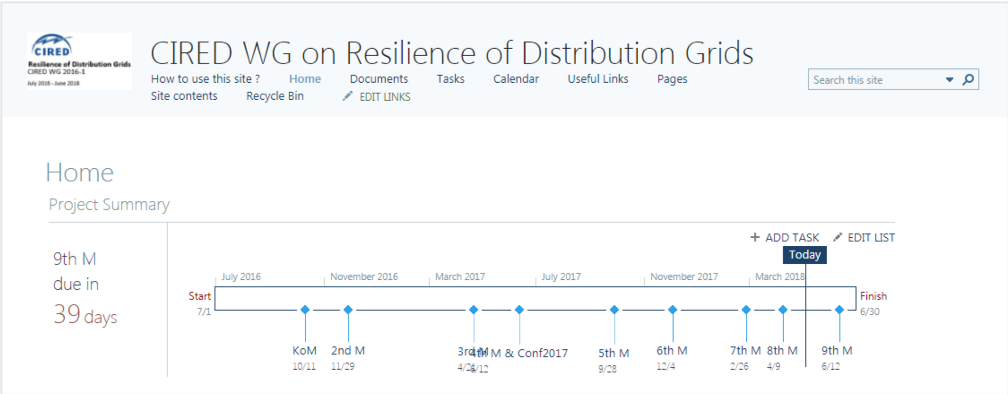

Figure 1 - WG SharePoint

This report includes fifteen case studies with the following typologies, Figure 2, framed in the main topics that constitute the body of the report.

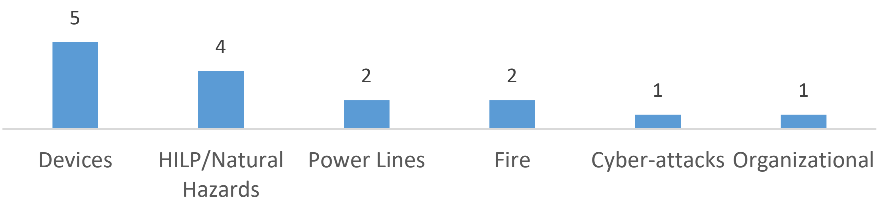

Figure 2 - Case studies typology

The case studies present the discussion around the main theme and present not only lessons learned but also recommendations based on experience.

As a final note, we hope that this report can be a one step to highlight the good practices that have been developed, not only in technical but also from a different viewpoint from another areas which also have as an effective contribution to the resilience of organizations.

Portugal – Winter 2017

2. IMPACT OF DIFFERENT EVENTS TO THE ELECTRICAL SUPPLY SYSTEM

2.1. INTRODUCTION

The work of this chapter will concentrate on the three event types: malevolent event, natural disaster and accident. In this first topic, the impact of such events on the power distribution system is described. Also, a distinction is given between classic concepts that increase the security in comparison to concepts that increase the resilience. This is used as a basis for further topics in the development of the case studies.

2.2. THEORETICAL FRAMEWORK

The threat category malevolent threats covers all types of threats that originate from intentional attacks on the power system executed by an adversary or a group of adversaries [7]. Typical adversaries are terrorists, extremists, vandals, cyber attacker but can also be insiders like employees. With the increasing dependence of the power system on IT components, cyber-attacks get an important threat vector [8]. The authors of [8] give what they call a cybersecurity case study and analyses the impact of recent cyber issues on the power system.

Natural hazards are events like hurricane, earthquake, tornado and flooding. These types of events have a high potential in disturbing the power system and to result in outages [9]. Due to the human induced climate change, extreme weather events are becoming more likely. The moment this report is written the east cost of the United States is hit by a series of severe hurricanes ("Harvey" and "Irma") leading among other damages to severe power outages [10].

The third type of threat are accidents. In its consequences, accidents can resemble very much malevolent threats. But they happen unintentionally, because of errors or failures. Especially dangerous are several smaller accidents that happen in a series. A prominent example of an accident that massively disturbed the power system are the wrong decisions that were taken on the 4th of November 2006 to allow the passing of a cruiser under two high voltage lines [11].

In specific cases, threats of different type can coincide, like it happened in Fukushima were accidents and natural hazards influenced each other with catastrophic results [12].

Despite the efforts of keeping the power flowing and the lights on under any *credible* events, power systems (and particularly distribution networks) are occasionally exposed to *extreme weather* and *natural hazards* (e.g. wildfires, storms and earthquakes), which as evidenced worldwide can be so intense that they can cause the collapse of power systems, leading to large and sustained power disruptions with great economic and social impacts. The threats of a power system can be broadly categorized in *credible* or '*typical' power system outages* and more *extreme events*, driven mainly by *natural disasters and extreme weather*, whose frequency and severity might increase as a direct impact of climate change [13]. Table 2 shows the distinct differences between these two categories of events [14].

COMPARISON OF TYPICAL POWER SYSTEM OUTAGES AND EXTREME EVENTS

Typical Power System Outage	Extreme Event
Low impact, high probability	High impact, low probability
Preventive & corrective control measures portfolio in place	No control measures in place (typically)
Random location and time of occurrence	Spatiotemporal correlation between faults and event
Supported by contingency analysis and optimization tools	Limited mathematical tools
Limited number (single or double) of faults due to component failures	Multiple simultaneous faults
Small portion of the network is damaged/collapsed	Large portion of the network is damaged/collapsed
Quick restoration	More time and resources consuming/longer restoration

Table 2 - Comparison of typical Power System Outages and Extreme Events

Distribution networks have been traditionally designed and operated to be *reliable* (secure in particular) to the more typical threats. Nevertheless, experiences around the world are now signifying the increasing importance for power networks to also achieve high levels of *resilience* to natural hazards and extreme weather [15, 16, 17], the so-called high-impact low-probability events, in order to mitigate the impacts of such events and quickly recover. Table 3 shows some of the key features that set the concept of security apart from the one of resilience [18].

COMPARISON OF SECURITY AND RESILIENCE

Security	Resilience
High-probability, low-impact	Low-probability, high-impact
Based on average indicators, e.g. loss of load frequency	Based on risk profile, e.g. conditional expectation
Shorter term, typically static	Longer term, adaptive, ongoing
Evaluates the power system states	Evaluates the power systems states and the state transitions
Concerned mainly with customer interruption time	Concerned with customer interruption time and infrastructure recovery time

Table 3 - Comparison of Security and Resilience

2.3. CONTRIBUTIONS - CASE STUDIES

Case Study 1 is a general investigation of the impacts of natural hazards on the electric supply system. It also investigates strategies to increase the resilience from a grid planning perspective against this type of threat.

Case Study 2 is based on an event that happened in the Norwegian distribution grid in 2007 and was caused by a natural hazard.

Case Study 3 relates to a disturbance caused by a combination of several accidents in the Norwegian high-voltage grid in 2004 that led to a wide area outage.

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Case Study 1 | Impact of natural hazard on the electrical supply system and strategies to increase the resilience

Synopsis

This case study starts with the identification of impacts natural hazards can have on the electrical supply system. Then measures to increase the resilience of power systems in the case of natural hazards are discussed. These measures focus on the domain of network planning.

Findings

Overhead lines are often exposed to extreme weather, especially thunder-/winter storms and hurricanes. They are exposed to a high probability of destruction through bend down trees or fragile power poles.
The n-1 safety rule is not sufficient for every case, especially when large areas are affected by floods, storms and hurricanes. Often the particular backup paths or components to repower the affected areas are also affected by the weather event.
Placement and elevation of substations can be not sufficient in terms of resilience in case of hazards. Flooding of substations which are still powered can cause severe damage to the equipment and presumably results in long repair times [19,20].
Also, the placing and quantity of switches in the power system play an important role. Sometimes switches are not remotely controllable or located in places which are affected by the hazard and therefore not controllable. If only very few switches are available, it is not possible to isolate only a small part of the grid. Instead whole feeders/large areas should be isolated [21].
If the power grid does not contain any micro grid capabilities, isolated areas are not able to restore/repower themselves and cannot make use of DERs and battery storages.

Discussion

Cables instead of overhead lines reduce the risk of damage through bend trees, instable poles and short circuits through foreign objects. These circumstances mostly occur during severe storms. In case of a flood and storm surge, overhead lines can be the better choice over cables, if substations are elevated or capsuled against ingress of water. Another opportunity is the choice of a different path of the lines/cables to minimize the risk of damage through natural events.
For already highly meshed grids like high and medium voltage power systems, n-2 and higher safety measures are relatively easy to realize. For low voltage grids, this may not be reasonable with regard to expenses and the usual small expansion of the grid.
Placement and quantity of switches is important to confine the impact of destroyed equipment to a small area and a small number of customers. This is only reasonable if the DSO is able to control the switch in case of a hazard, e.g. by remote control or manual access through staff.
Micro grids enable small areas of the grid to run in island mode. This is useful if a part of the grid is isolated and there is no potential of repowering through the separated grid. This is only possible if enough plants, DER´s, battery storages and control options are available.

Conclusion

Most problems in power grids result from the choice of wrong type of technology (e.g. line vs. cable) or the wrong placement of equipment. It is important to assess possible risks and events affecting the area of the planned grid and to adapt the technology respectively. Sometimes the least expensive implementation is not the best solution regarding future dangers.

Recommendations

The simplest and perhaps most effective solution to most of the risks through natural hazards is the choice of the right path and the right placement of lines and substations, to eliminate the most likely dangers right up front. But often the amount of existing placing options is small so one needs to determine the best solution for the respective case.

Highly meshed grids, n-(2+x) safety and micro grids seem to be the best methods to reduce the chance and the duration of large outages during natural disasters if the placement of equipment is immutable.

References

[19] J. M. Boggess, G. W. Becker, and M. K. Mitchell, "Storm & flood hardening of electrical substations," in *2014 IEEE PES T D Conference and Exposition*, 2014, pp. 1–5.

[20] S. Mohagheghi and P. Javanbakht, "Power Grid and Natural Disasters: A Framework for Vulnerability Assessment," in *2015 Seventh Annual IEEE Green Technologies Conference*, 2015, pp. 199–205.

[21] M. Zare, A. Abbaspour, M. Fotuhi-Firuzabad, and M. Moeini-Aghtaie, "Increasing the resilience of distribution systems against hurricane by optimal switch placement," in *2017 Conference on Electrical Power Distribution Networks Conference (EPDC)*, 2017, pp. 7–11.

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Case Study 2 | Breakdown of both power lines to Steigen – Norway 2007

Synopsis

Steigen – a small community with less than 3000 inhabitants in Northern Norway – lost its power supply for nearly 6 days in January 2007 due to failures and breakdown of both 66 kV lines supplying the community. This event was triggered by heavy storm, and the repair work was delayed by the harsh weather.

Findings

Two unwanted events occurred. The first was the breakage of the wire on overhead line (OH) 1 due to strong wind combined with heavy icing. Overhead line (OH) 2 was immediately connected to supply the load. During the night, this line disconnected twice due to short circuit/overload. Then OH 2 was permanently disconnected due to earth fault caused by breakage of the wire. Shortly after the OH2 was repaired and reconnected, a new breakage of the wire occurred. Which then was repaired, but after OH 2 gradually was uploaded, the OH2 line broke again. In total three line breakages occurred on OH 2, and constitute the second unwanted event. After the third repair, the OH 2 line was loaded to handle about 50 % of the load demand. Meanwhile the repair of OH 1 was interrupted and delayed by the continuous harsh weather (strong wind and snow, restricted view and lack of daylight). Power supply was partially and temporarily restored using a few reserve supply units and the available capacity in OH 2 was shared between the different zones by rotating connections. In addition, several parts of the distribution network were damaged.

Discussion

Steigen is normally supplied by one 66 kV line (OH 1) while the other line (OH 2) is on stand-by (hot). A similar event occurred on OH 1 about 13 years earlier, but with a limited consequence as OH 2 was connected to restore the supply. Due to this experience and the fact that there had been very few faults on these 66 kV lines during the past 10 years, there was no reason to believe that such an extraordinary event could take place. However, in the meantime OH 2 which was more than 50 years old had deteriorated and the technical condition severely weakened. Both lines are routed in areas with harsh weather conditions, making the lines exposed to failures and harsh conditions for repair work. There is no local generation in this area, and Steigen is vulnerable to the loss of both lines. There are plans for a hydro power station in the area which will cover the whole consumption of Steigen.

Several barriers have been identified to having the potential of limiting the extent of the power system failure or reduce the consequences. These have been divided into four categories based on their ability to prevent component failure, power system failure, long-term power system failure and reduce end-user's consequences. Barriers to prevent component failure, include adequate choice of right-of-way's regarding wind and ice-loads, good construction work and commissioning tests, better inspection and condition monitoring skills, competences and routines, reinvestment in deteriorated lines, and testing of capacity of lines used for hot stand-by. Barriers to prevent power system failure, include better risk and vulnerability analyses and contingency plan regarding loss of both lines, and establish local generation such as the planned hydro power station. Barriers to prevent long-term power system failure include transport preparedness, sufficiently available amount of spare parts and personnel, stand-by arrangements like large mobile reserve units/power plants, and plans for number, capacity and connection points for reserve units. Barriers to reduce end-users consequences, include coordination of emergency preparedness in the community and with the network company, alternative sources of energy, emergency fuel supply, reserve units, shelters, and provision of and access to alternative/emergency communication.

Conclusion

Most problems in power grids result from the choice of wrong type of technology (e.g. line vs. cable) or the wrong placement of equipment. It is important to assess possible risks and events affecting the area of the planned grid and to adapt the technology respectively. Sometimes the least expensive implementation is not the best solution with regard to future dangers.

Recommendations

Steigen lost its power supply for nearly 6 days due to failures and breakdown of both 66 kV lines supplying the community. This event was triggered by heavy storm, and the repair work was delayed by the harsh weather. Steigen is normally supplied by one 66 kV line (OH 1) while the other line (OH 2) is on stand-by (hot). However, deteriorated and the technical condition had severely weakened the 50 years old OH 2. This in combination with the fact that no local generation was installed in the area, made Steigen vulnerable to the loss of both lines. Therefore, one preventive measurement is establishing local generation. There are plans for installing a hydro power station in the area which will cover the whole consumption of Steigen.

References

[22]. Nybø A., Kjølle G. (2010). Project memo: Analysis of blackouts and extraordinary events in the power system. SINTEF Energy Research

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Case Study 3 | Delayed protection response - Western Norway 2004

Synopsis

A large area of Western Norway experienced blackout on February 13th, 2004. The situation occurred due to a failure of a line joint followed by delayed and unselective protection response causing two 300 kV lines to disconnect.

Findings

Four unwanted events occurred. The first was a line split due to gradual deterioration caused by overheating due to current transferred through the steel core of the line/joint. The area was normally connected to the rest of the grid through two 300 kV lines in the south and one in the north. Therefore, the occurrence of this line spilt on one of the southern lines was first interpreted as a high impedance fault by the distance protection, and thus the breakers did not disconnect. This delayed and unselective protection response on the two southern lines was the second unwanted event. As the fault current increased, it was detected by the protection on both southern lines which then tripped their respective lines. The remaining connection in the north experienced a 50 % overload and tripped, separating the area from the rest of the grid. The third unwanted event was malfunction of frequency protection causing too many generators to fall too early in the separated grid. This ultimately led to collapse of the whole area, and the fourth unwanted event. Almost 500 000 people and several large industrial sites were affected by the blackout. 2400 MW were interrupted, but most of the power was restored within 1 hour.

Discussion

The affected area was characterized by limited transmission capacity from the central grid. In 2004 three lines made up two interfaces with the central grid, making these interfaces critical for the supply of the area. After the blackout, the system was in a vulnerable state until the damaged 300 kV line was repaired and the normal operation resumed (approx. 3 days after the blackout). Malfunctions of protection made the system vulnerable to the failure of a single component by allowing one failure to trip two critical lines. Protection also disconnected generators early, making it more difficult to limit the voltage drop.

Four barriers have been identified as having the potential to limit the extend of this type of power system failure (or reduce the consequences). One barrier to prevent component failure is to have better instructions/competence and choice of material when installing the line joint. Another barrier is monitoring components. One solution is having a thermograph, which might have revealed overheating of the line joint (causing mechanical degradation). One barrier for preventing power system failure is increasing the redundancy in the grid. This could be achieved by increasing transmission capacity and /or increasing production. Another barrier is increasing the selective line protection and increasing the performance of the generator protection.

Conclusion

Three lines made up two interfaces with the central grid, making these interfaces critical for the supply of the area. When a line split on one of the southern lines occurred, it was first interpreted as a high impedance fault by the distance protection, and thus the breakers did not disconnect. This led to increasing fault current which was detected by both the southern lines which then tripped. Malfunctions of protection made the system vulnerable to the failure of a single component by allowing one failure to trip two critical lines. The remaining connection in the north experienced a 50 % overload and tripped, separating the area from the rest of the grid. The frequency dropped fast, generators disconnected and the whole area collapsed. Almost 500 000 people and several large industrial sites were affected. 2400 MW were interrupted, but most of the power was restored within 1 hour. Some suggestions with the potential to limit the extent are monitoring components, increase the redundancy, and more selective line protection.

Recommendations

For this blackout, barriers with the potential to limit the extent of the unwanted event or reduce its consequence have been identified. It should be noted that the improvement potential and the costs of enforcement varies significantly between the different barriers identified, and it was outside the scope to assess this explicitly, in the memo used as a reference for this use case.

References

[22] Nybø A., Kjølle G. (2010). Project memo: Analysis of blackouts and extraordinary events in the power system. SINTEF Energy Research

3. INTERDEPENDENCE OF THE ELECTRICAL INFRASTRUCTURE AND OTHERS

3.1. INTRODUCTION

Several projects around the world have demonstrated so far, the necessity to understand how heterogeneous infrastructures work together and how vulnerabilities and failures on one infrastructure can have negative (if not catastrophic) impacts on other interdependent infrastructures.

Considering the scope of this CIRED working group, identifying interdependencies between infrastructures is a major task in order to propose accurate responses to hazard or common mode failures, more specifically we are interested in sharing experiences about how this new digitalization and the global vision of Systems-of-Systems has had an impact on the power distribution network resilience.

Therefore, the first step is to identify the types of interdependencies according to the literature, the second step is to share real cases where a failure on another infrastructure or a common cause event have impacted the business continuity of the power distribution network.

Finally, we consider important to define the level of dependency existing between the different sectors, which will help us to define a response strategy to High Impact Low Probability (HILP) events.

3.2. THEORETICAL FRAMEWORK

Nowadays it is clear that there are dependences between Critical infrastructures, however they are either tangibles or intangibles and build a complex coupled System-of-Systems (SoS) which is complex to protect [23]. A SoS is characterized by highly automated networks with multiple complex interdependencies. Many efforts have been made to classify the type of interdependencies of critical infrastructures. The first known paper on this subject identified four types of interdependencies [24, 25]:

1. *Physical*: Represented by a physical linkage between the inputs and outputs of two agents in different infrastructures, e.g. power systems supply power to oil infrastructures for pump stations and control systems.

2. *Cyber*: connects the state of one infrastructure to others, depending on information transmitted through the communications infrastructure, e.g. water facilities depend on ICT to supervise and monitor the water pumping and cooling. Other authors proposed to call it “Informational,” in order to include hardware and software [26].

3. *Geographic*: Infrastructures geographically located at the same place, where a single event can negatively affect them, e.g. in power substations when a transformer explodes and the fire burns communication cables, affecting the information and communication system. The term "geospatial" was proposed as well in the literature [26].

4. *Logical*: When the state of one infrastructure depends on the state of another infrastructure via a connection that is not physical, cyber nor geographic, e.g. the European

outage in 2006, despite it was a 30 minutes outage, French relief centers were inundated with calls [27].

Stefano di Porcellinis et al proposed a fifth interdependency called '*Social*', when the functioning of the whole system relies on the human behavior and activities, e.g. when a worker's strike blocks off train rails [28].

Type of failures

Since CIs are interdependent, a failure on one infrastructure can have a catastrophic impact against other infrastructures in the System-of-Systems. Three types of failures are identified [2423]:

1. *Common mode*: Occurs when two or more infrastructures are affected simultaneously because of an external and common cause, e.g. tornado and earthquake.
2. *Cascading*: Occurs when a failure in one infrastructure causes a failure in a second infrastructure.
3. *Escalating*: Occurs when a failure, resulting from the interaction between two infrastructures, exacerbates another failure.

Table below presents which CIs originated an event and which CIs are affected by the event. Data are from a database containing recordings of 2515 CI's failures in multiple CIs around the world. The energy infrastructure has the higher number of incidents affecting other infrastructures. As well, industry, telecom and water infrastructures have an impact on the energy infrastructure, illustrating the need to understand the causes of these incidents and how these infrastructures are linked. A complete analysis is presented by Eric Luiijf et al [29].

Therefore, as mentioned in [30], it is needed to create new conceptual approaches and extended analytical tools to knowledge the critical linkages between CIs in order to prevent critical failures and to improve the Power Systems resilience.

