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Aspects regarding the resilience concept in power system
Part I: Challenges and resilience in power systems

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Abstract. In modern society the power system infrastructure is critical as we continuously rely on electrical energy. For this reason, the power system resilience is vital in the face of natural disasters, climate change or human-caused hazards, in order to ensure the uninterruptible energy supply service. Governments, regulatory bodies, and utility companies are collaborating to establish frameworks aimed at fortifying the power system resilience. Urbanization and demographic shifts further underscore the need for resilient infrastructure, with a focus on smart cities. Climate change exacerbates the natural risks, in the form of extreme weather events characterized by high wind speeds, high temperatures, floods, rime, etc. that can damage the outdoor electrical equipment. A resilient infrastructure is characterized by its ability to absorb the various types of shocks through adaptation facilitated by modern technology and operational solutions. The term resilience differs from the terms reliability and robustness, as it has a wider meaning in the sense that it refers not only to the ability of withstanding threats, but also to the ability of recover gracefully from disruptions. Quantifying resilience involves assessing robustness, redundancy, quick response, and adaptability over different time horizons. The resilience is sometimes illustrated in the form of a triangle that show the relationship between the impact of a disaster and the time needed for recovery. This paper is intended to provide an overview on the term resilience applicable to power system, covering a broad range of causes, and the evaluation of their severity by using both indicators and graphical representations.

Keyword: power system resilience, extreme weather, quantifying resilience.

1. Introduction

Modern societies in the 21st century is highly dependent on the electricity consumption. Consequently, the electrical power systems are designed to ensure

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the supply of electrical energy continuously, at a certain level of quality, even under special conditions when they are subject to acts of vandalism such as cyber-attacks, to natural disaster events, such as the extreme weather (hurricanes, earthquakes, snowstorms, low temperatures or heat waves, drought, or floods, etc.).

Unexpected extreme events, characterized by a low probability of occurrence, affect power systems more and more frequently, with consequences regarding the destruction of infrastructure and the interruption of electricity supply.

Being a critical and vulnerable infrastructure in the face of climate change, the electrical networks require strengthening actions to improve resilience in the face of low-probability situations determined by extreme weather phenomena. Transmission and distribution system operators need to assess the multiple impacts of power outages due to severe weather conditions, which can lead to widespread breakdowns, with the goal of taking sets of preventive or corrective measures to absorb the effects of such events destructive and for the rapid restoration of normal functioning.

For this purpose, in part I, the paper makes an assessment regarding challenges at the forefront of the 21st century, vulnerabilities of power system, energy security as well as the concept and quantification of resilience. Several definitions and characteristics of resilience were reviewed, respectively the most common resilience curves - the triangle and the trapezoid - were explained, for the assessment of damages.

In Part II, for the qualitative assessment, but especially the quantitative one, methods of measuring resilience at the level of distribution and transmission networks are described, exemplified by some concrete solutions.

The measures to increase the resilience of the system will be classified into: those of long-term planning – which aim to make the system components more robust, but which, to be implemented, may require months; operational and real-time planning measures, that include systems for improving performance and actions that can be activated within short time intervals, such as changing operating conditions or active measures to alert repair teams.

Solutions are presented for the segmentation of large electrical networks at the continental level, in the USA, Europe, India, China, using HVDC or Back-to-Back links with the aim of avoiding the propagation of faults over large areas, for the accurate control of power flows between subsystems, respectively to improve stability. Aspects related to digitization and resilience against cyber-attacks are also described. The conclusions presented at the end also include some recommendations for future activities.

2. Challenges at the beginning of the 21st century

Over the past few years, the influence of both natural and human-caused hazards on vital infrastructures such as electricity, natural gas, water, and telecommunications has prompted governments, regulatory bodies, utility companies, and other invested parties to actively pursue the establishment of a structured framework. This framework aims to bolster resilience, with a specific focus on enhancing the resilience of electricity infrastructure.

Fundamentally, this formalization process seeks to outline tactics designed to enhance the capacity of a pivotal infrastructure to endure or absorb the effects of hazards. It aims to forestall the degradation of services to the brink of collapse, formulate effective responses to and recover from disturbances, and implement adjustments that ensure the sustained provision of vital services amidst evolving circumstances.

Table 1 shows existing challenges at the beginning of the 21st century as well as proposed regulations at European or global level, for the prevention and attenuation of consequences over power systems [1].

Table 1. Challenges, agreements and regulations.

Challenges at the beginning of the 21st century		Agreements and regulations
✓ Demographic changes (population migration) ✓ Urban development (megacities) ✓ Crisis at global level (hunger, water and energy shortage) ✓ Climate change (natural disasters) ✓ Power system vulnerabilities (blackouts, cyber-attack)	vs.	✓ Sustainable development strategy ✓ Smart grid objectives (towards smart cities) ✓ European Green Deal agreement ✓ European energy transition: decarbonation; digitalization; decentralization ; energy security ✓ Energy trilemma (WEC)

2.1. Demographic changes, and growing urbanization

Urban development appeared as a paradigm shift at the beginning of the 21st century. Moreover, smart cities became the focus of industry, political decision makers as well as the research community. While the 19th century was considered the *century of empires,* 20th was the *century of states,* 21st will be the *century of cities.*

Urbanization will increase dramatically worldwide, with the population migrating from rural to city, and from poor or in a state of social conflict countries to industrialized countries (UN: in 2005-2050, this migration will be about 100 million people). People migrate to cities in the hope of a better living, looking for a chance for jobs, education, health care, public safety, or simply access to culture. [2]

Metropolitan areas experiencing significant population expansion persistently grapple with economic, social, and ecological complexities in their day-to-day functions. As depicted in Figure 1, the urban populace, currently constituting over 55% of the global population, has nearly quadrupled since the 1950s. Projections indicate that urbanization will envelop 70% of the global populace by 2050, ushering in an unparalleled surge in the utilization of present resources like energy, food, and water.

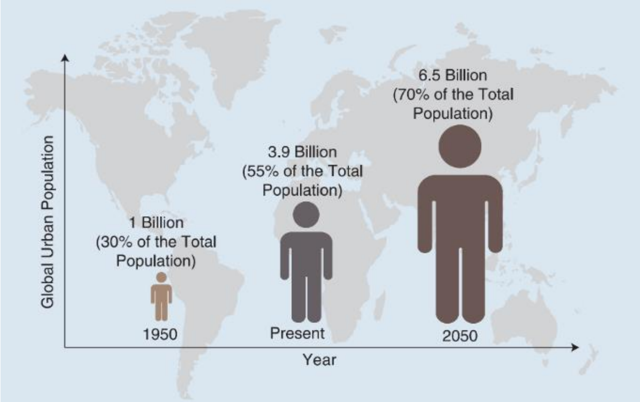


Fig. 1. The growth in urban population [3].

In 1950, 70% of the world's population lived in rural areas, in 2013 half of the global population lived in cities. According to the United Nations, if in 1970 there were two mega-cities (with over 10 million inhabitants) in the world (New York and Tokyo), 23 were in 2011 and 28 cities in 2014; for 2030 it is estimated that there will be 41 mega-cities. Fig. 2 shows a comparison of Shanghai city in the 1987 versus 2013.

(a) (b)

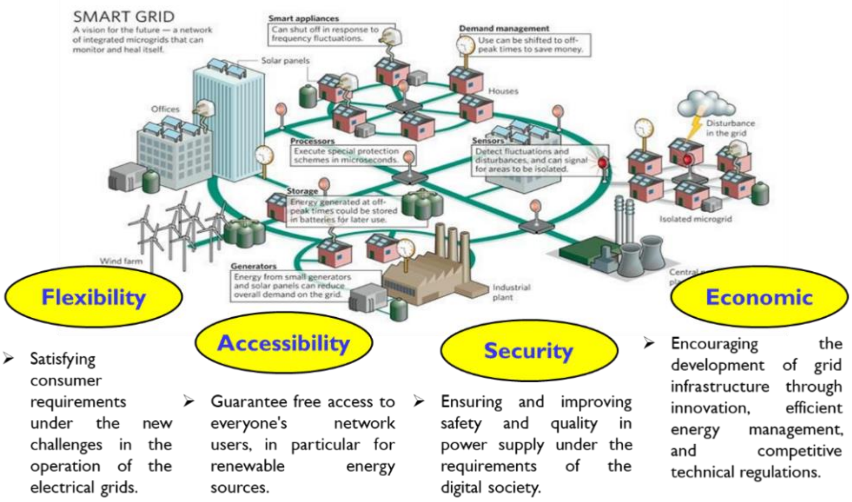
Fig. 2. Shanghai city in 1987 (a) versus 2013 (b).