Events categorized by initiating and affected sector (# of events)

	INITIATING SECTOR											
CI SECTOR	No Sector	Energy	Financial Services	Government	Health	Industry	Internet	Postal Services	Telecom	Transport	Water	**TOTAL**
EDUCATION	1	1	-	-	-	-	-	-	-	-	2	4
ENERGY	515	65	-	-	-	4	-	-	2	1	3	589
FINANCIAL	34	5	3	-	-	-	3	-	15	-	-	60
FOOD	4	3	-	-	-	-	-	-	-	1	-	8
GOVERNMENT	27	17	-	1-	1	1	4	-	14	1	1	67
HEALTH	23	11	-	-	2	-	-	-	2	-	1	39
INDUSTRY	12	12	-	-	-	1	-	-	-	1	1	27
INTERNET	109	14	-	-	-	-	10	-	27	-	-	160
POSTAL SERV.	1	-	-	-	-	-	-	-	-	-	-	1
TELECOM	170	62	-	-	-	-	1	-	57	5	-	295
TRANSPORT	294	98	-	1	-	3	-	1	5	15	5	422
WATER	58	14	-	-	-	2	-	-	-	-	2	76
TOTAL	1248	302	3	2	3	11	18	1	122	24	15	1749

Table 4 - Events categorized by initiating and affected sector

3.3. STATE OF THE ART

Three main activities sectors have been identified by the WG as dependent infrastructures on power distribution networks: Telecommunication facilities that supports coordinate emergency responses under HILP events. The transport sector, that frequently share corridors through the road system with the power systems. And the third one, a secondary but important interdependency exists between electricity networks and water infrastructure. Some of these interdependencies are presented through the case studies.

External events, such as fire, floods, hurricanes, can impact power distributions networks as well. For instance, overhead power lines might be vulnerable to fire, as is the case in Australia, where those lines are predominantly supported by hardwood timber poles. Native Australian hardwoods are a comparatively dense and long-lived material, and while originally original slow-growth premium timbers without chemical preservative treatment were originally used. Currently plantation timber chemically treated with Copper-Chromium Arsenate is widely used, although alternative materials such as spun concrete, tubular steel, treated softwoods and fibre-reinforced cement are also used.

Many projects have deal with critical infrastructures interdependencies. For instance, STREST EU funded research project targeted four main objectives: to establish a common and consistent taxonomy of Critical Infrastructures (excluding Nuclear facilities), to develop a modelling approach to hazard, vulnerability, risk and resilience assessment of HILP events, to design a stress test framework to address the vulnerability, resilience and interdependencies of Cis and to enable the implementation of European policies for systematic implementation of stress tests.

RESILIENS project is also interested on the cross sectorial interdependencies and the cascading effects. This project highlighted the need of a formulation of definite guidelines and an in-depth analysis of interdependencies, mostly because this work has been done on other projects predominantly in the context of risk management and not in the context of resilience management.

3.4. CONTRIBUTIONS - CASE STUDIES

Hereafter two case studies are described. The first one, Case study 4, concerns the study of interdependencies of a Power Distribution Network under Fire Conditions. The other one, Case study 5, is an example of a power outage of Oslo Central Station, which caused malfunctions on several communication systems and the interruption of train traffic in Eastern Norway.

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Case Study 4 | Interdependencies of a power distribution network under fire conditions – Australia

Synopsis

A particular concern in the Australian context arises from operational interdependencies between agencies responsible for emergency response in bushfire, cyclonic and flood situations, with these agencies in turn relying upon physical infrastructure, particularly telecommunications, water, transport and electricity.

In densely populated areas, reliance can be placed on telecommunications facilities either offered by Government agencies or by commercial telecommunication service providers under secure service level agreements. In more sparsely populated areas, reliance may be placed on satellite communications or shared telecommunications facilities offered by local bodies (e.g. Mining operations) or local government providers. In each case, security of power supply must be dealt with on a locational basis with specific factors considered.

Transport infrastructure is seen as a two-way interdependency. In urban areas, traffic signaling is reliant on electrical supply, conversely access to electricity infrastructure subject to fire impact is enabled by traffic signaling. In rural areas, access to electrical infrastructure subject to fire impact is enabled by aerial and road traffic infrastructure. In both cases, electricity infrastructure may be a causal factor for fire.

Findings

Power Distribution Networks as a source of ignition for fires

The Electricity Supply Industry in Australia has responded to previous bushfire events associated with overhead lines by establishing Energy Network Association (ENA) Industry Guidelines for disabling auto-reclose functions on Overhead Lines on high bushfire risk days and prevention of pole-top fires, widespread use of Aerial Bundled Conductor at low voltages, establishing firm operating protocols for the management of privately-owned overhead lines, engaging in extensive research into vegetation management, low fire ignition risk apparatus, etc. As previously noted, the diversity of operating environments for electricity assets in Australia results in solutions tailored to suit local circumstances. However, in a more general sense, Industry Guidelines for the design and operation of overhead power lines have been widely adopted since the 1960's (most recently, Australian Standard 7000:2016 Overhead Line Design [31]) and these Guidelines are directed towards establishing design parameters which minimize the likelihood of Overhead Line failure which may (among many other things) cause fires.

While the management of vegetation adjacent to powerlines has significant variation across Australia, this is widely recognised as the primary risk management control for the prevention of fires ignited by overhead power lines. However, it is also recognised that under extreme climatic scenarios (especially high temperature, low humidity, high wind) that there are limits to the effectiveness of vegetation management in managing fire risk. In particular, the distances to which vegetation is cleared away from power lines are dictated by electrical safety, not fire risk. As a result, these distances are significantly smaller at low voltage even though the fire ignition risk from a low voltage line is demonstrably the same or greater than that for a high voltage line. The practical difficulty in increasing clearance distances at distribution voltages to reduce fire risk is highly significant.

Fire risk in suburban and urban areas is more commonly associated with substation facilities which often contain flammable materials (especially mineral oil) in substantial quantities. Australian Standard (AS) 2067:2016 Substations and high voltage installations exceeding 1 kV a.c. [32] and ENA Doc 018 – 2015 Guideline for the Fire Protection of Electricity Substations [33] contain extensive material detailing design and operating principles to reduce the risk of fire spread within substations and from substations to adjacent properties and infrastructure. Of these principles, the use of segregation and fire-proof barriers are perhaps the most important, with a particular focus on the ability of fixed structures in substations to survive fire events in order to reduce restoration time.

Power distribution equipment and Overhead power lines as an asset vulnerable to damage during fires

Industry collaboration has again been the dominant mechanism by which this issue has been managed. ENA Doc 026-2010 Guide for the selection and management of poles to reduce damage and loss when they are exposed to bushfires [34] deals extensively with this issue. AS 2067 and ENA Doc 018 also refer extensively to the ability of substation installations to survive fire events, whether they are internally or externally initiated.

As noted above, vegetation management clearance distances are largely dictated by voltage and electrical safety, not fire risk. As a result, the survivability of distribution installations in fire conditions is much lower than for transmission, and naturally distribution installations are much more widespread.

It is noted that in a recent economic determination, the Australian Energy Regulator (AER) declined to approve an application for a step change increase in vegetation management expenses resulting from a proposal to enhance bushfire risk management in an area with a particularly high exposure. Additionally, and in conflict with the findings of the Victorian Bushfire Royal Commission [35]*, the AER is not generally supportive of accelerated programs for aged asset replacement.*

Electrical supply to emergency response telecommunications facilities (and inter-agency coordination).

In a rural or semi-rural setting, this will generally result in additional measures to reinforce the reliability of electrical supply through redundancy or back-up systems, although reliance can also be placed on satellite communication systems, as well as radio and mobile telephony.

In an urban setting, further measures are available to ensure the security of electrical supply to emergency telecommunications facilities.

In Australia, emergency telecommunications facilities are offered by a combination of commercial and Government providers on a largely regional basis. For example, in NSW a Government Radio Network (GRN) offers partial regional coverage of the jurisdiction to not-for-profit emergency service providers, which provides direct radio contact with a central control room tasked with surveillance and coordination between providers. Discussion continues as to whether electricity networks recently transferred to private operation and control can continue to access these facilities without breaching regulatory provisions designed to protect the commercial rights of telecommunications service providers. Emergency coordination in the case of major fire events would clearly dictate in favour of continued access by the electricity networks. In areas not covered by the GRN a variety of solutions are used with the electricity networks making extensive use of their own internal telecommunications facilities.

Interdependencies with the transport sector

In a rural setting, the road system is frequently quarantined by emergency services for a week following an extensive bushfire, especially in a treed region. This is largely based around a safety case ensuring that trees are not likely to collapse. Initially, aerial surveillance can be used (by fixed wing, helicopter or drone) to assess the extent of damage, however, roads and tracks need to be released to allow access by electricity personnel for supply restoration, which usually requires detailed inspection followed by heavy equipment (pole trucks, elevating work platforms, cranes, etc.).

Rural electricity networks are frequently at least partly radial i.e. supply cannot be switched to an alternate source. Further, an extensive fire event may damage multiple lines, rendering redundancy ineffective and automation (e.g. sectionalisation) only partially effective.

In an urban setting, loss of supply to road transport signaling systems limits the ability of emergency services personnel to rapidly access and extinguish a fire (increasing the potential extent of damage which may impact a major electricity network installation or other significant infrastructure facility) and also reduces the speed with which electricity network personnel can restore supply to re-enable traffic signaling.

Interdependencies with water infrastructure

In urban areas, water pumping stations with redundant secure supplies ensure that sufficient quantities and pressures of water are available at hydrants installed at substation locations. Loss of supply to pumping stations arising from fire is rare.

In rural areas, most reliance is placed on mobile facilities (e.g. fire trucks with water tanks), and accordingly the critical interdependency during emergency response is between transport and portable water.

In some jurisdictions, Memoranda of Understanding are in place between emergency services providers responsible for fire response and electricity networks. These Memoranda make provision for safe access and site control for firefighting, in concert with building regulations which specify the availability of pressurized water supplies at major electricity installations and other significant facilities and buildings.

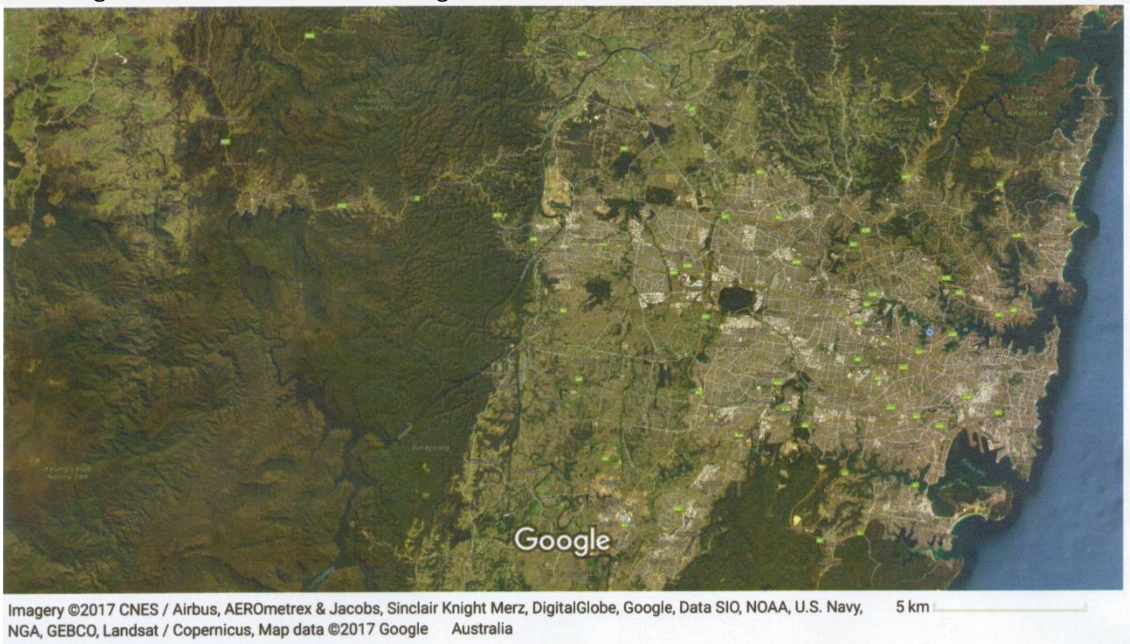

Figure 3 - Sydney, New South Wales, Australia, showing infringement of urban development on high fire risk areas.

Conclusion

The Regulatory focus in Australia has been almost exclusively focused on managing the risk of fires CAUSED by overhead power lines and associated facilities in rural and urban fringe areas.

Electricity organizations in Australia have collaborated extensively to develop practices intended to reduce the likelihood of fire ignited by electricity assets, and to improve the physical resilience of electricity assets against fire damage.

The Australian Energy Regulator is not supportive of measures designed to reduce fire risk if this results in increased cost to customers.

The critical infrastructure interdependencies are with **telecommunications** for coordination of emergency response, and **transport** for access to electricity network facilities. However, the focus has been on coordination between different authorities for emergency response rather than specific measures related to grid resilience except on a local needs basis.

References

[31] Australian Standard 7000:2016 Overhead Line Design

[32] Australian Standard (AS) 2067:2016 Substations and high voltage installations exceeding 1 kV a.c

[33] ENA Doc 018 – 2015 Guideline for the Fire Protection of Electricity Substations

[34] ENA Doc 026– 2010 Guide for the selection and management of poles to reduce damage and loss when they are exposed to bushfires

[35] Victorian Bushfires Royal Commission

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Case Study 5 | Fire at Oslo central station - Norway 2007

Synopsis

In 2007 a minor fire in an 11 kV cable caused a power outage and evacuation of Oslo Central Station. Several communication systems were put out. The train traffic in Eastern Norway was completely out of service for 20 h, effecting 80 000 passengers, while the telephone and computer traffic was disrupted for approximately 10 hours, effecting more than 25 000 customers. The cause of the fire was a permanent earth fault on another cable on the same transformer circuit, caused by digging activity in the area [36].

Findings

Four unwanted events occurred. The first was a damaged cable caused by digging. Then a permanent earth fault induced failure led to disconnection of two cables. This is the second unwanted event, and it led to fire in the nearby cable culvert damaging electricity and telecom cables. The third cable which supplies the central station was automatically disconnected, leading to the area being without external supply. Then the traffic monitoring central was powered by emergency supply (UPS). The third unwanted event is that the electricity in the area had to be cut off. This was done to facilitate safe working conditions for the firemen. After the fire was extinguished, the emergency generator was turned back on. Supply was restored by provisional cable after approximately 15 hours, while the permanent repair took additional 7 hours. The forth unwanted event is that there was not sufficient emergency generator capacity available.

Discussion

The fact that many cables were placed in the same culvert and / or within the same fire cell made the system vulnerable. In addition, emergency generators were not sufficiently available and tested, and thus did not function properly. The emergency preparedness was not adequately planned, and areas of responsibility were not properly defined.

Several barriers have been identified to having the potential of limiting the extent of the power system failure or reduce the consequences. These have been divided into four categories based on their ability to prevent component failure, power system failure, long-term power system failure and reduce end-user's consequences.
Barriers to prevent component failure: include vigilance during construction work, and replacement of 11 kV cable joints particularly susceptible to earth faults.

- Barriers to prevent power system failure: include redundancy in systems; both in case of failure and in case of fire, limit the amount of cables in the same culvert, and improved registration and handling of earth faults.
- Barriers to prevent long-term power system, include available and well maintained and tested emergency generators as well as defined responsibilities for these, and use of provisional cables in the restoration process.
- Barriers to reduce end-users consequences, include back-up solutions in connected infrastructure (ICT, railway), barriers to reduce vulnerabilities related to the interdependencies between electric power and ICT and other critical infrastructures, and coordination of efforts and clarification of responsibilities between different actors.

Conclusion

In 2007 a minor fire in an 11 kV cable caused a power outage and evacuation of Oslo Central Station. The cause of the fire was a permanent earth fault on another cable on the same transformer circuit, caused by digging activity in the area. The fact that many cables were placed in the same culvert and / or within the same fire cell made the system vulnerable. In addition, emergency preparedness was not adequately planned, and areas of responsibility were not properly defined. The problems related to this blackout, were mostly related to inadequate back-up systems in connected infrastructure.

Recommendations

For this blackout, barriers with the potential to limit the extent of the unwanted event or reduce its consequence have been identified. It should be noted that the improvement potential and the costs of enforcement varies significantly between the different barriers identified, and it was outside the scope to assess this explicitly, in the memo used as a reference for this use case. Still, because the problems related to this blackout were mostly related to inadequate back-up systems in connected infrastructure, the focus should be on barriers reducing the end-users consequences.

References

[36] José Sanchez Torres (2013) Vulnerability, Interdependencies and Risk Analysis of coupled infrastructures: Power Distribution Network and ICT. PhD Dissertation, Grenoble INP - G2ELab.

Abruzzo – Winter 2017

4. EVALUATION OF NEEDS AND EXISTING RESILIENCE

4.1. INTRODUCTION

Building resilient distribution networks that can withstand and quickly recover from extreme events is becoming of increasing concern and importance for distribution system operators worldwide given the significant social and economic impact of these disastrous events. This is becoming of growing criticality given the emergence of transformative technologies and the transition from the classical centralized systems to more decentralized systems with the large deployment of distributed energy resources, where new resilience and flexibility services are arising. Hence, resilience has become highly critical and the concept of critical infrastructure resilience is now quite well known, not only by the risk analysis experts. Regulatory Authorities and Critical Infrastructure manager are more and more conscious of the need to increase the resilience of the Critical Infrastructures.

However, there are still various critical questions to answer as power engineers in order to make the shift towards resilience-oriented thinking and engineering. How can you decide if a critical infrastructure is resilient or not? How can you establish that a system is more resilient than another one? How can we measure resilience? How can we select the priorities in a plan for increasing the resilience of a distribution grid? What are the best strategies to consider and apply for boosting resilience? Do we make the network smarter, bigger or stronger? When a critical infrastructure can be considered resilient enough?

Comparisons, priorities, targets imply the need to find a way to assess the present resilience of critical infrastructures and to focus a target, to set an acceptable resilience level.

Therefore, the scope of this chapter is to define a reasonable and common way to measure and quantify the resilience of a particular set of critical infrastructures, the electrical distribution grids.

4.2. THEORETICAL FRAMEWORK

As the resilience of a critical infrastructure concerns its ability to withstand extraordinary and extreme events, minimizing outages and recovering rapidly normal operation from disruptions, a resilience index set of resilience metrics should take care of the following main parameters:

- How likely is the extraordinary event and how severe is the event (event probability and intensity);
- How does the system behave during and following the event;
- How sturdy and reactive is the system (system robustness and recover capacity);
- How heavy are the outages and the consequences for the stakeholders (disruption impact);
- How long does the outages last (disruption, reaction and recovery duration);
- How do we measure the different aspects of the multi-faceted concept of resilience (e.g. infrastructure and operational resilience, as well as business continuity)?

Further, the set of metrics used for quantifying resilience should be capable of measuring both short-term and long-term resilience. The former refers to those metrics for quantifying the resilience performance of the network before, during and after an event, while the latter refers to the metrics for quantifying the long-term adaptation, transformation, planning and decision-making for improving the robustness of the network to future catastrophic events.

The analysis of the resilience of the electric distribution grid involves several different stakeholders (the electrical system regulatory authority, the HV grid system operators, the several electrical distribution grid companies, the final users), therefore the set of resilience metrics indexes should result as much as possible from measurable and objective parameters. Even though several indexes can be considered, when you have to compare different situations you should select only a single representative index.

In Chapter 2 "Impact *of different events to the electrical supply system*" the majority of the events that can threat an electrical distribution system were considered, Chapter 3 "*Interdependence of the electrical infrastructure and others*" described the many interdependencies between Critical Infrastructures. The set of resilience metrics should be of generic applicability and validity for a lot of different events that could threaten the system, in order to match the resilience of the system against all of them, and these metrics should as well give a Global System Vision about the impact of other infrastructures on the Power Distribution Resilience.

4.2.1.EVENT PROBABILITY AND IMPACT

Event probability and event intensity are generally related, as frequent events generally have lighter (or none) consequences, while low probability events can be very disruptive. Based on this and simply defining risk as the product of probability and impact, there are thus two mains categories of events that a distribution network should be capable of dealing with: high-probability, low-impact and low-probability, high impact. Traditionally the distribution networks have been designed to be reliable to the former, but less resilient to the latter mainly due to the uncertainty related to their frequency of occurrence (making it thus difficult to justify large investments to deal with threats whose frequency is low or unknown).