By 2050, the world's population will grow to 9 billion and population in cities is expected to grow from 3.6 billion to 6.3 billion. Current estimates of the United Nations suggests that by 2030, over 60% of the world's population will live in cities especially in origins of Africa, Asia and Latin America. Furthermore, by 2050, India will reach 1.7 billion inhabitants, with significant growth in Mumbai (42 million inhabitants) and New Delhi (36 million) while China will remain at 1.4 billion inhabitants, with Shanghai playing a large part (21 million inhabitants). Finally, Nigeria and Indonesia will the grow to 350 million and 300 million inhabitants respectively. Although in 2015 the urban population in the European Union was 72% of the total population, it is estimated that it will grow to 80% by

2050. Even though cities occupy only 2% of the globe’s surface, these contain approximately 50% of global population, consuming 75% of total energy produced and being the source of 80% of CO_2 world emissions [3].

The smart cities of the future rely on efficient and reliable power systems that are capable to supplying interrupted power. The Smart Grids European Technology Platform defines Smart Grids as Smart grids that can intelligently integrate the behavior and actions of all users connected to it – generators, users and those who fulfill both roles – to ensure a sustainable, cost effective, secure power supply.

Figure 3 shows a concept of an EU future smart grid, which will ensure 4 main objectives: flexibility, free accessibility, security and cost effectiveness [4].



- Satisfying consumer requirements under the new challenges in the operation of the electrical grids.
- Guarantee free access to everyone's network users, in particular for renewable energy sources.
- Ensuring and improving safety and quality in power supply under the requirements of the digital society.
- Encouraging the development of grid infrastructure through innovation, efficient energy management, and competitive technical regulations.

Fig. 3. Structure and objectives of future smart grids [4].

A smart city comprises an assemblage of urban infrastructures united by a shared objective: facilitating specific goals such as energy efficiency, transportation optimization, and municipal enhancements. These infrastructures serve as the foundational pillars underpinning a city's effectiveness, livability, and sustainability in its operational endeavors.

Future cities must adapt to mitigate the effects caused by [2]:

- ✓ climate changes.
- ✓ population growth.
- ✓ globalization of the economy, demographics, risks, and ecological dependencies.
- ✓ technological developments.
- ✓ geo-political changes,
- ✓ urban mobility.
- ✓ social tensions and inequality
- ✓ aging population.
- ✓ uncertainty (in terms of energy, food, water)
- ✓ changes in governmental and institutional areas.

2.2. Consequences of climate change and vulnerabilities of electric power systems due to natural disasters

In the last century, industrialized societies have used with high intensity various fossil fuels, leading to pollution and climate change (more frequent heat waves, intense drought, violent rains, large amounts of snow, floods, etc.) – considered to be severe phenomena. Increasing the frequency of production of cyclones, typhoons, floods etc. cause great damage to power systems (Fig. 4).

Fig. 4. Consequences of climate change.

A big role in establishing the resilience strategy is attributed to knowing and assessing vulnerabilities (in the context of climate change), extreme weather, earthquakes and preparation of quick response strategies. Even though it is impossible to maintain the structure intact, it is necessary to elaborate solutions that ensure immediate recovery to normal operation. In the case of power systems that are strongly interconnected, it is important to evaluate means of propagation of exceptional events.

Table 2 indicates some of the challenges that determine vulnerabilities which originate from extreme atmospheric phenomena and can cause disturbances to power system operation.