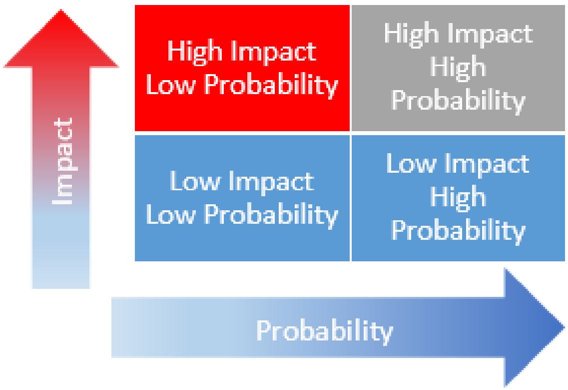

Figure 4 - A simple Risk Matrix

If a certain kind of event has already occurred several times in the past, the statistical analysis of the historical data (if available) can generally provide insights to a statistical distribution that links the intensity of the event and its repetition probability, allowing to set a value to the probability that an event of a certain intensity will happen again. This is the case of the majority of the weather-related events. This repetition frequency could be expressed as event "return period" (as per CEI EN Standard 50341-1, "*Overhead electrical lines exceeding AC 1 kV, Part 1: General requirements - Common specifications*", [46]). So, the "return period" of the event, usually measured in years, could represent the occurrence probability of an event with a certain intensity and can provide strategic insights on which events can be considered credible and non-credible.

Much harder is to set the occurrence probability of an event that never happened before, or happened only a few times (like a cyber or a terroristic attack, a transmission grid blackout, a disruption of the whole communication system).

If the probability becomes very low, also the risk (in terms of probability x consequence) becomes very low, often insignificant, and no measures are taken anyway. Still, the consequence may be unacceptable and measures must be taken to avoid the event, cf section 4.2.6 on "reverse analysis".

4.2.2.SYSTEM ROBUSTNESS

The threatening event is not part of the system and the event "return time" is not a characteristic of the system. Instead, the robustness and the reaction capability are peculiar characteristics of the system.

It is possible refer to the system robustness also with its opposites: system vulnerability (or survivability), system fragility [37], or system susceptibility [45][3]. Anyway, the underlying concept is the ability of the system components to resist without failures to the aggression of the threatening events in order to prevent or mitigate the propagation of the component failures. This property is strictly related to the design criteria and realization quality of the system components, but also to the aging and the correct maintenance of the system components.

The relation between the event intensity and the component failure is a probabilistic "S" curve, where the failure probability increases between a minimum threshold to a maximum threshold of the event intensity (fragility curves). Below the minimum threshold the component is surely safe, above the maximum threshold the component is surely broken [37].

A generic fragility curve showing how the failure probability of a component can related to the weather (or hazard) intensity is presented in Figure 5.

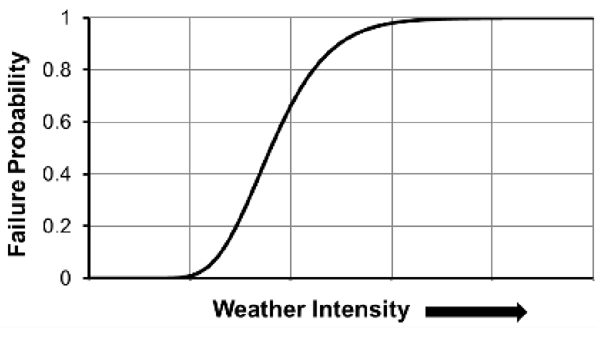

Figure 5 - Generic weather resilience curve related to an individual component

[3] Susceptibility is usually referred to human feelings, it is an excessive sensitiveness, with dudgeon. Vulnerability is referred to something that could be hurt and is usually referred to human body or feelings. It could be also referred to systems, when parts of the system fail. Fragile is something that could be broken. It could be referred to human feelings, or to the system components. Therefore, in this case, "fragility" seems preferable.

Different curves have to be considered with different kinds of solicitations, of threatening events, and the component fragility curves could generally vary in the time domain, with maintenance and ageing.[4]

However, this level of detail is possible only for not too extended system analysis. Otherwise, if so detailed information is not manageable, simply an event threshold intensity could be considered. For example, this threshold could be set equal to the solicitation which breaks component.

Finally, after the event return time, the failure probability of the system components should be considered in the resilience index.

4.2.3.RECOVERY CAPACITY

The electrical distribution grids are usually designed to avoid disruptions even in case of failures of one or more components (redundancies). More than one supply lines could often supply the critical nodes of the meshed grid. So, the distribution grid has a structural capacity to cope possible outages in a very short time, with automatic fault selection devices or remote-controlled switching operations. In particular, remote control operation allows to minimize the outage disruption time in the impacted areas, without direct intervention on site of the rescue teams, as seldom the weather and road conditions could be prohibitive and precarious, and people movement could be risky.

In the resilience assessment, usually you can neglect these transient outages and consider only the disruptions that the structural reactivity of the network could not cope in a short time.

Where the automatic devices or the remote-control operations are not available or not sufficient, skilled personnel could operate locally the electrical station switchgears to reconfigure the network. Moreover, after localization of faulted components, intervention teams could recover the grid operation by restoring or replacing faulted components. However, the time for local operation with intervention teams is relatively long and depends drastically by the location of the faults, the extension of the affected area, the weather conditions, the accessibility to the sites, the personnel safety conditions. So, after the first few minutes, the availability of human work forces with adequate rescue facilities and the organizational factors become fundamental for the recovering process.

4.2.4.DISRUPTION IMPACT AND OUTAGE DURATION

When the intensity of the event is so high that part of the system fails, the system disruptions occurs. The resilience index has to measure the impact of the disruptions. For an electrical distribution network, you can measure the outage impact by the number of users affected by the loss of electricity, or by the amount of unavailable electrical power.

[4] The complexity could further increase if you have to consider the effects of more than one solicitation at once.

However, in the resilience evaluation the time dimension is fundamental, because a short time outage could have minor or no practical consequences at all, but the longer is the outage duration, the harder are the consequences for home and industrial users.

In order to consider this time component, you should integrate the number of impacted users by the time duration till the restoration of the service. Otherwise, the energy not supplied could be considered as a parameter for resilience index.

This way you consider the outage impact (and therefore the resilience) proportional to the outage duration, but probably the user hardship is not simply proportional to the duration of the suffered outage. Perhaps specific discomfort curves could be studied and applied in order to amplify the negative effect of long lasting outages.

4.2.5.VULNERABILITY, RISKINESS

Instead of the resilience quantification, you can find conceptually easier thinking of its opposite, that could be referred to as “vulnerability” [37], or riskiness. Actually, a risk index could be considered proportional to the number of user impacted (eventually integrated by the outage duration) and to the repetition frequency of the threatening event (the inverse of the return time). This index could be expressed as number of impacted user by outage hours per year. Further, given the nature of these high-impact low-probability events, using the traditional reliability indices that focus on expected, “average” events are not sufficient. It is rather more efficient to use risk-based indices that focus on the tail of the probability distribution of the impact of the events, such as Value at Risk (VaR) and Conditional Value at Risk (CVaR).

4.2.6.REVERSE ANALYSIS FOR RESILIENCE

Another fruitful way to approach a resilience assessment is starting from the tail [38], analyzing the outage historical records and considering only the permanent located failures. A statistical study of such databases, could put in evidence all the major outages historically suffered by the distribution grid and give also the key information to reconstruct the causes of the outages. As the HILP events generally concern wide territory areas, this analysis should adopt suitable grouping criteria.

Moreover, this big data analysis should consider that the system is not static with time but could have modified its structure and coping capability (some components could be aged, some components could be replaced, new components could be added, and so on).

4.3. STATE OF THE ART

A description of a suggested methodology is provided in the paper " A Framework For Handling High Impact Low Probability (HILP) Events" [39].

Defining and measuring resilience has recently attracted the interest of several researchers, which resulted in the development of many resilience-oriented studies, including modelling techniques, enhancement strategies and metrics. Differently from the traditional reliability indices (e.g. SAIFI and SAIDI), various metrics have been proposed for specifically quantifying resilience. For example, in [40, 41, 42] resilience is quantified as the ration between the area of the real performance, i.e. during and following the event, and the targeted performance curves. A different way has been proposed in [43] where measuring resilience is focused on the proportion of the delivery function that has been recovered from its disrupted state. In [44] resilience is measured as the difference between the capacity of the fully functioning system and post-event capacity. In [45], a novel resilience metric framework has been proposed for specifically modelling and quantifying the resilience performance and behavior of a power system during an event, which is based on the new concept of resilience trapezoid.

4.4. CONTRIBUTIONS - CASE STUDIES

Hereafter two case studies are described.

The Case study 6 concerns the development of indicators for monitoring the vulnerability of power lines and the Case study 7 is an example of a resilience assessment for medium voltage distribution grid.

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Case Study 6 | Developing indicators for monitoring vulnerability of power lines

Synopsis

The case study shows how information from vulnerability analyses and existing maintenance management systems can be combined with information about threats and criticality to establish vulnerability indicators for power lines. The main focus of the study has been on lagging indicators. Results from one regional grid lines are presented in the paper used as a reference for this case study.

Findings

It was decided to establish four indicators that cover all dimensions of vulnerability. These are indicators covering threats, susceptibility, coping capacity and criticality, and are summarized in Table 5. The indicator for threat focuses on weather and climate stresses that either can cause an immediate failure or can lead to deterioration in the technical condition of the power line. Susceptibility is covered by an indicator that presents the technical condition of the power line based on data from periodically conducted maintenance inspections. Coping capacity is described by an indicator that considers the accessibility of the pole location for repair work if a failure occurs. This is estimated based on the time needed to reach that location. Consequences for society are measured with an indicator that is based on the location of critical loads and power switches in the network.

Table 5 - Selected approaches for vulnerability indicators Method

	Method	Data source	Scale
Exposure	Expert assessment based on available information	Reports about corrosivity, wind speed and ice loads	0 (extreme) 100 (little) Steps of 20
Condition	Calculation based on data	Reported deviations from maintenance inspections	0 (very poor) 100 (perfect) Steps of 25
Accessibility	Expert assessment based on available information	Map material	0 (hard) 100 (easy) Steps of 20
Consequence	Expert assessment based on available information	Location of circuit breakers and location of critical loads	0 (critical) 100 (little) Steps of 20

When studying a power line, it will usually be necessary to aggregate indicators into a composite indicator or a smaller set of indicators, either because the number of indicators is large or that the goal is to summarize the multi-dimensional aspects of vulnerability. There are at least two challenges when aggregating indicators. The first one is the scale and unit of the indicators, and the second to decide on an aggregation rule securing that no crucial information is lost through the aggregation process. A weighted average the method used for both aggregating and combing indicators in this study. The four indicators are calculated at electricity pole level and aggregated to indicators for the whole power line with the aggregation rule.

The results from one power line in the regional grid was illustrated both by an extraction of results at the single pole level, and by the aggregated results at the power line level. At both levels, indicators describing different dimensions of vulnerability were aggregated to a combined indicator. After aggregating the indicators, the results for the power line show that the condition indicator has a very high value, i.e., very good condition, exposure and accessibility is average, while the potential consequences are considered critical. However, the aggregated values must be treated carefully, since they are directly dependent on the aggregation method and weighting.

Discussion

One important lesson learned from the case study was that it is hard to find data of the required quality to assign values to the indicators at electricity pole level. Most of the indicator values were therefore assigned based on subjective assessment. A more data based approach to assign values to the indicators would be preferable to allow for a fast update of the indicators when new data are available in the maintenance system and to use the method more quickly for several critical power lines. In addition, the specification of weights for aggregation has quite an influence on final results and should be subject for a more thorough analysis. Weights should be chosen in a way that the aggregated indicators get values as would be expected from an expert user.

Conclusion

In the referenced paper, a framework for developing vulnerability indicators was presented and applied to several case studies that focused on the vulnerability of power lines. Indicator values were assigned by using available data from the maintenance systems combined with expert evaluations at the network companies. Based the work, several conclusions were drawn:

- The vulnerability framework is applicable to measure the vulnerability of power lines with indicators.
- More effort is required for developing a set of indicators that represent the whole vulnerability picture – some example indicators are tested, but a consistent set is still missing
- Weighting and aggregation rules should be evaluated to represent the understanding of vulnerability on an aggregated level.
- Leading indicators are a remaining challenge and more effort has to be invested in the further work to design leading indicators.

References

[47] - Hofmann, M., Gjerde, O., Kjølle, G. H., Gramme, E., Hernes, J. G., & Foosnæs, J. A. (2013). Developing indicators for monitoring vulnerability of power lines-case studies.

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Case Study 7 | Impact of different events to the electrical supply system

Synopsis

This case study describes the methodology adopted by e-distribuzione in order to assess the resilience of its electrical distribution grid in the case of snow and windstorms affecting the medium voltage overhead lines.

Findings

A resilience assessment of the Italian electrical grid

Worried by the impact of high impact low probability critical events, since 2016, the Italian Regulatory Authority for Electrical Energy invited the electrical transmission and distribution system operators to analyze the resilience of their grids. The Italian Transmission System Operator and Distribution System Operators considered and proposed to analyze several possible threats: mainly meteorological events, but also landslides or earthquakes, according to their specific operating experiences.

Icing and snowfalls

After a first stage of analysis, the snow precipitations were considered the most critical threats affecting the Italian electrical overhead grid. In fact, the majority of the Italian territory is mountainous, and it is not unusual that over Italy cold air masses coming from northeast regions meet warmer humid air masses coming south Mediterranean area, bringing on intense precipitations.
Mostly, severe snowstorms are becoming more and more frequent in Italy, cause of the recent global climate changes, especially in areas where once snowfalls were really unusual, in the central and southern regions, at relatively low altitudes.
The impact of a critical event is bigger just where you do not expect to have a risk.

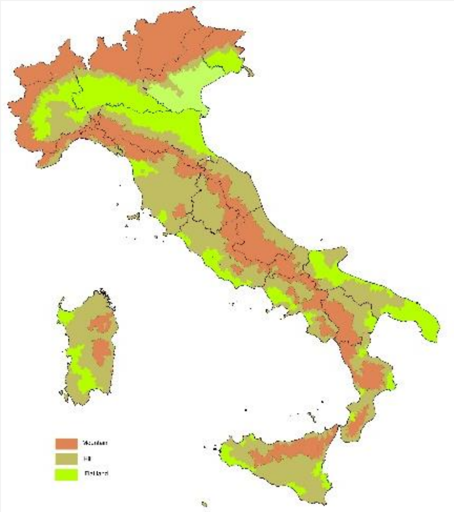


Figure 6 - map of the Italian altimetric bands: flat, hilly, mountainous lands

The icing phenomena and the snowfall can cause the formation of ice and snow sleeves on the components of the overhead lines. When the amount of ice and snow on the line structures is exceptional, the consequent overload can cause the disruption of conductors, insulators, poles, or towers.
Moreover, the snowfall can load also the tree nearby the overhead lines, so that branches or the whole tree could fall on the line conductors or poles, breaking them. The arrival of strong winds after exceptional snowfalls emphasizes the criticality, providing an additional overload to the lines.
According to e-distribuzione fault data records, roughly the 90% of faults during heavy snowfalls affect the overhead line bare conductors and wet snow precipitations are the most dangerous, because they can produce snow sleeves with thickness of several centimeters, whose overload can break the bare conductors of both MV and HV overhead lines.
Wet snowfalls are predominant in central-southern Italy. They occur at temperatures between 0.5°C and 2°C and the accretion of the snow sleeves particularly increases with weak winds, between 2 and 3 m/s (7 ÷ 11 km/h), up to 8 m/s (30 km/h).

Sometimes, after the end of the snowfall and the formation of snow sleeves on the overhead lines, more intense winds may rise to solicit the conductors.
For a complete discussion, see also ref [50, 51, 52].

The guidelines and standards

The Italian Electrical Energy Regulatory Authority in 2016 promoted, through the resilience worktable, the constitution of the CEI (Italian Electrical Standardization NC) TC 8/28 Resilience Workgroup. Member of this workgroup were the Regulatory Authority itself, the Italian TSO, the Italian DSOs (including e-distribuzione), the Italian research institutes RSE and CESI.

The Italian TSO and the major Italian DSO (e-distribuzione) had similar problems with the wet snowfalls and agreed the opportunity to refer to the CEI EN 50341-1 standard [46] and its technical National Normative Annexes (NNA) [48], as a solid reference point. In fact, in the European standard EN 50341-1 [46], "the general principles of structural design are based on the limit state concept used in conjunction with the partial factor method" and with a statistical approach coherent with the Eurocodes.

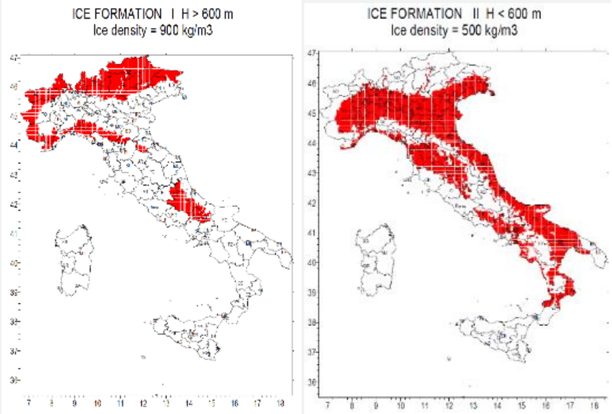


Figure 7 - An example of the icing zones defined by the CEI EN Standards, [48]

The EN 50341-1 standard [46] invites to refer as far as possible to the NNA, where available, to determine the reference values for the action of the wind and the ice or snow sleeve. The Italian NNA constitutes the Standard CEI EN 50341-2-13 [48], which gives three different types of ice or snow load. Wind speed and ice sleeve thicknesses become differentiated on a regional and / or district basis and variable with the altitude above sea level. Moreover, it defines wind coefficients according to the orography of the ground, the height above the ground, or the shape of the components.

Actually, until 2011, the Italian CEI 11-4 standard [49] for the construction of the overhead lines had a quite easier approach to the snow loads on the overhead lines and considered simply two zones:

- zone A: including places at altitudes not exceeding 800 m a.s.l. of central, southern and insular Italy: no ice sleeve accretion at all.
- zone B: including places of northern Italy and places of central, southern and insular Italy at altitudes above 800 m a.s.l.: 12 mm ice sleeves (density 920 kg/m^3) to be considered

Therefore, most of the Italian overhead lines were built according to this standard, coherent with a different climate scenario.

Figure 8 - Italy map with two ice zones, according to Italian Standard CEI 11-4:1998

Discussion

The climate changes

Even though, the Italian NNA (CEI EN 50341-2-13: 2017, [48]) marked a decisive step forward in comparison with the previous standards, nevertheless the fault events that occurred in

recent years in some Italian regions seem to overcome the expectations of NNA related to the thickness of the ice or snow sleeve.
Therefore, also the Italian Regulatory Authority recommended the electrical grid operators to consider also the most recent climatic events, and not only the values of the NNA standard in the assessment of their grid resilience.

The icing model methodology

Consequently, in order to consider also the most recent climatic events, e-distribuzione undertook a study with CESI (main Italian research institute) in 2016 to create an icing model which, starting from historical meteorological data, for each Italian municipality, estimates the conductor overload due to the possible formation of ice or snow sleeves. The methodology adopted by e-distribuzione is compliant with CEI EN 50341-1 standard [46], Appendix B, according to whom extreme ice loads can be calculated by means of an icing model.
The standard requires recording the annual maximum ice loads I_m, obtained by means of an "icing model" based on meteorological analysis. Appendix B asserts that:

- "an icing model of this type should analyse meteorological data over a period of 20 years or more"
- "a correct calibration of an icing model requires at least 5-10 well-documented icing events"

After a wide range analysis of the available technical documentation concerning this matter, the CESI task force proposed to start from the "Chaîné and Skeates" model, which resulted best suited to the daily granularity and type of the available weather data. The model took the name Pre.Ma.G. ("Ice Sleeve Forecast") and evaluates the ice or snow sleeve accretion, according to the type of conductor under examination and the local daily climate data [53].
CESI and e-distribuzione collaborated and added several modifications and improvements to the original model, aimed at better simulating the atmospheric phenomena and addressing the actual events. Nowadays, the model evaluates the increase or reduction of the sleeve for several consecutive days checking the temperature ranges suitable for the formation or melting of the ice sleeves. The model is mainly targeted to the wet snow phenomena, but considers the sleeve accretion also for low temperatures icing phenomena (glass).

Meteorological Historical Dataset

The icing model is based on meteorological historical data. In order to have sufficient data for a statistical analysis, according to appendix B of CEI EN 50341-1 [46], the input for the icing model consisted of at least 20 years of daily records of meteorological parameters.
In Italy, the military air force provides certificated weather data in just over 100 meteorological stations on a daily basis ("syrep" protocol). Moreover, the civil airport control agency (ENAV) provides additional not certified hourly data ("metar" protocol).
In order to evaluate the stress on the line bare conductors, it was assumed that the daily weather conditions were homogeneous within the territory of each Italian municipality.
A specialized company processed the historical data of the meteorological stations through distance weighted extrapolation algorithms, which allowed estimating the daily weather parameters for each Italian municipality for 21 years (from 1997 to 2017).

Matching real events

e-distribuzione grouped the overhead line conductors into different clusters, considering the most widespread types of conductors on the network (e-distribuzione standard bare conductors). Each cluster has peculiar mechanical characteristics (tensile strength, modulus of elasticity) and initial laying conditions (initial pitch of laying and length of the reference span) differentiated for the climatic zones A and B (compliant with the old historical standard prescriptions).

Starting from the available weather data, the model estimates the accretion of ice or snow sleeves on the conductors of the overhead lines in each Italian municipality, day by day, for each municipality and for each cluster of conductors.
Then, according to weather conditions, you can calculate the overload on the conductor due to both the wind pressure and the weight of ice or snow sleeves. The consequent tensile stress is compared with the tensile strength of the conductor cluster, highlighting when, where and for which type of conductor the tensile strength was exceeded.
The disruption data given by the model were matched against the significant severe events that occurred in Italy between 2012 and 2017, in order to properly set the several parameters of the model. So, real events allowed the model calibration.

The Pre.Ma.G. icing model and the distribution of Gumbel

The Pre.Ma.G. icing model gives therefore daily data as result of the meteorological parameters of the site.
So, according to Annex B of the CEI EN 502341-1 standard [46], you have to select the maximum ice or snow load I_m calculated by the icing model for each year of analysis (for each Italian municipality and for each reference conductor type). Moreover, Annex B proposes to perform a statistical analysis of the obtained yearly maximum snow loads by means of the Gumbel distribution.
In fact, the Gumbel distribution function, starting from a series of yearly-recorded maximum values, is able to estimate a probable extrapolated value in a longer period. This is particularly useful when you have to evaluate the probability of occurrence of critical events, such as the floods of rivers.

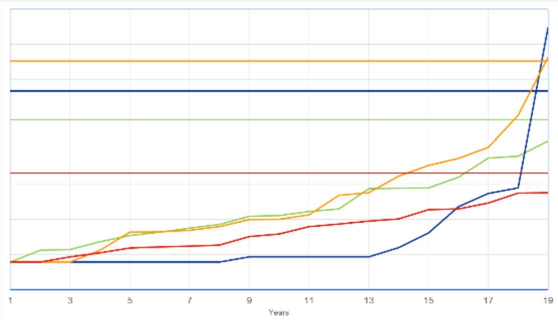


Figure 9 - Example of Yearly Maximum Values and Gumbel 50 Years Reference Value

Annex D (informative) of the CEI EN 50341-1 standard [46] suggests how to process the recorded data, in order to obtain, through the distribution of Gumbel:

- the reference value with a return period of 50 years,
- the «coefficient of variation" of the distribution ($v = \sigma / \bar{x}$, according to the dispersion of the experimental data)
- the parameters C_1 and C_2 on the basis of the years of observation.

In this case, starting from the data recorded in each year of observation (for 20 years), the statistical function allows evaluating the ice or snow load expected in period of 50 years. The CEI EN 50341-1 [46] defines this as a reference value, the extreme ice load I_{50} corresponding to a "return period" of 50 years. The "return period" is defined as the mean interval between successive recurrences of a climatic action of at least defined magnitude. The inverse of the return period gives the probability of exceeding the action in one year. This reference value has a 2% probability to be trespassed in each one of the 50 years.

So, the ice or snow load obtained from the icing model data are calculated in accordance with the guidelines of the CEI EN 50341-1 standard [46], and thus they are comparable with ice or snow loads provided by the National Normative Annexes (NNA, standard CEI EN 50341-2-13 [0]). Finally, we were able to count on two reference values of reference ice load with a return period of 50 years: the Pre.Ma.G. icing model value and the NNA standard value.

From the reference ice load I_{50} to the return time T_r of the sections of the network

For each type of standard conductor, applying the (CEI or PreMaG) local ice load I_{50} and wind force to the overhead line, we could calculate the resulting tensile stress on conductor, which

can be compared with the conductor tensile strength. Then you need to know which is the return period of the critical event of such intensity that the calculated tensile stress is equal to the conductor tensile strength.
The CEI EN 50341-1 standard [46] indicates that, starting from the values of "extreme" snow or ice loads, corresponding to the return period of 50 years, any other return period value can be calculated using the Gumbel function (appendices B and D of the standard CEI EN 50341-1)

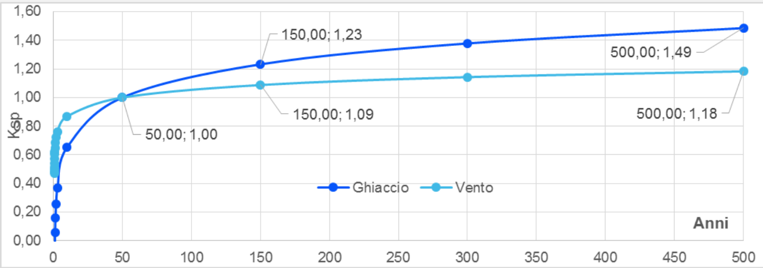


Figure 10 - The curves of ice loads and wind intensity according to the standard parameters set by the CEI EN Standard 50341-1

$$K_T = \frac{1 - K_{sp} * \ln\left(-\ln\left(1 - {}^{1}/_{T}\right)\right)}{1 - K_{sp} * \ln\left(-\ln\left(1 - {}^{1}/_{50}\right)\right)}$$

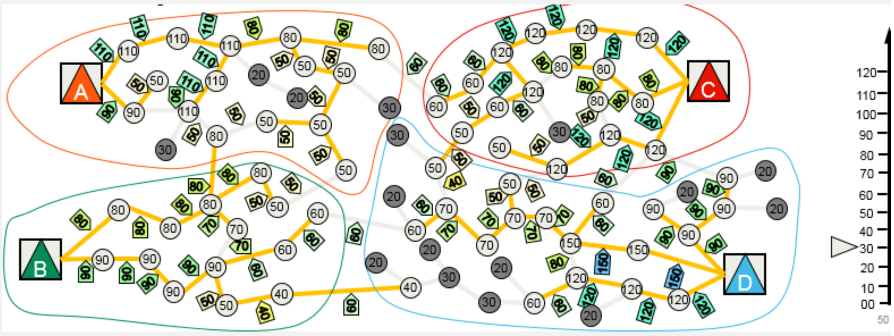
A recursive calculation for subsequent approximations is necessary to calculate the relevant return period. So, for each municipality and for each conductor cluster, we could calculate the return time T_r of the event that leads to the failure of each section of vulnerable line. Therefore, we could state that in a certain municipality the disruption of a certain conductor cluster will probably occur every T_r years. This value is the inverse of a probability.

Finally, we associated a specific "return period" to each section of the overhead lines, according to the relevant cluster of conductor and the municipality climatic history.

Identification of the most resilient path for the supply of the MV/LV substations

The MV/LV substation are the main point of analysis of the distribution network, because they feed all the MV and LV users. Therefore, the next question is which is the return period of the critical event of such intensity that it can involve the permanent outage of each MV/LV substation.
To solve this problem, we took the whole distribution network in its standard arrangement, but considering also the possibility to close every possible back-up supply line. We assumed that, for a certain return period T_r, all the sections of the network with a return period equal or minor of T_r would be unavailable. Moreover, we assumed invulnerable the HV grid supplying the HV/MV substations.
Erasing the unavailable sections of the network (light grey segments in the example), we could see all the MV/LV substation de-energized (dark grey nodes in the example)).

Figure 11 - A simplified scheme showing how the procedure evaluates the loss of supply in the MV/LV stations according to their return period



A suitable algorithm of graph visit was able to discover the most resilient supply route from the relevant supplying HV/MV substation to each MV/LV substations. The minimum return period of a supply route is the return period of the weakest section of the path, which is the section with the minimum return period along the route. Therefore, the most resilient supply route (when several supply routes are possible) is the one with the highest minimum return period. In the end, the graph visit algorithm associates each MV/LV substation to its relevant outage return period.

Impact of the disruptions

The return period of each network node ($T_{R\text{-}node}$) will be equal to the return period for which the network node power failure occurs, due to the collapse of the most fragile sections of the most resilient supply lines.
The DSO calculates the return period $T_{R\text{-}CS}$ for each MV/LV substation, on the basis of the return times of the MV supply lines, assuming the HV network invulnerable.
On the meanwhile, the TSO calculated the return period $T_{R\text{-}CP}$ for each HV/MV substation, on the basis of the return times of the HV supply lines, up to the main HV/HV network stations.
So, you can define the "disruption risk index" (IRD), as the product of the severe event probability and the related damage index (N_{ud} :number of affected customers). The disruption risk index is the inverse of the resilience index associated to any climatic event, whenever there is a relation between intensity and repetitiveness of the phenomenon.
This methodology was proposed to the CEI TC 8/28 Resilience Workgroup, and was adopted by the Electrical Regulatory Authority in the "Guidelines for the Presentation of Work Plans for the increase of the resilience of the electricity system", where the disruption risk index I_{RD} is considered equal to the ratio between number of disconnected users and return period (N_{ud}/T_R).
The guidelines of the Electrical Regulatory Authority defined the "equivalent return period" of the MV/LV substation $T_{R\text{-}CS\text{-}eq}$, which corresponds to the minimum value between the return period of $T_{R\text{-}CS}$ and the return period of the HV/MV substation $T_{R\text{-}CP}$, which normally supplies the MV/LV substation: $T_{R\text{-}CS} = \min(T_{R\text{-}CS}, T_{R\text{-}CP})$.

Likely the impact of the critical event could be better measured by the energy not supplied E_{ns}, because it takes care also of the MV users and of the duration of the disruption, but these aspects were however considered in the subsequent cost benefit analysis.

It is not easy to solve the problem to associate a right predetermined disruption duration to the possible critical events.
The fault records could help to find a correlation on average between the intensity and the extension of the critical event and the duration of the outages. In fact, we noted that the time for reparation usually increases when many disruptions contemporaneously occur and when the faults take place in mountainous regions.

Conclusion

The result of this study was the possibility to set a ranking of the MV/LV substation, with the possibility to compare different grids and situations on a common base and to perform a cost/benefit estimation.

Recommendations

The importance of the homogeneity of the parameters used in the calculations

The main goal of the Italian Electrical Regulatory Authority was to define resilience indexes as simple as possible and to obtain risk indexes consistent with the CEI EN 50341-1 standard and comparable between the various operators. To get these results:

- the meteorological data underlying the model should be the same for all the operators
- all the operators should adopt the same icing model, calibrated with the same parameters

- the Gumbel distribution parameters for calculating the reference wind intensity and the ice load should be calculated in the same way by all the electrical system operators and should be consistent with the underlying model data

Implementation

On the basis of the actual results, the TSO and DSOs developed, according to the authority guidelines, a resilience plan of interventions.

References

[46] CEI EN Standard 50341-1:2013 "Overhead electrical lines exceeding AC 1 kV, Part 1: General requirements - Common specifications"

[48] CEI EN Standard 50341-2-13:2017 – "Overhead Electrical Lines Exceeding AC 1 kV Part 2-13: National Normative Aspects (NNA) for Italy (based on EN 50341-1:2012)"

[49] CEI Standard 11-4:1998, "Installation of Overhead Lines"

[50] «Guidelines for meteorological icing models», CIGRE TB 291, working group B2.16, task force 03, April 2006

[51] «Mapping of the Italian territory with reference to ice (snow) and wind loads and analysis of the mechanical sizing of existing lines according to the CEI 11-4 standard», CESI / Tests and Components, December 2005

[52] «Characterization of the phenomenon of icing of power lines», CESI Research, February 2008

[53] "Evaluation of the risk for exceptional weather events affecting the e-distribuzione MV grid", CESI 0216/2017, reserved document

Italy – Winter 2017

5. STRATEGIES FOR PLANNING, CONTROL AND OPERATION

5.1. INTRODUCTION

This section investigates strategies originating from gird planning as well as from grid operation and control to increase the resilience against these threats. Section 5.2 and Section 5.3 mainly focus on already established strategies related to grid planning and against natural hazards.

The case studies attached to this section deals with strategies to counteract cyber-attacks and strategies for appropriate outsourcing in response to high impact low probability events (HILP).

5.2. THEORETICAL FRAMEWORK

During the last decades, in classic planning and operation of power systems, strategies to increase the resilience played a minor role. However, approaches like the n-1 security and a certain level of redundancy that are generally known in power systems can be considered as resilience enhancing strategies. Nowadays, resilience is not only a side-effect but actively investigated in research and development.

The need to reduce the risk associated to the reliability of a distribution network and to mitigate the most devastating effects of a service break is impelling; all documented cases prove it. Again, the concept of resilience plays a key role in stimulating the evolution of the procedures and criteria currently adopted within:

- The design and maintenance of components;
- Network planning;
- Network operational planning;
- Normal and emergency network operation;
- Electrical system restoration;
- The study and development of innovative technologies.

Today, advanced solutions can be achieved by improving the robustness or the redundancy of components, exploiting the flexibility of network devices, adopting advanced protection, control and defense criteria and finally improving management and maintenance procedures.

In addition, a close collaboration between Utilities (I.e.) and local Public Administration in order to defense electric infrastructures from natural events with two types of intervention should be one the most efficient solution; in particular through:

- The design and construction of power lines projected to be resistant to natural calamity;
- Optimum emergency management before, during and after the event.

An optimal management of the Medium and Low Voltage networks in case of a meteorological emergency can be done by alerting teams for the quick reset of broken lines and restoration, where possible, of network connections. This would be possible if local and national operators were constantly up to date on the upcoming and ongoing risky events. Unfortunately, not all utilities, however, enjoy these possibilities. In this case, a further complication could be made up by the fact that the discovery and elaboration process of data on natural events is often spread among different companies characterized by multiple purposes. The dissemination of competences between central and local authorities often leads to problems of data retrieval and homogenization, so whoever works on Electrical Systems must necessarily depend on a preliminary work of collecting and interpreting data made by people with different skills.

About the temporal evolution of an extreme event (*multiple contingency*) in a resilient system, two approaches can be used to increase resilience:

- ***A passive approach*** aimed at improving the system's ability to avoid malfunctions by preventing and minimizing the impact of these ones by:

  - The reinforcement of components;

  - The use of protective devices;

  - The introduction of redundancies.

The first two approaches reduce the *vulnerability of components*, preventing threats that could damage network infrastructure (i.e. aerial distribution lines into cables conversion);

- ***An active approach*** aimed at minimizing the impact of critical events on exercise and improving restoration by increasing the flexibility and adaptability of the system.

In exercise planning, active approaches take into account the intensity of existing or planned threats in defining security margins: this method reduces system vulnerability about component failures. An active approach also plays a key role in defense plans and manual intervention procedures, aimed at limiting the impacts of the degradation process and thus mitigating disadvantages.

To cope with a severe networking event, a resilient system can be divided into subnets to limit the propagation of the perturbation and allow users to be properly fed at least by areas not affected (i.e. through network reconfiguration). Likewise, the restoring activity can benefit from "active" approaches, which can adapt general recovery strategies to each specific case of disservice and to the evolution of the recovery process.

Finally, there are interventions that can be classified as intermediaries like the increase of emergency control resources (for example, interruptible loads) or the availability of recovery facilities in the most critical areas.

5.2.1.PROBABILISTIC METHODS FOR NETWORK PLANNING AND OPERATION

Various probabilistic methods have been proposed in recent years in the context of network planning and the operation of electrical systems. An approach based on the concept of probability and risk is indeed the most appropriate way to deal with rare impact events.

However, there are barriers, both technical and operator-related (eg modeling complexity, poor availability of managers to provide fault data, difficulties while translating results into control actions, lack of trade tools) to the application of probabilistic methods and tools based on risk.

All this makes it clear how far the road is long for a complete assimilation of the concept of resilience in the planning and network contexts of the network.

5.2.2.T&D NETWORK PLANNING AND RESILIENCE

Development planning for modern transmission and distribution networks is always aimed at achieving specific system adequacy objectives (defined by the usual indicators such as LOLP-Loss of Load Probability (EENS-Expected Energy Not Served)). However, in order to contribute to the improvement of resilience, planning must take into account the following factors:

1. The growing uncertainty of future generation / load scenarios (linked to different development hypotheses of power installed from renewable sources, nuclear choice, fossil fuel prices etc.);

2. The increasing presence of new technologies that provide additional degrees of freedom to planners (e.g. on high-temperature and low-speed conductors for transmission networks, HVDC connections, HVDC multi-terminal networks for the integration of renewables, on distribution networks);

3. The increasing frequency of extreme events affecting the electrical system, which requires the design of network components that taking into account the actual features of territory (in terms of exposure to threats);

The current (and further envisaged) future generation of renewable energy sources on the European interconnected network is the main driver for network planners who need innovative tools to evaluate non-technical barriers to network development and renewable energy integration compatible with the European market and conduct cost-benefit analysis to determine investment in new technologies (including DCs) more appropriate to foster the integration of large-scale renewable generation into the European transmission network.

In this context, it is essential to develop transmission network planning, models that can handle mixed AC / DC networks in order to meet the new needs of integrating and transporting energy from renewable sources into large systems interconnected dimensions. In fact, the ever-increasing size and complexity of the current transport systems of electricity, the presence of substantial exchanges between distant areas in order to make the best use of the advantages offered by renewable sources, the problems associated with the management of reactive flows and voltage levels to ensure the quality of the exercise, tend to favor the spread of network portions, which are no longer reducible to individual cables. It is therefore a strong interest in having a suitable model of Optimal Power Flow (OPF) for planning and development studies in the following areas:

- network expansion procedures;
- procedures for probabilistic evaluation of the degree of reliability.

5.3. STATE OF THE ART

To withstand the effects of static and dynamic loads induced by ice and wind on the lines, it is necessary to increase the mechanical / structural seal of the line and its components.

The reference values of the loads to which structures must resist must be assessed on the basis of historical records and experience gained in line management. In this respect, it is worth noting the general difficulty of finding historical measurements of ice loads.

In Italy, design choices have determined a basic type of supports and conductors with their use shooting. This condition is maintained for the general case except for special cases such as the Ligurian-Emilian areas of the Apennine in Italy and particular environments such as mountains with an altitude of more than 1200-1500 m or particularly critical areas.

The choice of special zones is one of the designer's design responsibility variables.

With regard to measures to counteract the emergence of the gallop phenomenon on the lines (phase overlapping), studies and experiments (with wind tunnel measurements campaigns) have allowed to thoroughly analyze the phenomenon. Anti-galloping devices (capable of decoupling the torsional frequencies from the vertical ones at the origin of these phenomena in the case of conductor bands) were designed and installed on those lines that were subject to the phenomenon with excellent results (no more gallopper phenomena are observed).

5.3.1.NORMATIVE ASPECTS OF LINE DESIGN

Given the difficulties and limited applicability of snow and ice overload containment methods, national and international regulations provide line design criteria that will enable them to withstand the worst predicted conditions for the area concerned. The standards design criteria may be deterministic or probabilistic. In the first case, external actions, such as wind or ice loads, are translated into "work loads" on the line, which are associated with safety factors for the various components of the line (foundations, supports, conductors, ...) to take into account the elements of uncertainty present both in the determination of the loads and in the resistance of the components.

In the probabilistic design, the concepts of line reliability are introduced, understood as the ability to resist climate events (wind, ice, wind and ice) with T return periods throughout the design life of the line.

A climatic event return period is the mean value of the time interval between two climatic events of greater than a defined minimum value. The reverse of the return period (1 / T) represents the annual probability that is exceeded by this value having a return period T.

In Italy, the CEI (Italian Electric Committee) adopted the above-mentioned CENELEC standards, as required by the Community's obligations, and published them in 2005 in Italian with the abbreviations CEI EN 50341-1 and CEI EN 50423-1 and has prepared National Standards Aspects that complement the CENELEC Standards for their applicability in Italy.

In order to make the European standard effective, the CEI has drafted a new text of the relevant Technical Standards. This text significantly updates the one currently in use. The "Line Norms" currently in use have been conceived about 60 years ago and involves the adoption of schematic wind and ice loads, with project modes to the eligible states.

The new probabilistic design of the line limit states, however, provides for the security of the work to be assessed on the basis of a concept of risk that must be the same for all electrical lines (condition not guaranteed by verification of the permissible stresses of the standard CEI 11-4).

For the correct assessment of the risk according to the new regulations, an assessment of the environmental loads arising from the current Italian climatic situation is also needed; in particular, for wind loads, reference was made to the "Technical Standards for Construction", while for snow or ice loads and their combined actions with wind power, they were based on a thorough study sponsored by the Electricity and Gas Authority.

In accordance with the provisions of the CEI EN 50341 standard, the map is based on statistical analysis of experimental data on lines, meteorological data and line behavior analysis for adverse meteorological events.

The study carried out has produced a new territorial division of Italy for snow and ice loads: the design of the lines is in fact planned for almost all of Italy, except for the islands and a few other areas of the Tyrrhenian and Ionian regions at rates below 600 m.