Table 2. Risks and challenges in power systems [5]

Component	**Risk**	**Potential impact**
Generation in thermoelectric power plants	Excessive ambient temperature	Reduction of power plant efficiency and availability
	Excessive temperature of open circuit cooling water	Reduction of power plant efficiency and availability
	Drought and water shortage	Reduction of power plant availability

Component	**Risk**	**Potential impact**
	Storm	Rise of failure
	Flooding	Rise of failure
Generation in hydroelectric power plants	Excessive air temperature, with high losses through evaporation	Reduction of power plant availability
	Change of precipitation regime	Limitation of power plant estimated availability
	Flooding	Rise of outage risk
Generation in wind power plants	Variation of wind regime	Uncertainty of estimated power production
Transport and distribution: transformers	Excessive air temperature	Transformer denomination, decrease in transmitted power, accelerated aging
	Excessive air temperature	Reduction of available capacity
	Fire	Risk of power line faults
	Extreme storms, including extreme overhead line icing	Risk of power line and pole fall
	Presence of large birds	Risk of power line and pole faults
	Earthquakes, landslides	Risk of power line breakage

Historic data shows that 90% of power outages originate from distribution networks. Such outages affect not only supply of residential, commercial and industrial loads but also the availability of critical infrastructure, such as water, telecommunication and transportation networks as well as hospitals and emergency services, whose activity is essential in restauration efforts after catastrophic events [6].

Presently, the frequency of occurrence of atypical phenomena (characterized by high stress) is rising and the risk of structure collapse is growing over accepted values. The number of extreme events has risen 4 times since 1980, and the number of tornadoes has grown with over 40% globally. According to NOAA (National Oceanic and Atmospheric Administration), beginning with 1980, the United States of America has had 258 weather and climate disasters, that amount to over 1 billion in losses. Because of extreme weather, in the last decade, multiple power outages have occurred (Table 3) [7].

Table 3. Outages due to extreme weather, around the globe (Adapted from [7])

Country	Date	Number of affected users (million)	Event
Fukushima, Japan	11.03.2011	8.5	9.0 Richter earthquake and tsunami, shutdown of nuclear power plant
USA	27.08.2011	6.5	Irene hurricane
USA	06.2012	4.2	Derecho storm

Country	Date	Number of affected users (million)	Event
Northern India	31.07.2012	670	Repeated overload and blackouts
USA	29.10.2012	9.3	Sandy hurricane, severe flooding
Philippines	15.07.2014	13	Rammatsun typhoon
Holland	23.03.2015	1	Heavy weather conditions
Sri Lanka	03.03.2016	10	Severe storm with lightning strikes
Australia	28.09.2016	1.7	Storm with heavy rainfall and hail
USA	04.10.2016	3.5	Mathew hurricane
Macao, China	08.2017		Hato typhoon, leading to line and substation disconnection
USA,Porto Rico	20.09.2017	1.57	Maria hurricane
Hawaii	05.2018	0.014	Earthquake 6.9 Richter
Japan	06.09.2018	5	Earthquake
Macao, China	06.09.2018		Manglhut typhoon
USA	12.2018	0.5	Snowstorm and blackout in south-east
Great Britain	09.08.2019	1.1	Thunderstorm over a gas plant and an offshore wind power plant
China	10.08.2019	2.7	Lekima typhoon
Japan	09.09.2019	1	Faxai typhoon
USA	09.10.2019	2	Forced offloading of transmission power lines to prevent fire

Natural disasters can cause prolonged power supply interruptions: as an example, due to sever storm on Vancouver island (Canada), in 2015, 700000 consumers were left disconnected for a period of 72 hours; prolonged heat wave in 2015 led to steep demand growth in the city of Milan and to multiple medium voltage network failures; extreme drought in 90% of the western states in the USA contributed to reservoir drainage on the Colorado River and to 38% reduction of produced power from the hydroelectric power plants in California etc. Furthermore, earthquakes represent another cause for outages, an example of this being the event in 2018 in Hokkaido (Japan), that affected 2.95 million inhabitants.

Because electric networks span over large areas, outages can appear due to overhead lines or pole damage, as well as from faults in substations (Fig. 5 and Fig. 6 show examples of incidents from the Romanian Grid).

Fig. 5. Breakdown of an overhead line due to a tornado.

Fig. 6. Icing of an overhead line.

There have also been extreme weather conditions in Romania, such as drought (reduction of water level in the Danube River as well as in hydroelectric dams), flooding, high air temperature, earthquakes, landslides etc.