For the Italian territory, there are usually checks with snow loads (density 500 kg / m3) and ice (900 kg / m3), with increasing thickness (varying depending on the area and whether it is snow or ice) in altimeter function (over 600 m) and in the presence of high snowy phenomena frequency according to the following map.

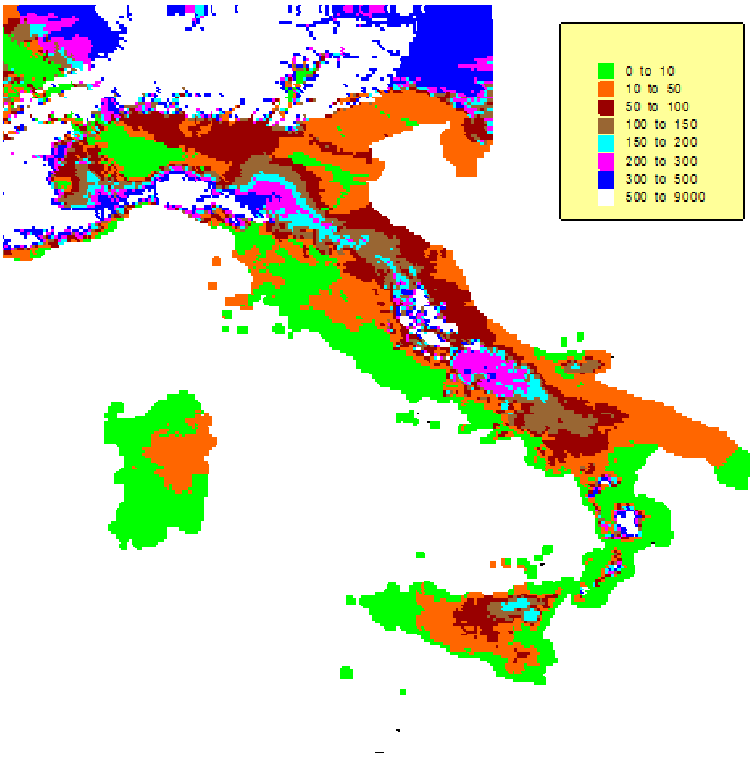


Figure 12 - Snowy phenomena (lasting over 24 hours in last 100 years) mapping [E. Ciapessoni et al., "La Resilienza del Sistema Elettrico", Alkes editor, 2017]

It is interesting to note that, in agreement with recent extreme climatic events, a snowmobile check is also planned on the Adriatic dorsal, with values similar to those for northern Italy.

The new mapping, besides extending the areas of Italian territory in which snow and ice load testing is required, also significantly increased the thicknesses (now varying by the altimetric dimension) of the sleeves: in the case of lines of medium voltage, the new loads can reach up to four times the values of the CEI 11-4 standard.

Damage to airlines resulting from these extreme weather events provides the first evidence of the adequacy of the new load values adopted.

5.3.2.SMART PLANNING OF DISTRIBUTION NETWORKS

The "smart" planning of distribution networks turns out to be a challenging aspect for industry experts nowadays. Traditional plant engineering solutions, based solely on network reinforcements, have to add more innovative approaches to consider solutions such as electrical storage devices. When considering the emergency situation, consideration should be given to the common considerations of operating constraints (lines flow, node tension, short-circuit currents and continuity of service).

The commonly considered criteria are:

- Investment cost for the network to assess the need to adapt the distribution network as a result of increased electrical load and / or the presence of Distributed Generation (GD) on the network;

- Joule losses, in order to assess the energy efficiency of the system;

- Evaluation of continuity of service. In order to assess the reliability of the distribution network, the value of the energy not provided to customers can be calculated, in addition to those introduced by the Integrated Quality of Electrical Services (TIQE) Text in order to establish and evaluate correctly the system of prizes and penalties introduced by the same text;

- Connection charges. Connection charges, evaluated according to different calculation methods, allow to establish, along with other cost factors, the economic feasibility of GD connection on the network;

- Cost of installation, management and maintenance of GD units. The term stated relates to the installation of GD units and the related generation of electricity, taking into account the primary source of production;

- Ancillary services and active network management. Ancillary services that GD unit owners can provide to the distribution network.

The search for the optimal solution is subject to technical constraints on voltage profiles, conductor capacities, and any active management interventions (network reconfiguration, generation and load control, active and reactive generation dispatching generation), to try to solve the critical issues through targeted actions. Such interventions, however, involve specific investment costs (automation, communication and control infrastructure) and exercise (contractual remuneration for the subjects involved).

Deterministic approaches (Fit & Forget) often yield results that involve high investment costs due to the need to ensure proper operation even in extreme, generous and minimum load conditions (dedicated line constructions for each GD), especially heavy for networks (excessive overvoltages).

Probabilistic planning, which considers an acceptable risk threshold of 3% for the violation of operational constraints, is able to allow, with respect to the Fit & Forget case, lower investments, with virtually no chance of violating operating limits.

This allows to subdirect the distribution system over traditional planning (Fit & Forget); if the risk of exceeding the operating technical limits is lower than a threshold deemed acceptable, it will result in a less costly investment configuration without significantly compromising system performance. The introduction of active-type control systems, with the ability to centrally manage the power of distributed generation, can allow a significant reduction in network investment over traditional planning with passive management even if conducted with the probabilistic approach. Finally, the presence of accumulation devices, devoted to the offset of energy distributed by the distributed generators, can allow minimal network investment in the face of costly storage costs.

In the probabilistic approach, for each solution obtained, the residual risk is exceeded by the predetermined operating limits (maximum and minimum voltage at the nodes, maximum current at the branches) where the generic risk expression is given by the following product:

$$R = p_e \cdot p_d \cdot d$$

where p_e is the generic likelihood of a potentially unfavorable event (in the case of the electrical system the number of times a network configuration occurs during the year), p_d is the probability that the event will be damaging (specifically the likelihood of violating operating limits) and d is the magnitude of the damage.

Pd depends on the particular network configuration and specific load and generation conditions (hence from the time of the day the network configuration is shown), which result in a different probability distribution for the voltage to the node or current to the branch.

However, additional information is required for choosing the best solution. Passive network management may be preferable by a DSO, saving on network investments compared to a traditional (deterministic) planning approach, with lower risks and inconsistencies related to the use of new technologies. In any case, the construction of long power lines may result in delays due to the possible expropriation of land and obtaining administrative permits.

5.3.3.NETWORK SMART OPERATION WITHIN NEW SCENARIOS

In fact, a "smart" exercise on the network increases resilience. In fact, as a "good" network planning and probabilistic design of the lines can allow for network upgrades, an exercise that uses advanced operating features and systems that implement them can reduce the effects of a network disruption or reduce recovery times.

A brief mention of functions is required:

- Manual Supervision and Control Functions: Security depends on the ability of such systems to control the network based on the accurate knowledge of the states of the networks and associated components;

- Automatic control functions: these are electrical quantities (frequency and voltage) that are required to maintain stability during normal operation and disturbance;

- Security features: The system must be protected against component faults that can lead to physical infrastructure damage and security issues;

- Defense Functions: While security systems focus on faulty components, maintaining the system in service when there are serious disturbances (e.g. multiple contingencies) may require specific defense interventions by dedicated devices and systems;

- Restore Functions: Very severe events can lead to extensive disruption. In this case, quick and reliable restoration is required to minimize the energy that is not supplied and therefore to increase resilience. Restoring from a complete blackout is a well-known task but also very complex and challenging where pre-defined strategies need to be adapted to the actual blackout scenario based on available resources.

5.4. CONTRIBUTIONS - CASE STUDIES

The Case study 8 investigates possible counter measures against cyber-attacks to increase the resilience of the electrical supply system.

The Case study 9 investigates appropriate outsourcing strategies against high impact low probability events in the electrical supply system.

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Case Study 8| Impact of cyber-attacks on the electrical supply system and strategies to increase the resilience

Synopsis

This case study starts with the identification of impacts cyber-attacks can have on the electrical supply system. The measures to increase the resilience of power systems in the case of cyber-attacks are discussed. These measures focus on the domain of control and operation of the power system.

Findings

In recent years the dangers that result from cyber issues have moved from a fictional idea to real threats. The authors of [0] give what they call a cybersecurity case study and analyses the impact of recent cyber issues on the power system. Apart from temporal outages resulting from false activation of load shedding or tripping of protection, the authors identified the coordinated connection and reconnection of generators as a major danger. Resulting in an improper synchronization this can physical destroy the generators bearing the risk to result in long lasting black outs, as the replacing of generators can take weeks up to months. With regard to the vulnerabilities that arise from attacks via the communication network the authors of [55] give a classification of attacks that target the classic information security triad: availability, integrity and confidentiality in a smart grid environment. Attacks on the availability are generally denial-of-service (DoS) attacks that aim to make a resource unreachable and unresponsive. Attacks on the integrity inject false data or modify existing information to induce a desired behavior. Confidentiality is attacked by capturing unauthorized and private data. As all control actions that are taken in a modern power system, depend on the estimated state of the grid, false data injection attacks that manipulate measurements can have severe consequences. [56]

Discussion

The research on reliable strategies to increase the resilience against ICT related failures and attacks is a very active field. The prevention of major consequences of such issues starts with the IT and ICS cybersecurity planning and implementation [54]. A major group of strategies originate from the research field of cryptography. Technics like encryption, authentication and key management [55] are important aspects to prevent unauthorized access to private data. And also, classic concepts like physical or software access control help to anticipate or impede the execution of cyber-attacks [57]. If attacks cannot be prevented, there detection is a major strategy to anticipate large-scale consequences. This is especially true for DoS attacks [55] and for the detection of intrusions [57]. Another active field of research is the development of in depth defend strategies, for example against false data injection attacks [56] like protection of basic measurement sets etc. But also, the architecture that is chosen for the control system of the power system has an important influence on the overall resilience against cyber-attacks. Centralized systems contain a single-point of failure while distributed or decentral control systems propose an inherent redundancy but can be more difficult to maintain.

Conclusion

The development of resilience strategies against natural hazards has already some tradition in the power system. But not only recently, the awareness has risen that the “smart” and communicating power system is highly vulnerable against attacks and failures originating from

the ICT domain. Until today the general solution of utilities are firewalls and other classic security mechanisms known from the office IT system. But the power system is no office IT system but a highly cyber-physical system.
What complicates the issue is that strategies to cope with cyber-attacks generally do not belong to the field of expertise of power engineering. Thus, collaborations between IT specialists and power engineering are necessary to develop effective strategies against this type of threat.

Recommendations

This case study presents a set of possible strategies ICT related threats. But none of these strategies is already fully ready for the market. Thus, the major recommendation for today's utilities is to respect the resilience increasing concept of segregation: The separating of major functions of the power system so that disturbances cannot cascade.

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Case Study 9 | Ensuring outsourcing response to HILP events on the electrical supply system

Synopsis

When a utility has high outsourcing levels for construction, maintenance and service activities in face of a high impact low probability event, a fast response from the contractors to mitigate impacts and reestablish service must be guaranteed.
This case study presents an approach to crisis response and contractors coordination in such scenario.

Findings

In recent years Portugal has faced the impact of several extreme events (flooding, forest fires, etc.), making it one of the countries which suffered most from extreme weather events in the last 20 years [58].
High dependence on outsourcing has a greater risk than insourcing maintenance/service teams in case of crisis. Utilities facing major events need to provide a fast response and allocate teams to secure supply and ensure grid and people safety – if these jobs are outsourced, utilities rely on the contractor's workforce and availability. Since the contractor's teams are planned for Business as Usual scenarios, when these events occur the contractors may not be ready and/or have the conditions to give an adequate response.

Discussion

To assure a fast and appropriate response to HILP events utilities that rely on outsourcing could have insourced teams for a fast response, and should establish a response coordination team, as well as incorporate in the outsourcing contract a crisis operational procedure that states what are the contractor's responsibilities, how to actuate and the according compensation.
In the Portuguese case as the outsourcing is done by geographical areas, if the effects of an HILP event surpass the local contractor capacity – high impact on a limited area (flood), several areas affected, or great impact on the local contractor (forest fires) – the crisis operational procedure must also ensure how to involve other contractor's teams (setting coordination structure, procedures and compensation).
The crisis operational procedure should also declare what are the mobilization requirements, preferably assuring that the utility assumes a proactive attitude and whenever there's a prediction for a disturbed or for an emergency state, it should communicate to the contractors and establish what are the means (workforce and equipment) that should be mobilized to a preparedness condition. If there is an evolution and a disturbed or emergency state is declared these means are actuated and are the first line of response.

Conclusion

When there is a high outsourcing level the utility must ensure that there is a crisis operational procedure in the outsourcing contracts that enable a true partnership between the utilities and the contractors in case of a High Impact Low Probability event.

Recommendations

A crisis operational procedure should exist establishing coordination structure and procedures.

Starting the response when there are conditions that predict that a HILP event could occur, mobilizing the teams and means to a preparedness condition ensures that if needed there are teams ready to actuate.
Enabling the involvement of several contractors from outside the geography affected by the event mitigates the dependence on local contractor's workforce and ensures faster response and lower service recovery times.

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Guangzhou, China

6. OVERALL STRATEGIES FOR CITIES IN CASE OF AN HILP EVENT INCLUDING CRISIS STRATEGIES OF UTILITIES

6.1. INTRODUCTION

This topic identifies the city resilience strategies already in use relating to the High Impact and Low Probability events and what kind of strategies cities and electric utilities have.

Cities around the world are frequently exposed to external shocks, the so-call high-impact low-probability (HILP) events, such as storms, floods, earth quakes, cyber-attacks, terroristic attacks, etc. A resilient city should be able to provide life-sustaining services and goods even during these extreme events and rapidly recover to its pre-event resilient state. Globally people are moving into cities and megacities, which makes city resilience increasingly important. However, currently in cities (both in developed and developing countries) the society and people are even more affected in electricity blackouts and the outage damage is significant.

Electrical grid cannot be studied exclusively. Other infrastructures and public and private sectors are interconnected to electric distribution as described in Chapter 3. A resilient city should ensure the uninterrupted power supply to critical infrastructures and functions, or restore the power supply as soon as possible. Hence, resilient control strategies of cities during these HILP events have to be considered.

6.2. THEORETICAL FRAMEWORK

Urbanization is one of the megatrends shaping the world. In 1970, there were two megacities (populations > 10 million) — Tokyo and New York. In 2017, there are 39 megacities [59]. The question of urban system resilience is particularly urgent. By 2030 over 60% of the world's population will live in cities. Recent incidents, including natural disasters and deliberate attacks, have increased worldwide concerns about urban vulnerability. It is important to develop and implement policies for enhanced city resilience, since trends suggest greatly increased complexity for future urban systems [60].

The increase of large cities will also lead to high impacts if infrastructures like the power grid is severely damaged, reducing its capability of providing reliable power supply. Many city functions depend either on electricity or IT-systems. IT-systems interrupt simultaneously with electricity interruptions, unless when connected to uninterrupted backup power supplies. Also, other critical city infrastructures like food supply, energy, logistics, health care, finance and industry all rely heavily on electricity. For example, logistics are nowadays highly centralized and automated and rely on IT-systems and communications, both deeply interconnected with electricity supply.

Advanced resilience strategies include also social and organizational conceptions in addition to technical and physical methods. Social and strategic factors may be more crucial for city resilience than the physical factors. For example, in Concepción in Chile, the restoration of social and human effects of a massive earthquake took longer than to restore physical elements [61].

Modern cities are exposed to a large number of threats which are often dependent on their geographic location. For example, cities often tend to develop and grow around seas, lakes and rivers, thus floods affect these cities significantly. Cities could also be exposed to other catastrophic hazards, such as earthquakes (e.g. Chile) and wildfires (e.g. Mediterranean countries). It is therefore highly critical to develop those resilience strategies that would help reduce the impact of these events on the socio-economic sustainability and growth of these cities.

6.3. STATE OF THE ART

The necessity of taking actions to boost power grid resilience to HILP events has been recognized by the majority of electrical utilities worldwide. These efforts aim to achieve system and city adaptation, in the sense of reducing the impacts of future events and reducing city vulnerability, hence boosting the city's ability to maintain an adequate functionality during and after an event. The strategies towards these goals can be broadly categorized into the resilience engineering measures, and disaster response and risk management for optimizing the response of the power grid following an event, Figure 13 [62].

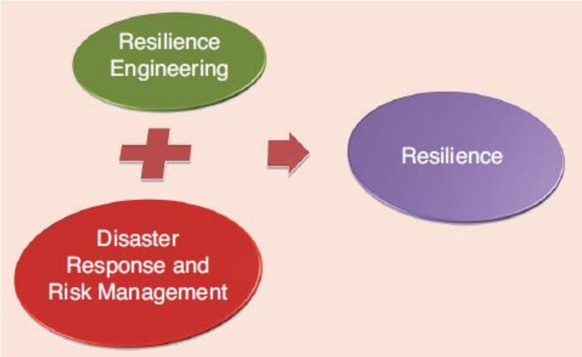

Figure 13 - Key categories of strategies for boosting power grid resilience

The resilience engineering strategies can be further categorized to the traditional hardening measures (i.e. making the network *stronger* and *bigger*) and smart operational measures (i.e. making the network *smarter* and more *responsive*) to the external shock Figure 14 [62], which could have a different impact on improving the resilience of a city, but may come at a different cost too.

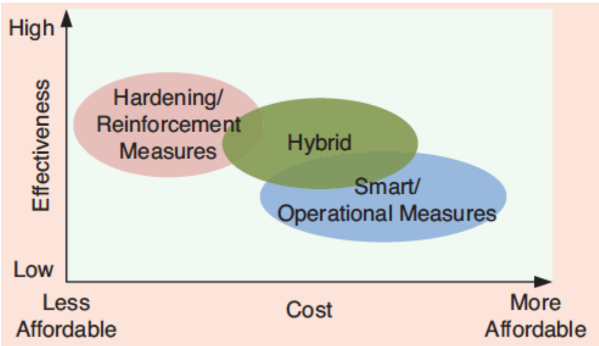

Figure 14 - A conceptual comparison of hardening and smart resilience measures

In Finland, there is a law that a city has to develop contingency planning and pre-arrangements to ensure the continuous functionality of critical city services even in exceptional circumstances. The preparedness in case of emergencies is coordinated by National Emergency Supply Agency. The focal points of emergency supply are safeguarding the critical infrastructure (including electricity), ensuring critical production and services and ensuring the continuity of crucial organizations and co-operating networks. The organization of National Emergency Supply Agency is divided into following sectors: food supply, energy, logistics, health care, finance and industry and other (digital and media). The consolidation and preparedness are planned and exercised in regional levels in Finnish provinces. This consolidation and co-operation applies also to city level.

In the capital of Finland, Helsinki, the resilience and continuity management prepares for such city-level risks, where the probability can be very low, but the consequences are very high. These risks are often characterized so that city actions can not influence their realization. Preparedness to these risks requires planning of operating principles, or resourcing and co-operation in order to maintain an acceptable service level and limit the consequences of the situation. Helsinki has published a preparedness guide to support this planning [63]. The preparedness guide also specifies the collaboration at both national and regional level.

Helsinki has a resilience co-ordination team to help in contingency planning and in exercises to ensure that all services and infrastructures are prepared to secure vital functions in all circumstances. City Emergency Manager is in charge of the resilience co-ordination. Critical city functions are assorted into different responsibility sectors. Helen Ltd., the Energy company owned by Helsinki City, is in charge of handling energy and its subsidiary company Helen Electricity Network Ltd. is in charge of electricity supply sector in Helsinki. The different responsibility sectors are obliged to make their own plan and implement preparations in case of severe incidents or emergency. In addition to this city order, Electricity network companies in Finland shall have to make a preparedness plan also by law, by Electricity Market Act.

Helen Electricity Network maintain and develop its resilience against HILP- events by:

- 24/7 operation of disturbance communication and information, both to other critical city and national sectors and to public;
- Standby agreements;
- Maintenance and investment programs;
- Utilization of new technology;
- Spare parts and spare parts contracts;
- The security of supply and planning principles;
- Meshed network structure and network interconnections;
- Operation planning, contingency plans;
- Predefined and known critical points in network;
- Disturbance training and exercises;
- Preparedness plan;
- Co-operation with authorities and other sectors, joint exercises and training.

The co-operation includes also TSO (Fingrid) and neighboring/major DSOs. Fingrid is in charge of the stability of Finnish electric grid, so a national level disturbance management is led by Fingrid.

One of lessons learnt from large storms in Finland in 2011-2012 was the importance of disturbance information to public and the situation awareness between those parties that are involved in emergency restoration. Helen Electricity Network uses a digital situation awareness platform, which supports collaboration and distributes information between different critical authorities and enterprises. To inform the public, there is a web-based disturbance map and mobile text messages are also sent to affected customers.

Helsinki has a vision, that it is a resistant city against climate and has adapted to climate change and is prepared for extreme weather events. In this vision, there are four priorities: Risk identification, planning and construction, disturbance management and global preparedness and awareness. Helsinki has integrated the adaptation to climate change in city planning and is constantly developing adaptation activities. One example of adapting this vision is the flooding strategy [64]. The flooding strategy includes all vital sectors of the city. In Helen Electricity Network all new network connections points (power substations, distribution substations, distribution boxes, connection boxes) are installed above the set flooding level. The city land use planning must follow this level in new area planning, in order to ensure risk-free location.

Resilience strategy in the city of Oslo in Norway has similarities to the resilience strategy of Helsinki. The Directorate for Civil Protection and (DSB) is in charge of the National, regional and local coordination. In Oslo, the Preparedness Office is in charge of the emergency preparedness in the city. Preparedness office has divided preparedness levels into strategical, tactical and operational levels. In the Preparedness Office is an Emergency Forum, which facilitates emergency coordination of the various members and ensure that emergency preparedness information is made known to relevant participants. Emergency Forum consists of representatives of municipal, state, volunteers and private businesses that are part of the emergency preparedness work in the city [65, 66].

New York was severely affected and damaged by Hurricane Sandy in 2012. In 2013 the city of New York published a throughout resilience report "A stronger, more resilient New York" [67]. The resilience report consists of climate analysis, city infrastructure and resilience plans. In infrastructure / utility chapter is also a long-term climate change impact analysis, Figure 15.

Risk Assessment: Impact of Climate Change on Utilities—Electric System

Major Risk / Moderate Risk / Minor Risk

	Scale of Impact			
Hazard	Today	2020s	2050s	Comments
Gradual				
Sea level rise	Minor Risk	Minor Risk	Minor Risk	Minimal impact
Increased precipitation	Minor Risk	Minor Risk	Minor Risk	Minimal impact
Higher average temperature	Minor Risk	Minor Risk	Minor Risk	Minimal impact
Extreme Events				
Storm surge	Major Risk	Major Risk	Major Risk	Much of the critical infrastructure is in floodplains; flood risks will become worse over time
Heavy downpour	Minor Risk	Minor Risk	Minor Risk	Minimal impact
Heat wave	Moderate Risk	Major Risk	Major Risk	Increased risk of outages due to the impact of heat waves on peak demand and on electric infrastructure
High winds	Moderate Risk	Moderate Risk	Moderate Risk	Risk of damage to overhead power lines

Figure 15 - Impact of climate change on electric utility, New York [67]

Con Edison is charge of the electivity supply in New York, USA. As a result of Sandy, Con Edison has launched massive actions to harden the substation protection against flooding events.

Major elements of Con Edison's storm improvement plans include [68]:

- Building flood barriers around critical equipment and higher perimeter walls around substations;
- Installing flood gates at tunnel openings;
- Installing additional submersible electrical equipment in flood-prone areas of the electric distribution system;
- Redesigning some underground electrical networks. The new smart grid designs will allow the company to pre-emptively de-energize customers in flood-prone areas, restore power faster when floodwaters recede, while keeping customers in the surrounding areas with power;
- Installing thousands of switches and devices to isolate damaged area and thus help facilitating faster restoration;
- Installing stronger utility poles in storm-prone;
- Installing additional high-powered flood pumps in advance of storms;
- Deploying water-resistant sealant in conduits containing electrical circuits.

In Great Britain (GB), the major threats to the resilience of the power grid (both transmission and distribution) are windstorms and floods. In order to evaluate the impact of these catastrophic events on the power grid resilience, several studies have been performed using a simplified version of the GB transmission network [69, 70, 71, 72]. These models are generic enough to be applicable to distribution networks. Specifically, probabilistic multi-temporal and multi-spatial resilience assessment tools have been developed to capture the impacts of these events as they move across the power network. To reflect the effect of these events on the vulnerability of the individual power system components, the concept of fragility curves has been used. They express the individual failure probability of these components as a function of the hazard intensity (i.e. windspeed and rainfall for windstorms and floods respectively in this application). Figure 16 shows an example of the wind fragility curves considered for the transmission towers and lines, demonstrating as well how these curves can be modified to consider more or less robust structures [71]. Figure 17 shows an additional example of the curves related to floods for electrical power substations [72].

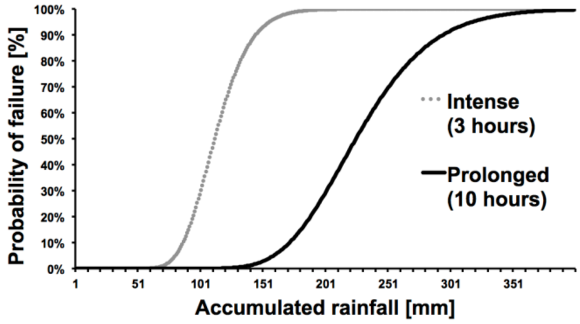

Figure 16 - Floods by intense or prolonged rainfall fragility curves

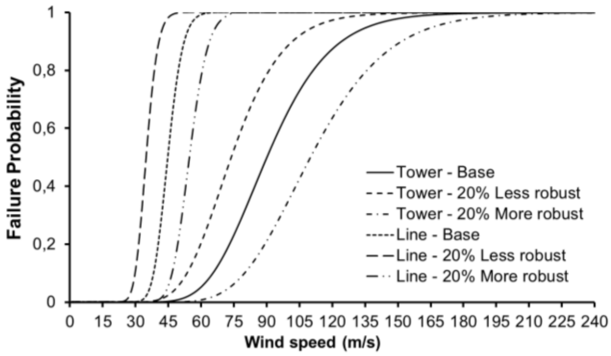

Figure 17 - Wind fragility curves for transmission lines and towers (demonstrating how the robustness of these components can be varied for different case studies)

In order to quantify power system resilience during and following these disastrous events, a combination of traditional reliability index's (e.g. Loss of Load Frequency, LOLF, and Expected Energy Not Supplied, EENS) and newly designed resilience metrics (i.e. the ΦΛΕΠ resilience metric system [71]) have been used. The use of such resilience metrics that are capable of modelling and quantifying the response and resilience performance of the power system exposed to the event is critical as it helps get a better understanding of the problem and how to develop appropriate strategies for boosting the power grid resilience. Similarly, to the strategies, specific resilience and adaptation strategies have been considered, namely: *robustness*, i.e. making the network stronger to the weather events, *redundancy* and *responsiveness*, i.e. improving the restoration times of the damaged components. The effect of these strategies has been evaluated using both reliability and the specifically-designed resilience metrics. The simulation results show that making the network stronger to the event is the most effective strategy for improving the resilience of the grid for a wide range of hazard intensities. However, it is shown that being more responsive to the highly severe events (i.e. recovering the damaged components faster) is more effective than being redundant, as the redundant components will still be exposed and damaged by the hazard. Hence, these results imply that the traditional way of improving resilience by adding more and more elements in the system is not always the best solution. These key findings thus provide very useful insights and support on the decision-making on the most appropriate resilience enhancement strategic planning, which would help an electrical utility decide which strategies are the most suitable for boosting its resilience to specific threats. Apparently, this analysis is case- and threat-specific.

6.4. CONTRIBUTIONS - CASE STUDIES

Case Study 10 present the concepts and methods used by Guangzhou Power Supply Co. (GZPS) to improve the resilience in a major city and nearby provinces. Case Study 11 present the improvements in business continuity in the Technology and Normalization Department in EDP Distribuição.

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Case Study 10 | Ensuring outsourcing response to HILP events on the electrical supply system

Synopsis

Guangzhou is a major city located in Southern China and it is the 3rd largest city in China. Guangzhou Power Supply Co. (GZPS), is a wholly-owned subsidiary of China Southern Power Grid.

The company serves 17 million people and has 11,000 employees. In 2017, the total power supply load in the GZPS 16,360 MW. GZPS is ranked the 3rd place in terms of reliability in power supply companies in China.

The problem described in this study case is, how to maintain adequate power supply to the most important supply points in a city, in order to sustain the most vital services in emergencies. This case study presents the resilience strategy and concepts developed by GZPS.

Findings

In order to improve the resilience of major cities and to improve the emergency management of the utility, GZPS decided to develop a new resilience strategy. The company studied the risks that had been realized in history and completed a shareholder analysis: which are the factors that are most valuable to our shareholders. In this strategical analysis, two critical issues were chosen for more detailed research and planning. The first item was, that the principles and the constructions of the power grid shall enable different criticality classification, based on the criticality of the customer effects in power outages. The second chosen item was that a company shall improve contingency planning and improve the emergency management mechanism.

Discussion

1. Construction of a guaranteed power grid (GPG)

The idea is to identify the key users and areas, restore this information and implement user and grid classification based on this information. The developed concept to enable the criticality classification in GZPS was called a guaranteed power grid (GPG) [73].

1.1. Key locations and users

The important key users were identified and classified. The most important customers, key users, were classified as class I and class II. Totally there are 200 important users in Guangzhou, among them there are three special important users.

The most important area was classified as a Core area. Power supply areas with a load density of 30 MW / km2 and above were included to the Core area. This core area includes the central urban area and nine regional centers in strong wind areas. The prioritized part of the network is called guaranteed power grid, and it is constructed with Core area and Key users as shown in the Figure 18. This prioritization is in line with the distribution network development goals of State Grid Corporation of China, in which the goal for average interruption duration index for major cities in 2020 is 5 min, whereas the equivalent goal in rural areas in 2020 is 5.9 hours [74].

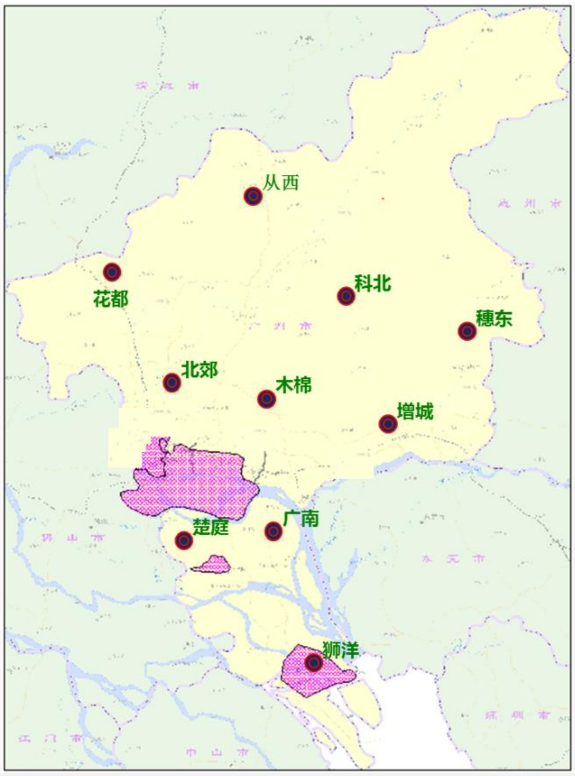

Figure 18 - Key locations and users

1.2. How to guarantee the GPG

The enhanced reliability in GPG is guaranteed by means of special operation and maintenance strategies and differentiation in grid construction.

In GPG special operation and maintenance principles have been designed. According to the health and importance of the equipment, the operation and maintenance grade is determined. After this, according to the four operational levels assessed, GZPS will develop operational and maintenance measures and implement them. Equipment risk matrix, as shown in the Figure 19.

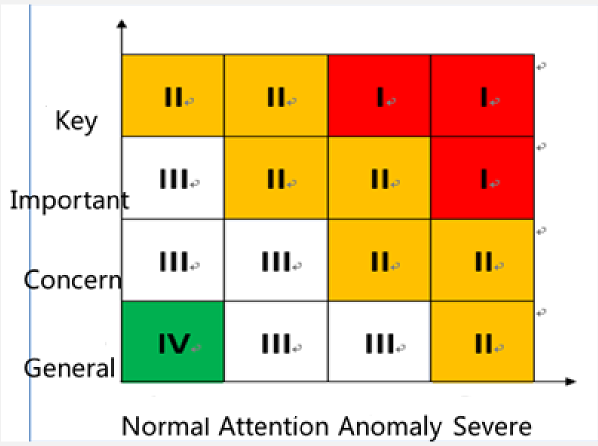

Figure 19 - Equipment risk matrix

Differentiation in grid construction includes that the limited power grid construction resources will be invested in the key transmission channels and power supply of GPG. The minimum grid structure covering the main core areas was designed. The GPG should cover the power supply route of the central city, the county center and the delivery channels for the disaster resistant power supply.

In principle, GPG should cover first class and the first tier users. The other users, such as large residential areas, which are likely to be seriously affected by long-term blackouts, will not be included in the key users of the power grid. They should be provided by their own emergency power supply or mobile emergency power supply. GPG construction is based on guaranteeing the important load and ensuring the needs of the people's livelihood.

1.3. Guaranteed range

In GPG the failure probability and losses are minimized and power supply can be restored quickly after failure. To verify this, these principles are maintained:

（1）All new 110 kV substations are indoor substation with high level of disaster prevention and low probability of outage

（2）All of them have the ability of quick restoration when any 220 kV substation is out of voltage

（3）By 2020, the loss of voltage in the whole station of 500 kV station will not cause heavy load loss, and the loss of 220 kV stations will have the ability of quick restoration

（4）the protection of important users against disasters, requires the joint efforts of the users and the power grid enterprises.

2. Improving the emergency management mechanism

2.1. Construction of emergency management system

GZPS focuses on the construction of emergency management system on a concept of three systems and one mechanism, which is emergency organization system, emergency plan system, emergency support system and emergency operation mechanism.

2.1.1. Emergency organization system

An emergency command structure is established from the top to the bottom, consisting of emergency command center of the operational units and of the temporary emergency command headquarters to ensure an effective operation of the emergency management work.

2.1.2. Emergency plan system

GZPS has established an emergency framework, which includes an overall emergency plan, special emergency plans, department emergency plans and site disposal emergency plans. According to the requirements of the emergency plan, every unit is obliged to formulate an annual exercise plan, carry out an emergency drill according to the plan and prepare blind (no notification of time, place nor the content) emergency exercises.

2.1.3. Emergency support system

According to a principle of internal and external combination, 46 emergency repair teams were set up to cover transmission, substation, distribution and other functions. Also a team to support the power supply was set up by the Guangdong military region. A pool of emergency experts was established and a supporting system was established to regulate the management and linkage mechanism of the external and internal emergency teams, to ensure a rapid response after an emergency occurred.

The emergency equipment quota reserve is carried out in accordance with the model of one emergency equipment warehouse plus five regional emergency packages. The emergency reserve material inventory is dynamically updated to enable a real-time grasp of emergency material storage situation. GZPS developed a differentiated material and equipment distribution plan and set up an efficient distribution team to ensure 24-hour fast allocation.

Also, an emergency command platform covering all levels of command is established. The platform has visual docking with the municipal emergency platform, and has the function of video consultation. Internal and CSG emergency command center, the grass-roots units emergency command headquarters, field command and emergency repair site audio and video connectivity, to achieve emergency command and disposal and other aspects of visualization. To guarantee the emergency communication, a system of satellite communication vehicle, digital satellite telephones, 3G / 4G mobile video terminal and an UAV (unmanned aerial vehicle) communication is established.

2.1.4. Emergency operation mechanism

In order to have efficient emergency operation, GZPS has developed an emergency operation supporting management system including an emergency plan, a standardized emergency handling operation process, clear early warning system, response, disposal and other aspects of the specific requirements and priorities. A working mechanism of emergency command headquarters at all levels to cooperate and standardize, to transfer emergency instructions efficiently and smoothly, and to collect and transmit emergency information quickly is established.

Second method was to establish an emergency working mechanism with linkage to the government. The municipal government was urged to set up the power infrastructure construction headquarters under the command of the mayor, sign a strategic cooperation agreement with the Guangzhou Forestry and Forestry Bureau, and have successively promulgated administrative law enforcement measures for electric power. A series of important documents, such as the rules for finding and handling plants hazarding the power lines, rules for speeding up the construction of power grids, and the linked work plan for prevention and control of power network risks, are constructed for the joint handling of unexpected situations and for the safe operation of the power grid.

GZPS has actively expanded the industry linkage mechanism and have signed strategic cooperation agreements with railways, traffic, news media, water supply, oil supply and major communication operators. This plays an important role in emergency management of typhoons and other emergencies.

2.2. Emergency Management based on new IT technology

The purpose for the upgrade of GZPS emergency command system (ECS) is that it shall fully integrate all kinds of emergency resources and data. ECS includes online acquisition and monitoring, graph analysis, dynamic monitoring of emergency resources, emergency command effective linkage and efficient transmission of emergency information. The whole process of emergency command and disposal is considerable, controllable, traceable and evaluable.

ECS improves the information on the daily emergency management, emergency disposal and other business processes. Emergency management can be visualized through the cockpit. ECS integrates emergency resources and external systems meteorological system and production management system. The integration continues with GIS (Geographical Information System) and other systems integration to achieve the all emergency situation awareness. The main construction of ECS includes:

1. Information interaction across the board
2. Emergency communications in all directions
3. Considerable and controllable deployment of resources
4. Effective linkage of disaster risk
5. Special emergency focus
6. External system connectivity.

The system support power from receiving an outage report from customer to the power restoration. The fault management is fully supported by complete solution, from platform solutions to mobile application on the field.

Conclusion

The concept of Guaranteed power grid and described developments in emergency management has improved the focusing of limited emergency resources and processes first to most critical targets. Also, the most critical points of the network are better protected.

In 2017 average travel time for low voltage fault was 41 minutes, decreasing 32 % from previous year, power restoring time was 75 minutes, decreasing 29 %. In 2017, GZPS and ECS handled almost 40 emergency responses. ECS plays a supporting role in information reporting

and in emergency management. The emergency command center actively arranged emergency power generation to the provincial and municipal governments and to Guangzhou city areas to ensure the restoration of power supply. GZPS also actively responded to the needs of emergency repair materials in Macao and co-operates closely with the provincial Hong Kong and Macao Offices and urgently allocated over 50 emergency generators to help the rebuild in Macao after a Typhoon disaster. GZPS coordinated via ECS emergency generation vehicles, personnel, material and effectively assisted in the deployment of emergencies.
ECS integrates the relevant resources to achieve online monitoring of emergency preparedness in key places. It helps to achieve key places, distribution equipment, power supply wiring diagrams and emergency teams. Materials and equipment, emergency power generation vehicles, satellite vehicles and other information is shown on a map display supporting in comprehensive control of the power supply situation and effectively supporting the emergency command work.

Recommendations

Reliability and criticality based planning and maintenance will improve the reliability and resilience of distribution network. In emergency situations comprehensive situation awareness, communication and coordinating with all other supporting officials and industry will support effectively the emergency management.

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Case Study 11 | Business continuity in the Technology and Normalization Department

Synopsis

The Technology and Normalization Department, from EDP Distribuição, is responsible for the specification of equipment and materials as well as for the analysis of supplier's proposals. With the goal of normalizing technical and operational rules to install and operate equipment, there was a need to create a Technological Knowledge Management System (SGTC). In order to align the process of the SGTC with EDP Distribuição's policies for business continuity several measures were implemented within the department.

Findings

In the past, in the department of Technology and Normalization, each person was responsible for the management of several grid equipment and there was information that only the person responsible had access to. This led to knowledge being lost when people left the department and impacted on business continuity. This problem has been particularly relevant in recent years as the number of retiring employees has been significant in the department as well as the number of new collaborators hired.

Furthermore, there was a necessity in the department to identify risks in material's supply to incorporate the knowledge acquired in the preparation of specifications as well as during the process of the technical qualification of products.

Discussion

In order to respond to the problem of loss of knowledge, several measures were studied and proposed including keeping written records of the decisions made while preparing specifications as well as involving multidisciplinary teams in its elaboration. Furthermore, committees were created to increase the organization's involvement in the preparation of specifications. Moreover, a risk matrix was proposed to identify risks in material's supply (Figure 20).

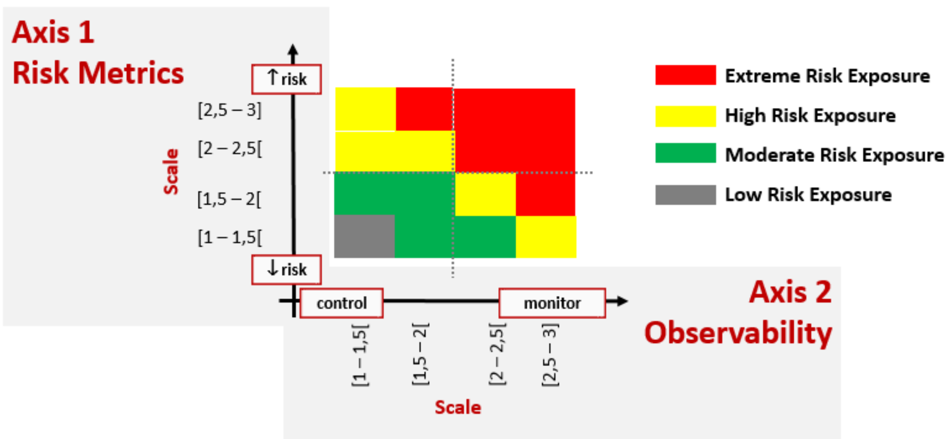

Figure 20 - Risk matrix for a specification

Conclusion

With the number of retiring employees rising, the department of Technology and Normalization faced problems concerning loss of knowledge. As a response to this necessity, several measures where proposed and implemented in the department to keep written records of decisions made as well as to involve more people in the processes leading to a higher involvement of the organization in the work done by the department. Additionally, tools were created to identify risks in material’s supply.