In order to deliver a comprehensive overview of major blackouts triggered by extreme weather incidents, technical malfunctions, and cyber-attacks, the authors in [8] utilize a graphical format that relies on both the magnitude of impact and historical context. The radius of these events reflects the impact on millions of users (Fig. 7). Recent, in June 16, 2019, a blackout in South America (most of Argentina, all of Uruguay, parts of Paraguay) caused power outages to more than 48 million customers. Also, a blackout in August 3, 2019, in the capital city of Indonesia caused the power outage to more than 10 million customers.

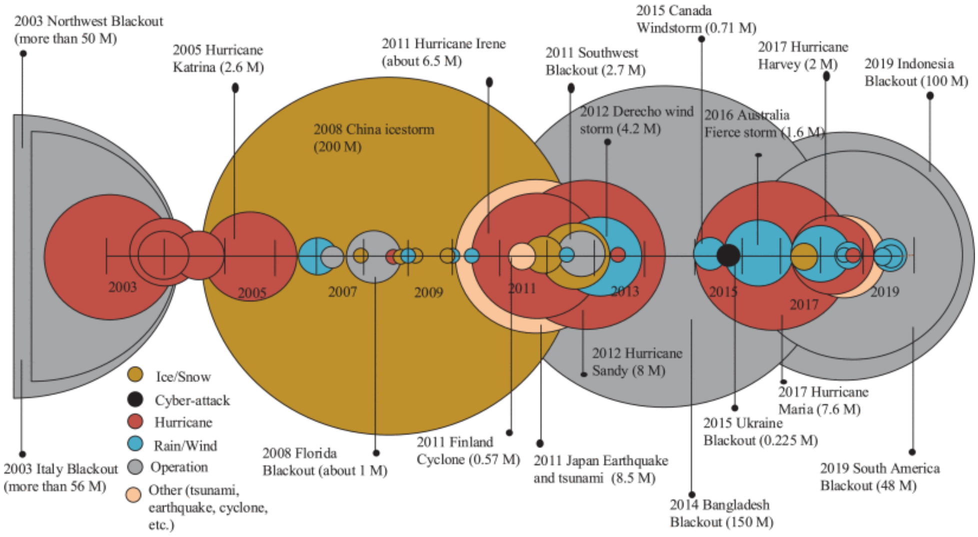


Fig. 7. Time span of extreme events and number of affected clients [8].

Yet, there should be a clear distinction between blackout and disaster, as defined in [9]:

- A blackout occurs when a large proportion of a power grid disabled by a combination of unplanned contingencies, which result in a temporary power interruption. A reliable and well-designed power system should be capable of minimizing the amount of power disruption and of recovering very quickly from a blackout.
- A disaster, which usually includes a blackout, refers to severe and rapidly changing circumstances possibly never before experienced. A disaster can cause the incapacitation of several and often large parts of a power grid, which may last for a long period depending on the extent the disaster. Hence, a power infrastructure that can maintain high level of performance under any condition should be reliable to the most *common* blackouts, but also resilient to much less frequent disasters.

Furthermore, according to [9], disasters can be separated into three categories:

(i) Physical attacks (e.g., weather events, accidental events and terrorist attacks).
(ii) Cyber-attacks (e.g., data centers and communication channels}.
(iii) Cyber-physical attacks (e.g., control centers)

Normally, blackouts can happen due to:

- Natural causes (such as floods, earthquakes, landslides, solar magnetic storms etc.) or human causes owing to an error in operation and management of the power grid.
- Major disturbances that make the power system vulnerable and cannot be anticipated by system operators.

3. The concept of resilience in power systems

In 1973, C.S. Holling introduced the concept of resilience, defining it as a gauge of the endurance of systems and their capacity to assimilate change and disruption while upholding consistent relationships among populations or state variables [10]. Following Holling's pioneering work, various interpretations of resilience have emerged, leading to a diverse range of definitions. Particularly within the domain of power systems as critical infrastructure, the landscape becomes even more intricate, given that the notion of resilience has only gained prominence over the past decade or thereabouts.