Recommendations

The implementation of measures to prevent loss of knowledge and identify risks in material’s supply is of extreme importance to guarantee business continuity within the department. It is also important to periodically check and evaluate the effectiveness of the measures and make the necessary updates.

Implementation

In order to respond to the problems of loss of knowledge and supply risk, the implementation of several measures was proposed, namely:

- creation of multidisciplinary teams with two elements for the management of products, corresponding to the product manager and the department manager;
- establishment of a process that allows to create a repository of the information supporting the creation of a specification;
- creation of an annotated and commented version of specifications, to keep track of the decisions made during the preparation of the document;
- creation of a Technological Committee to monitor and aggregate all the information concerning technological development;
- creation of a Technical Committee to monitor and validate the implementation of the activities related with the SGCT and the decisions concerning technological changes;

establishment of a Supply Risk Matrix in the context of the technical qualification of products, in order to identify risks in materials supply.

These measures are extremely important to guarantee business continuity within the department.

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Italy – Winter 2017

7. ROLE OF INNOVATIVE NETWORKS AND DISPERSED GENERATION AGAINST RESILIENCE

7.1. INTRODUCTION

It is expected that due to the ever-increasing amount of intermittent renewable energy sources in the electricity distribution networks the resilience of these networks will become worse. To prevent this from happening countermeasures are needed. These measures can be both of organizational and technological nature.

The Working Group Resilience of Distribution Grids has made an inventory of promising technologies and technological developments that might prevent the decrease of the resilience of distribution networks or even improve it. Furthermore, an inventory has been made of a number of case studies that demonstrate the positive impact of technology on the resilience of distribution grids.

7.2. STATE OF THE ART

It is believed that the following technologies can play a crucial role in maintaining or increasing the resilience of distribution networks in the near future:

- Devices that observe the actual status of the distribution network;
- Situation awareness tools;
- Microgrids;
- Dispersed generation;
- Storage;
- Technologies that support the interaction between TSOs and DSOs;
- Technologies that cope with the specific behavior of distributed energy sources;
- Intelligent networks/Distribution automation;
- Innovative network management strategies;
- Devices that cope with bad weather conditions;
- Devices that mechanically protect overhead lines;
- Mobile DC supply solutions;
- Solutions that can temporarily bypass unavailable assets;
- Flood sensors and smart metering of substations;
- Anti-vibration and anti-seismic support for distribution power transformers.

The listed technologies are described in more detail below.

7.2.1 SITUATION AWARENESS TOOLS

During a major power disruption, it is crucial for DSOs to get the right and most up-to-date information regarding the disturbance. In practice, this is still very difficult to achieve. Often the required information needs to come from different sources eg. lines sensors, field devices, electrical substations, SCADA and DMS systems. Gathering the information is therefore often time consuming and inefficient. So, called situation awareness tools tackle this problem. Such tools gather all required data in real time and present this data in a compressed and targeted way to all involved stakeholders. Situation awareness tools help decision makers to get a good awareness of the actual situation of the power system during a disruption.

The advantages of using a situation awareness tool is described in the next section.

7.2.2 MICROGRIDS

International Electrotechnical Commission (IEC) defines a MicroGrid as a group of “distinct distributed resources (DER) such as generators or loads”, located within close geographical proximity of each other, “so that they represent a single generator or load to the wider electricity system.”

Similarly, “microgrid” is defined as a group of interconnected loads and distributed energy resources (DER) within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid and can connect and disconnect from the grid, operate in grid-connected or island mode.

Even with a precise definition, a MicroGrid remains a live “ecosystem” where multiple functionalities and technologies can be integrated together (conventional and renewable generation, storage systems, automatic control, defense plan system, optimal power dispatch, critical loads management, safety and stability systems). The level of such integration is defining the added value a MicroGrid brings to the Grid system.

As a MicroGrid can be seen either as a portion of Grid (public or private) or a community of users (producers and consumers), the role of MicroGrid Operators can be very different and referring to different organization:

- Distribution Service Operators (DSOs) managing a MicroGrid as one or multiple nodes of the electrical public grid
- Private Operators managing a MicroGrid as one or multiple private districts including their energy networks
- Community Managers managing as a MicroGrid only connected users and not the grid itself, providing services like energy optimization and flexibility aggregation.

In the context of this report, the microgrid is considered as a key provider of services to help DSO to strengthen the resilience of electrical infrastructure against effects of disaster like extreme weather, or to improve normal operational conditions .

Some examples:

- Microgrid automatically disconnecting to the grid, delivering energy to MG's connected loads for critical infrastructures or group of customers, avoid entire black-out and improve continuity of service.
- Microgrid automatically reconnecting to the grid after synchro-check conditions.
- Microgrid delivering back-up power to hosted loads before entire grid recovery.
- Microgrid participating to the Grid Frequency stability.
- Microgrid solutions for DSO are still at early stage, however there are significant volume of research programs, pilots and first deployment on site, supported by large DSOs, and government agencies around the world

7.2.3 DISPERSED GENERATION

The application of dispersed generation can help to improve the resilience of distribution networks. A distinction can be made between large units, mainly installed at industrial sites and small units installed at houses. Regarding to the application of large scale dispersed generation for improving the resilience a number of challenges still exist. These challenges go from ownership (DSO cannot own DG), non-existing market and regulatory framework (how do you compensate usage of DG to the owners) to technical aspects (rules of connection, grid codes, technical requirements etc…). It should also be noticed that only specific types of DG can be used in emergencies, most of the inverter connected technologies are useless and difficult to control without coupling them with storage devices (PV, wind are variable and uncertain etc).

Also, private investors/owners of DG would have to overinvest into larger capacity DG to be able to supply the consumption in emergencies (again, technical and economic issues there).

A more promising option could be the concept of prosumers or flexible consumers. In this concept consumer have the capability to self-supply their own demand, while the network serves as a form of a storage. In this case the grid tariffs would probably have to be increased as the grid is less used than today, however it serves as a provider of reliability of supply to the prosumer which is a highly valued service.

7.2.4 STORAGE

The application of storage devices can improve the resilience of distribution networks. Firstly, they can be used as an N-1 alternative in remote areas and improve the quality of supply in remote areas or islands. It should be noticed that one of the biggest advantages of storage devices is that they could/should be made mobile – meaning you can move them to a different node of the network depending on the needs and requirements (such as emergencies).

Secondly the application of storage devices can mitigate the problems associated with the integration of renewable energy sources into the distribution network.

The widespread application of storage devices is currently still hampered by a number of factors:

- high investment costs: the investment costs are still high but decreasing. Making storage units more mobile could improve the investment return rate.

- regulatory issues: the roles of the different actors within the electricity market with regard to the application of storage devices are not always well defined.

7.2.5 INTELLIGENT NETWORKS

Intelligent networks are networks that apply intelligence to minimize the number and duration of supply interruptions. The intelligent networks are based on data that is coming from the power system.

An example of an intelligent network is the so called self-healing network. Self-healing networks are able to detect faults in the power system and to automatically recover from that while minimizing the outage time. Self-healing networks require changes in the number and type of protection, measurement, switching devices, communication and protocols as well as operational tools for the DSO. The introduction of the self-healing concept can therefore be very expensive.

Although the concept is very promising it is still not very wide spread. It is mainly applied is areas with very important customers like airports.

Intelligent networks have the potential to enable the DSO to optimize the network operation, especially in terms of losses. It is believed that loss reduction could be the driver for larger application of “self-healing” options.

A pre-requisite for the application of self-healing networks is that the network should have a ring of mesh topology. This is however not always the case, especially not for remote locations and/or islands.

7.2.6 INNOVATIVE NETWORK MANAGEMENT STRATEGIES

Innovative network management strategies involve strategies focusing at minimizing the risks of a power failure.

RSE is currently developing an innovative network strategy by connecting 2 products already used by them: WILD WOLF and VoCANT. WILD WOLF (Wet snow OverLoad alert and Forecasting) is a system that support assessments risk in the formation of ice snow sleeves with suggestion of minimum current that have to pass along each wire (*anti-icing current*). VoCANT is an OPF considering that anti-icing current as a constraint in its optimization procedure. The final result, tested in simulation phase, shows very good performances in order to dissolve sleeves and to prevent their future formation. The two products are, at the moment, installed separately on some Italian TSO’s and main national DSO’s parts of network.

Another example of an innovative network management strategy are network management systems based on autonomous agents. Instead of having a centralized control system, such systems are controlled by autonomous agents. The control strategy to be applied depends on the actual situation (e.g. normal, congested, post-contingency). For each situation ad-hoc federations of agents are created that execute the desired control strategy. The strategy may cover market based transactions, emergency demand response actions etc. Basically, the control system uses different control level. The level to be used depends on the local operating conditions. The responses to disturbances in the power system are sized proportionally.

7.2.7 ANTI-ICING CURRENTS TRIGGER

Warming conductors or guard ropes is surely the most effective way of preventing the formation of snow and ice sleeves on the conductors when snow events occur or particular, icing phenomena. CIGRE identifies in the "Guide for Thermal Rating Calculations of Overhead Lines" [76] the methods used to prevent and facilitate the dissolution or severance of the sleeve already formed on the conductor and classifies them as active mitigation strategies.

The main thermal methods exploit the effect of the heat produced by Joule effect from the current passage to a conductor. Preventive use of so-called anti-icing currents is advantageous since it uses only 20-30% of the required energy compared to posterior, de-icing operations when the sleeve is already formed. The difference in energy required is due to the high latent melting heat present in the snow or ice sleeve. For example, in case of wet snow for a ø31.5mm conductor, it is necessary to have a dissipation of about 8-10 kW / km to keep ice-free the surface, which is equivalent to a conductor current of about 400A.

The methods outlined give rise to two different strategies of use. The first can be used operably with the purpose of circulating in the conductors a current capable of producing a Joule effect sufficient to maintain the surface temperature of the conductor around 1-2 ° C with any flux of snow and air temperature. For this purpose, very useful predictive systems can be used to indicate these currents depending on the weather situation expected in the following hours. Operators have in this way the ability to assess the energy debt of the line to cope with the formation of sleeves and to make preventative decisions. The second involves the use of high currents, in order to reach the conductor temperatures close to operating limits to reduce the time of detachment of the sleeves, but this is a method of difficult practical application.

An anti-icing currents active mitigation strategy is primarily applicable to the high voltage grid, as it is only possible to route energy streams to it through protocols and very well-defined dispatching strategies. But not all trails can support an energy routing. So-called antenna lines, for example, which are non-counter-high voltage lines, represent a weak ring for this type of weather phenomenon, as the current flowing on the conductors is determined by only the consumption of the underlying user or the production of the 'Generation Plant Connected.

To increase the resilience of the system in the situations of production plants under an antenna line it would be necessary to predict a peak production in conjunction with the most intense events. Not being able to use anti-icing currents for guard ropes, and in many situations even for conductors, they are studying passive mitigation solutions based on ice-phobic coatings. The research on the materials is impressive in studying this type of solution, which the Operators are hoping for, but at this time, conductors with such coatings are not yet in production.

7.2.8 DEVICES THAT COPE WITH BAD WEATHER CONDITIONS

The continuity of supply is often threatened by bad weather conditions. Several technologies have been or are currently being developed to cope with these bad weather conditions.

Controlled Elongation Devices (CED) are essentially mechanical fuses sited at the clamping hardware of each overhead line. These components are activated when there is a mechanical overload on the conductor allowing a controlled elongation of the span and avoiding breakage. During 2015 several CEDs were installed on different MV lines in central and northern Italy. Anti-rotational devices, Figure 21, mitigate risk of forming ice snow sleeves. They are installed on several HV lines in central and northern Italy.

Figure 21 - Anti-rotational device structure and installation layout

Covered conductors. Conductors covered with XLPE insulation to prevent short circuit caused by line breakage due to ice snow sleeves. RSE is currently developing WOLF (Wet snow-Overload Alert and Forecasting), a warning system that can predict the most critical weather conditions, that could cause wet-snow sleeves, and estimate the related anti-icing current. This system will be explained deeper in the following paragraph. Consequently, RSE is developing a control algorithm for distribution networks that includes the anti-icing current constraint for most “sensitive” branches.

7.2.9 ALERT SYSTEMS AGAINST ICE SNOW SLEEVES SHAPING

The weather conditions that characterize the wet snow phenomenon are well-known, so you can make a specialized weather forecast. This type of forecast is obtained from numerical global weather forecasts, called NWP (Numerical Weather Prediction), issued by some international weather centers (ECMWF / UK IFS model, NCAR / USA GFS model), to which they engage limited area models with high spatial resolutions to obtain national forecasts. The RAMS and WRF limited range weather numeric models used in RSE operate operationally on the Italian territory with a horizontal spatial resolution of 5km. The transition from a global model (with spatial resolutions ranging from 15 to 50 km and a time span between 3 and 6 hours) to a limited range model (spatial resolution of 5 km) allows you to use different physical parametrizations, more accurate orographic descriptions, the activation of physical mechanisms also different from those triggered in the global models, and above all a time frequency of the larger outputs, typically the time and possibly even up to 10 minutes.

WOLF (Wet-snow Overload aLert and Forecasting) is developed on the model area outputs, developed by RSE, the specialized part for predicting sleeve configurations. This is an alert system that can provide the most critical weather conditions for snow overhead on the high-voltage national high-power lines under wet snow conditions, a unique Europe-wide system. The high resolution meteorological model outputs feed the sleeve growth model called Makkonen model (ISO12494:2017) [77].

The internationally acknowledged model as a wet snowmobile model suggests a cylindrical and conservative sleeve growth without shedding. The iterative application of the Makkonen model at the time outputs of a weather forecast model allows you to obtain hourly overhead forecasts per linear meter of conductor up to +72 hours from the date of issue, calculated considering also the expected dynamic wind thrust. WOLF also provides the estimate of the current required to maintain an electric line free from sleeve configurations on the basis of expected weather conditions, known as anti-icing current, supporting operators in adopting active mitigation strategies.

The anti-icing currents are determined by the thermal models of Shurig-Frick and CIGRE [76], to which adds the dependence on the precipitation snowfall that subtracts a considerable amount of heat from the conductor following the energy exchange by fusing the solid part of the precipitation. The spatial resolution with which information is available is about 5 km and the WOLF forecast update rate is daily.

A diagram of the WOLF operating chain is shown in the following Figure 22. Forecasts from the WOLF system are available through a dedicated WEBGIS site whereby it is possible to have a representation in the area of the areas where there is a significant overload of the snow sleeve network. Web site interactivity allows you to extract graphic information about snow phenomena, sleeve overloads and anti-icing currents on the model grid points. The information is related to the most common types of conductors, i.e. ø31.5mm for high voltage and ø4.6mm for medium voltage.

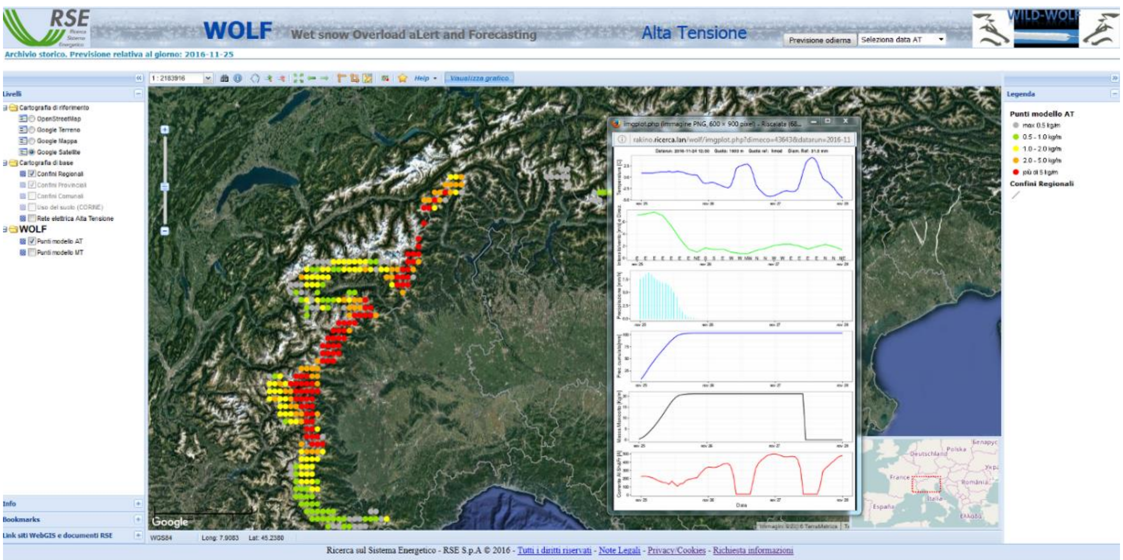

Figure 22 - WOLF website characterized by ice snow sleeves mechanical overload forecast in northern Italy (date:25/11/2016)

7.2.10 DEVICES THAT MECHANICALLY PROTECT OVERHEAD LINES

The reliability of overhead distribution networks is affected by unwanted collisions of objects and animals with overhead lines. For this reason, a number of devices have been introduced on the market that reduce the effects of these unwanted collisions. The following type of technologies can be distinguished:

- anti-collision equipment;
- anti-electrocution equipment.

DSOs are experimenting with the following type of anti-collision measures:

- signaling devices (spirals, flappers, reflective plates applied to conductors and guard cables)

Figure 23 - Bird flight divertes (spirals)

Furthermore, DSOs are experimenting with the following types of anti-electrocution equipment:

- Devices that deter birds to nest;
- Anti-perch devices;
- Protective devices that cover parts of bare conductors;
- Fully isolated overhead lines.

Figure 24 - Triangular pieces of plastic designed to stop large birds from perching along a stretch of power lines where an eagle was electrocuted earlier. (Iowa Source Media Group, Cedar Rapids, Iowa).

7.2.11 MOBILE DC SUPPLY SOLUTIONS

Many control and protection systems used in electrical distribution networks relay on a reliable DC supply system. It should be taken into account that during a large power failure the DC supply system could fail as well and that the DC supply system could also fail autonomously. To reduce the network restoration time in case of failure of the DC supply system, use could be made of mobile DC supply solutions. Such solutions can be used to temporarily take over the role of the failed DC system.

7.2.12 SOLUTIONS THAT CAN TEMPORARILY BYPASS UNAVAILABLE ASSETS

In case assets have become temporarily unavailable due to a major event, use could be made of solutions that can bypass these affected assets. An example of such a solution is the use of long flexible cables in case of broken conductors. Another example is the use of emergency poles that can be quickly erected to temporarily solve the problem of broken or fallen poles.

7.2.1 FLOOD SENSORS AND SMART METERING OF SUBSTATIONS

Flooding, theft, vandalism, terrorism as well as hotspots and corona discharges may have a significant negative impact on both the quality of service and quality of energy. To respond to these problems, EDP Distribuição has tested flood sensors and a system for smart monitoring of substations, including video surveillance, thermography and corona effect. The system for smart monitoring of substations significantly increases the monitoring effectiveness, resulting in a multispectral automatic system capable of providing faster and more complete information concerning the monitored area, in comparison with current visualization methods.

7.2.13 ANTI-VIBRATION AND ANTI-SEISMIC SUPPORT FOR DISTRIBUTION POWER TRANSFORMERS

EDP Distribuição has studied and developed a combined support system for the amortization of vibrations originated from distribution power transformers, in order to minimize noise and amortize, attenuate and significantly reduce seismic loads transmitted in an eventual earthquake. This support is an improved replacement solution compared to the traditional solution in the base of distribution power transformers.

7.3. CONTRIBUTIONS - CASE STUDIES

In this section, three case studies are presented that demonstrate that the application of technology can improve the resilience of distribution grids.

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Case Study 12 | Situation awareness tool

Synopsis

Elenia Oy, the second largest DSO in Finland has recently developed its own situation awareness tool. The tool has been piloted in a real major power disruption plus a number of smaller disruptions. Elenia has reported that the overall and detailed situation awareness has improved by the use of the tool. The time spent to gather and process data has been reduced significantly. The tool has enabled personnel to constantly analyze and compare the situations in different network areas and to make important decisions accordingly.

Findings

During a major power disruption, it is crucial for Distribution System Operators to obtain the right and up to date information regarding the situation in the affected area. Without a proper centralized system, the gathering and delivery of data from both internal and external parties can be very time consuming and inefficient.

Discussion

By making use of a situation awareness tool the management of a major power disruption can be done more efficiently. This results on shorter outage times for customers and reduced costs for the DSO.

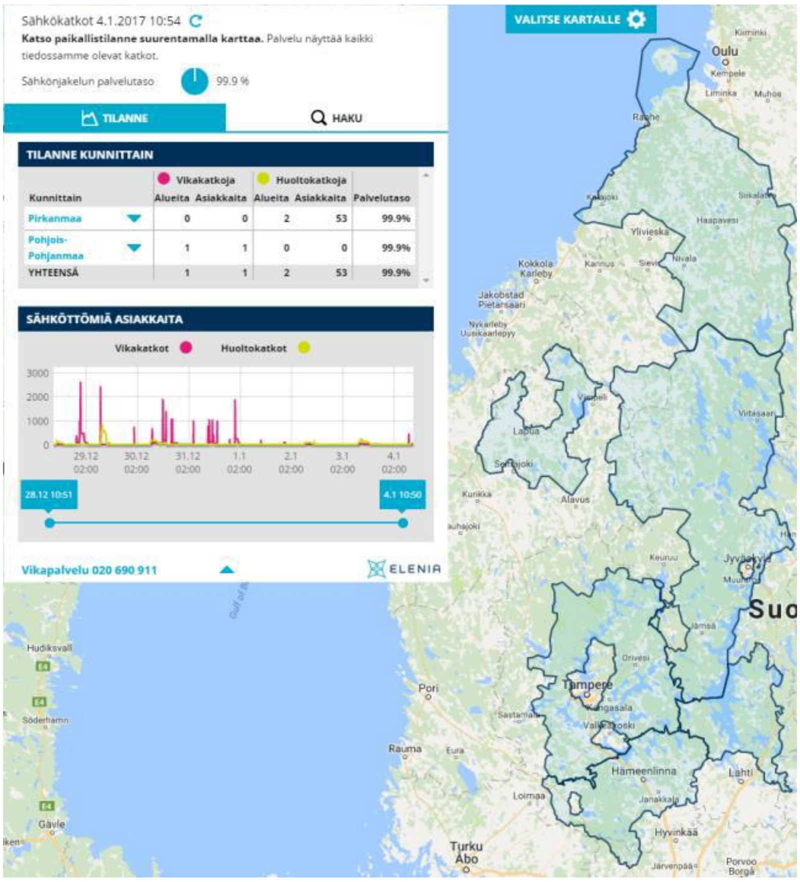

Figure 25 - Awareness tool

Conclusion

The situation awareness tool developed by Elenia has improved the overall and detailed situation awareness in case of a power failure. The time spent to gather and process data has been reduced significantly. The tool has enabled personnel to constantly analyse and compare the situations in different network areas and to make important decisions accordingly.

Recommendations

It is recommended to develop and use tools that support decision makers to take appropriate actions during major power disruptions and to recover from the disruption as fast as possible.

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Case Study 13 | Island mode

Synopsis

At several locations in Czech Republic experience is being gained with the island operation of (critical) electrical power systems during severe black out situation in the main supplying power system. This case study summarizes these experiences.

Findings

Vrchlabi, Czech Republic, is powered with only one 110kV non-backup HV line (Figure 26). In case of high impact-low probability event at this 110kV line it is possible to switch into island operation mode for 1879 supply points at HV 35kV and LV 0,4kV. Island mode was installed in June 2014 within "Smart Grid" project and consists of 1 cogeneration unit (1,6 MW), 7 transformer stations with remotely controlled circuit breakers, optical communication and WiMAX communication. Dispatching center was adjusted for island mode control. Max electrical load is 1,27 MW, min electrical load 0,4 MW. Switch into island mode can be done without interruption of electricity supply or "out of dark" from dispatching center. Additional electrical load (100kW) is used for source stability.

Coal power plant Kladno (524 MW total), owned by company ALPIQ Generation is located 30 km from Prague and in case of high impact-low probability event (black-out) this power plant can ensure the required power of critical infrastructure in Prague (e.g. airport). This project originated as cooperation between 2 distribution companies (ČEZ Distribuce, PREdi), Czech Technical University in Prague and ALPIQ. In the first phase after black-out two units 135 MW + 70 MW can start powering critical infrastructure in Prague in 5 minutes, other units 135 + 50 MW in 15 minutes. Cooperation between dispatchings of ČEZ Distribuce and PREdi is needed and complete island mode operation of critical infrastructure is reachable in 120 minutes.

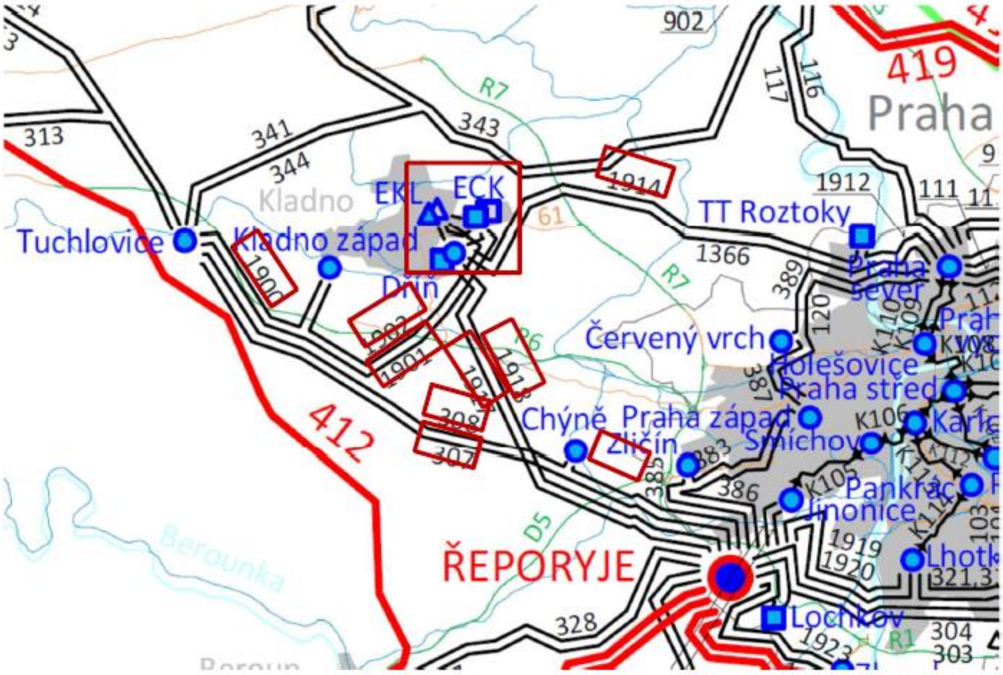

Figure 26 - Vrchlabi, HV line

Conclusion

The described case studies in Czech Republic demonstrate that island operation of critical infrastructures is a possible solution to increase the resiliency of distribution networks.

Recommendations

When studying measures to improve the resiliency of electrical power systems against high impact, low probability events, the possibility of intentional islanding should certainly be taken into account.

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Case Study 14 | Flood sensors and smart monitoring of substations

Synopsis/Executive Summary

EDP Distribuição is studying solutions to optimize grid operation and promote an increasingly more efficient management of its technical assets throughout their lifespan. Among the solutions studied and tested are flood sensors and smart monitoring of substations (video surveillance, thermography and corona effect). The system for smart monitoring of substations combines all its features to significantly increase the monitoring effectiveness, resulting in a multispectral automatic system capable of providing faster and more complete information concerning the monitored area, in comparison with current visualization methods.

Findings

Global warming is leading to the rise of the average sea level. Consequently, the risk of flood is increasing. Since EDP Distribuição has several underground substations which are susceptible to flood risk, it becomes increasingly important to implement measures to protect this type of equipment. A failure in a substation has a high impact on quality of service as well as on operational expenses.

Moreover, currently, EDP Distribuição's substations do not have any workers permanently monitoring them. Even though there are surveillance systems installed, most are not functioning due to their obsolete state. This has led to an increased risk of theft, vandalism and terrorism. The use of video surveillance systems is a method that can mitigate these risks.

Another problem faced by EDP Distribuição concerns hotspot detection in substations. Hotspots can lead to the deterioration of contact resistance, originating failures in equipment and consequently energy faults. Furthermore, corona discharge in insulators is another cause of concern since it may lead to an increased degradation of insulators, impacting on the quality of service and on the energy quality,

Even though EDP Distribuição currently monitors hotspots annually, using portable cameras, several constraints can be found in this method. Among these are the importance of the calibration type and thermic variation and the need to inspect the substation when installation exploration is at its load peak values which is not always possible. Additionally, the techniques currently used for monitoring substations are used as independent methods.

Discussion

In order to respond to the increase of flood risk in substations, EDP Distribuição has studied and tested flood sensors. These sensors aim to detect the occurrence of floods in underground substations or in substations with high flood risk (Figure 27).

On the other hand, to mitigate the risk of theft, vandalism and terrorism as well as to face hotspots and corona discharge detection issues, EDP Distribuição has tested a combined system for smart monitoring of substations. This system includes video surveillance in substations (Figure 28) in order to support maintenance operations as well as to detect unexpected movements, through the introduction of virtual barriers for intrusion pattern recognition. Furthermore, this system includes thermography with the aim of detecting, in real time, anomalies concerning overheating, through the incorporation of infrared cameras and sensors dedicated to covering hotspots, allowing the implementation of preventive maintenance. Finally, corona discharge detection is also included in the system, based on ultraviolet and ultrasounds, with the goal of detecting in real time corona discharges in insulators and preventing equipment deterioration through preventive maintenance.

Figure 27 - Risk of flood in substations

Figure 28 - Smart monitoring of substations

Among EDP Distribuição's concerns regarding substations are the increase of flood risk, the risk of theft, vandalism and terrorism as well as hotspots and corona discharge detection. These may have a significant impact on both quality of service and quality of energy. To respond to these problems, EDP Distribuição has tested flood sensors and a system for smart monitoring of substations, including video surveillance, thermography and corona effect.

Recommendations

According to the studies conducted, flood sensors are recommended for underground substations, allowing an improvement in quality of service and a reduction of operational expenses. The cost-benefit analysis of this solution shows that if three floods are avoided annually, for ten years, then the benefits will outweigh the costs.

On the other hand, the integrated smart monitoring system of substations also allows an improvement in quality of service and a reduction of operational expenses by detecting severe faults, reducing the number of visits to the substation and mitigating theft. Despite that the cost-benefit analysis is not beneficial compared to the current systems used by EDP Distribução. However, its use is recommended for critical substations with special needs of control and surveillance, to maintain business continuity.

Implementation

In order to prevent floods, flood sensors should be installed in underground substations. Furthermore, the integrated smart monitoring system of substations (thermography, video surveillance and corona effect) should be installed in critical substations, considering that:

Thermography: while installing the multispectral unit a survey should be conducted to determine the spots to be monitored, considering their location in space. Subsequently, considering (i) the camera's field of view, (ii) the area intended to be covered and (iii) the level of detail of the monitoring, the position for the multispectral unit should be determined, by minimizing the number of hidden spots. It is likely that more than one unit will be necessary in each substation.

Video surveillance: the optimization of the observing capacity of the system is conditioned by the space to be observed (substation) and by the sensor network installed, considering (i) quantity of nodes, (ii) spatial distribution of the nodes, (iii) node configuration and (iv) type of sensor to be used in each node (camera and lenses).

Corona discharge: the ultrasonic sensor developed has a detection cone with an aperture of 30º and maximum reach of 15 meters. Therefore, it should be installed in such a manner as to keep the points of interest inside the cone. The application of the sensor at less than 5 meters from the monitored object is not recommended as the source of the corona effect may saturate the sensor.

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WG | Resilience of Distribution Grids

Case Study 15 | Anti-vibration and anti-seismic support for distribution power transformers

Synopsis/Executive Summary

The current case study concerns the study and development of a combined support system for the amortization of vibrations originated from distribution power transformers, in order to minimize noise and amortize, attenuate and significantly reduce seismic loads transmitted in an eventual earthquake. This support is an improved replacement solution compared to the traditional solution in the base of distribution power transformers.

Findings

There are different types of anti-vibration supports available in the market, but none of those options guarantees simultaneously a high performance in the amortization of vibrations and an adequate behavior of the transformer in earthquake situations. For power transformers, the solutions available on the market are either only compression solutions which do not avoid instability and consequent malfunction (or even combustion) of the transformer in strong earthquake situations or they allow a fixation to the base, but the hardness is too high, overly restraining transformer chassis movements and leading to a transfer of seismic actions to the transformer, in earthquake situations, which can equally lead to failure of the transformer and consequently to failure in the electrical energy supply, which is essential, in particular, after the occurrence of a catastrophe, such as a strong earthquake. On the other hand, anti-vibration supports with fixation (with movement constraints in three directions), offered in the market, mainly use vulcanized rubber as an elastomer which does not allow to achieve a performance as high as the one obtained with other types of elastomers which are used as compression support.

Furthermore, these supports with vulcanized rubber lead to early aging, losing their resilient characteristics after a few years, particularly when under significant variations of the temperature, which happens in most power transformer installations.

Discussion

Taking into consideration market solutions limitations, an anti-vibration and anti-seismic support was developed (Figure 29). It guarantees a high performance in vibration amortization originated by the transformer due to the use of elastomers with high performance and durability, normally used as compression support, and also allows to control transformer displacements and to minimize the effects of an eventual seismic action. On the other hand, thanks to the modular characteristics of the proposed support system and to the non-vulcanization and non-gluing of the elastomers, it is possible to reuse most of the support elements in different situations.

In addition, it is extremely important to avoid that power transformers stop working after an earthquake, since there are multiple vital security systems and equipment which depend on the electrical energy supply, guaranteed by distribution power transformers, such as buildings considered sensitive, including hospitals, public buildings, airports, police stations and transport terminals.

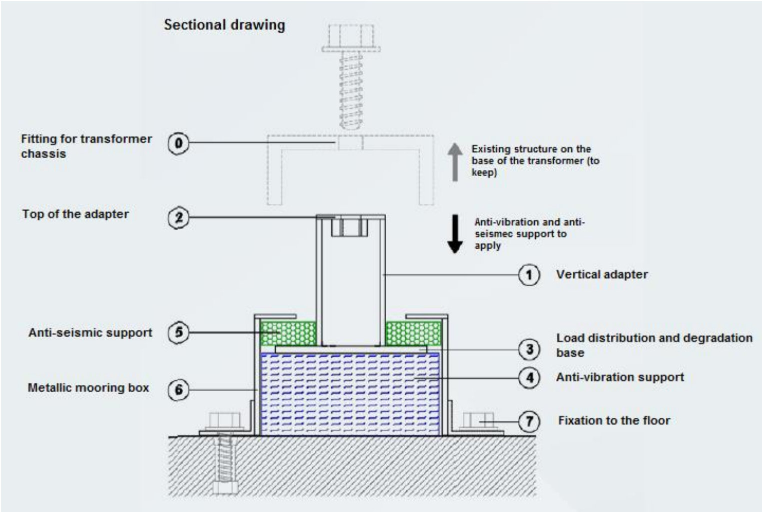

Figure 29 - Anti-vibration and anti-seismic support

Conclusion

Currently, the market does not offer solutions that can, simultaneously, attenuate vibrations created by power transformers and, at the same time, significantly reduce seismic loads transmitted in an eventual earthquake. In order to tackle this problem an anti-vibration and anti-seismic support was developed. The use of elastomers with high performance and durability is one of the main factors that contributes to the high performance of the solution. The modular characteristics of the proposed support system and the non-vulcanization and non-gluing of the elastomers allows the reuse of most of the support elements.
The cost of the solution is a differentiating aspect since it is in the same range as the corresponding support which only has an anti-vibration function due to the simplified production process.

Recommendations

The vibration control of a transformer can be done through the application of anti-vibration supports on the base of the transformer and by guaranteeing the non-existence of any type of rigid connection between the transformer and the constructive elements of the secondary substation enclosure.
If there are any rigid busbars in the earth connection these should be replaced with flexible locks. There are different types of anti-vibration supports available on the market which can substantially reduce vibration transmission, some of them with mechanical fixation capabilities and others simply on the floor. However, in earthquake situations it is important that secondary substations remain working. Therefore, this support should be able to not only solve noise problems, but also perform adequately in earthquakes, particularly on locations where there are higher seismic risks.
If the support is not attached to the transformer there is the risk that it may fall, during earthquakes. On the other hand, if anti-vibration supports with conventional mechanical fixation are used, falls of the transformer may be avoided. Despite that there is a strong risk that seismic actions may damage the transformer.
In order to effectively respond to these two types of requirements, an anti-vibratory and anti-seismic support may be used. When the transformer is directly on the floor, instead of on the rigid support, usually with a rotation system, it is suggested the use of the previously

mentioned support. It should be attached to the floor using a metal bushing. If the transformer is on top of a profile on the floor with a cavity underneath, before the application of the anti-vibration and anti-seismic support, base plates may be welded to the floor.
The modular characteristics of this support system and its controlled cost production are also differentiating. The cost of the described support is in the same range as the corresponding support which only has an anti-vibration function (for noise minimization) since each module uses a combination of materials available on the market, using normalized profiles, which simplify the production.

Implementation

The minimization of noise transmission to the installation surroundings, coming from the transformer, is guaranteed through a lower antivibration shim, with a parallelepipedal shape, with a resilient material chosen based on its dynamic hardness and on the transformer's weight, permanently keeping the same dimension inside the mooring box. The materials may be customized. Since the transformer chassis is made of two metallic profiles with an inverted U shape which are usually screwed to four rotation systems with high hardness (without the possibility of vibration attenuation) and because it is usually necessary to keep the distance between the chassis and the pavement, it will be necessary to use a vertical adapter with a specific height, which allows a higher fixation to the profiles and an inferior load degradation base which lays on the anti-vibration support.
The material for anti-seismic support will be chosen based on its dynamic hardness, on the predicted seismic impact and on the transformer weight. In this case, the flexibility of the material is much higher than for the anti-vibration support so that in earthquake situations in combination with the slack over the anti-seismic support, horizontal and vertical displacements are controlled and seismic energy transmitted to the transformer is dissipated. The vertical adapter may be built with fixed dimensions and different heights, depending on the height intended for the transformer chassis. The metallic modules of the support are produced from normalized profiles with variable plate thickness.

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8. CONCLUSIONS

Throughout this Resilience of Distribution Grids report the understanding is that digital transformation and climate changes, which are reflected on social, political and economic levels, will guide the DSO's short and medium term future, bringing new risks, demanding higher agility and proactivity in the prevention and response to emerging threats.

Events, such as cybersecurity incidents, failures in information and communication technologies, failures from critical suppliers in the value chain, failures in critical services supplied by utilities, wildfires, terrorism and natural disasters, completely change our perception of risk and security. These factors have modified the level of prevention to be considered in our daily lives, in our lifestyle, in businesses and in their management.

In every chapters, from 2 to 7, are presented several case-studies that were characterized and analyzed by different organizations and companies. These cases undoubtedly fall within the scope of the resilience of the distribution network as set out in the initial context of the report, contributing to the dissemination of existing good practices in the resilience of the distribution network.

The Chapter 2 states that despite the efforts of keeping the power flowing and the lights on under any credible events, power systems (and particularly distribution networks) are occasionally exposed to extreme weather and natural hazards (e.g. wildfires, storms and earthquakes), which as evidenced worldwide can be so intense that they can cause the collapse of power systems, leading to large and sustained power disruptions with great economic and social impacts.

Nevertheless, disruptions today are not only about power grid. Although the power grid is considered to be the mother of all networks, there are interdependencies with different operators and infrastructures that are equally important to continue to develop the activity and deliver the service. As discussed in Chapter 3, is critical to have both a resilient telecommunication infrastructure, for coordinating emergency response, and a transportation infrastructure, for access to grid facilities.

Moreover, as regards the evaluation of existing resilience, chapter 4 raises some important questions. How to decide whether critical infrastructure is resilient or not? How to define that one system is more resilient than another? It is presented a set of indicative topics that could be a first step to help define metrics for this evaluation, not neglecting the strategies coming from network planning, as well as from the operation and control, as presented in chapter 5. However, there are situations, for example in cybersecurity, which makes the issue more complicated since strategies for dealing with cyber-attacks generally do not belong to the field of energy engineering specialization. Thus, collaborations between IT specialists and energy engineering are needed to develop effective strategies against this type of threat.

These strategies are gaining importance considering the society trend where people are moving to cities and megacities, which makes the city's resilience increasingly vital, ensuring uninterrupted power supply, as discussed in Chapter 6. This way is crucial to develop strategies that also include the social and organizational aspects as well as the investment in promising technologies and technological developments that can prevent the decrease of the resilience of the distribution networks or even improve them, as presented in Chapter 7.

The issue of the resilience of the distribution grid and the way it is present in the companies and organizations, as mentioned initially, is a very broad subject, concluding that plenty has been developed, but there is room for improvement in research, analysis and deepening of the analyzed aspects and in others that contribute equally to the resilience of the distribution grid.

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