3.1. Concept of resilience vs. reliability vs. robustness

The concept of resilience is a subject of high interest, considering complex risks introduced by natural disasters, vandalism, cyber-attacks, antiquated equipment and climate change, which threaten production, transmission and distribution energy infrastructures. Storms with high wind speeds, heavy rain or drought, lightning strikes, excessive temperature (extreme highs or lows), tornadoes and hurricanes can affect operation of various power system components, if such events exceed the projected limit. Because nowadays power system components are equipped with automation and communication capabilities, risks related to cyber-attacks need to be properly considered.

Resilience is commonly characterized by three primary components:

(i) **Absorption of Shocks**: This refers to the system's capacity to endure and endure within a specific state despite the impact of a significant disturbance.

(ii) **Self-Organization**: This involves the extent to which the system can autonomously restructure and reconfigure itself in response to disruptions.

(iii) **Learning and Adaptation**: This component gauges the system's ability to cultivate knowledge and enhance its performance through adaptation.

Since its initial formulation, the concept of resilience has been extended to encompass power systems. The IEEE Task Force Technical Report PES [11] offers a definition of resilience within this context: The capability to withstand and mitigate the magnitude and/or duration of disruptive effects, which encompasses the ability to foresee, absorb, adjust to, and/or swiftly recover from such occurrences. In the realm of power systems, resilience pertains to the grid's aptitude to both prepare for and adjust to shifts in operational circumstances. This encompasses the grid's capability to endure and swiftly rebound from substantial disruptions brought about by natural events, incidents, or even deliberate cyber-physical attacks.

Firstly, resilience covers all types of threats and events, including accidents with low probability of occurrence and high impact, that are often excluded from reliability calculations. Secondly, resilience quantifies not only states in which systems end up after certain events (like reliability), but also transition states. Because of that, resilience needs a more detailed characterization of the preparation process before an incident occurs, of the process during an event and of the response after the incident. Thirdly, resilience tries to encompass effects over users, network operators as well as the networks themselves.

Even though resilience and robustness in some disciplines are used interchangeable, in power systems these terms are distinctive:

- Resilience is linked to system reliability while robustness is linked to resilience. Robustness is one of four main components of a resilient system and, consequently, stays under the umbrella of resilience.
- Resilience is integrated into operational components of a system, while robustness is involved in system design.

As defined by CIGRE Working Group 4.47, Power system resilience is the ability to limit expansion, severity and time duration of system degradation, after an extreme event [12]. System resilience is realized through a series of measures taken before, during and after extreme event occurrence (anticipation, preparation, absorption, adaptation, fast restauration, practice of lessons learned).

The definition given by EPRI (Electric Power Research Institute) specifies three main factors: prevention, recovery, and survivability [13]. These terms are described rather than being defined, and do not have metrics associated with them.

The concept of resilience differentiates with the notions of reliability and vulnerability through assessment of extreme and rare situations, that determine decommission multiple system components in parallel, affect a large number of users and require complex restauration strategies. Resilience quantifies the capability of a system to recover after a major fault, which does not necessarily ensure perfect restauration to normal parameters but a state of operation which is considered acceptable for a limited period of time. The concept of resilience is strongly linked to approaches based on risk assessment applied to power systems.

Resilience defines the capability of a structure to respond, absorb and quickly recover to initial functionality, after the occurrence of extreme events. It covers dynamic behaviour of a structure to an event, which makes it different from the term of reliability. It includes notions like flexibility and redundancy, at technical and institutional level. Each operator from a power system need to clearly define the concept of resilience for its specific conditions. In this regard, it is important to separate operational aspects (on the short term) from infrastructure (on the long term). Operation resilience concentrates on tasks that are achievable during or immediately after the occurrence of large disturbances (mainly frequency reduction as well as decrease in number of affected users) or reconnection of affected users. Long term aspects relate to characterization of future scenarios, that cover strengthening and robustness of a structure. Main aspects which are taken into consideration for resilience assessments are robustness, redundancy, organizational and technical adaptability, having the objective of restauration of functional capabilities of the affected structure. Many definitions or descriptions of resilience include some aspect of case of recovery, but do not show how to measure it as an intrinsic grid characteristic.

In [14], the author asserts that resilience is an inherent attribute of a grid or a portion of it. A grid with perfect resilience would not encounter outages. Consequently, any definition or metric reliant on quantifying the frequency, duration, extent, or impacts of outages on customers or systems fails to capture the core essence of resilience. Resilience manifests when the grid faces stress: how it withstands the erosion of capabilities or endures graceful degradation becomes its fundamental aspect. In response, a novel definition is proposed: Grid resilience is the capability to evade or endure grid stress events without undergoing operational compromise or to adjust and counteract the ensuing pressures in a manner that minimizes compromise through graceful degradation. This concept largely revolves around the events that the grid or electricity system avoids. This definition encompasses the ability to endure operational deviations beyond the normal scope while inherently tending to return to normal operation to resilience in that they provide some insight into how frequently resilience is.

3.2. Concept of dynamic resilience

Establishment of a resilient power system becomes an important component in the Energy Trilemma. More specifically, the dynamic resilience concept analysis, according to WEC, refers to 5 criteria which is useful for planning resilience growth in power systems [15].

- *Capability in situational awareness* includes the capacity to monitor, comprehend and evaluate the effects of certain events and to anticipate development of such effects nearby or in the whole system. Quantitative evaluations are necessary to assess the impact on system, so that decision makers have all data required to properly allocate resources and to mitigate consequences. Information structure plays an important role to obtain required data.
- *Baseline reserve* contains instruments, policies, collaborative networks and refers to systems, policies and processes that are taken into consideration to ensure resilience consolidation. With this regard, plans need to be elaborated in order to respond to different major incidents and to clarify the most efficient means in order to receive help from various experts in the field.
- *Agility and speed of response* refers to the capacity of fast assessment of a situation and the adoption of the most efficient policy for attenuation or adaptation. These include quick identification of priorities and coordination with interested parties. One of the most important benefits of an efficient response system is the capacity to react fast to a major event, thus reducing the amplitude of effects and the functional impact.
- *Adaptive capacity and flexibility* include an evaluation of resources, systems and existing capabilities to prevent future attacks and to enhance normal operational function.
- *Regenerative and preventive capacity.*

An immediate objective during an event is to recover as soon as possible and efficiently to normal operation. The accent is put on learning, anticipation, recognition, and approach of disruptive changes, that are characterized by novelty and uncertainty, through triggering response solutions based on operator expertise and collaboration. In the case of power systems, recovery to the functionality before fault occurrence does not refer only to affected components, but to the system in its entirety.

Even though it is considered that the most important vulnerabilities of a power system are directly linked to extreme weather conditions, some other vulnerabilities must also be recognized, such as cyber-attacks, inadequate equipment, unstable energy sources, lack of energy carriers, lack of investment etc.

4. Power systems resilience quantification

4.1. Components on analysis depending on time horizon

A system of resilience quantification is a useful instrument for guiding strategy elaboration and development planning for power systems.
Depending on the time horizon, existing evaluation methods concentrate on four main aspects, presented in Fig. 9 [16].

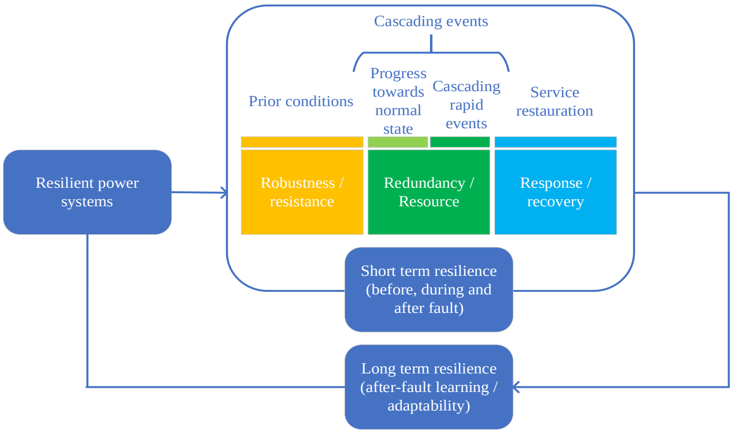


Fig. 8. Power system resilience on the short and long term [16]

Robustness / resistance: ability of a system to withstand during disruptive events and to maintain its operating state.
Redundancy / resource: capacity of a system to manage available resources (equipment and personnel) to maintain the operating state in critical condition, during disruptive events.
Quick response / recovery: ability of a system to quickly recover to a normal operating state or an acceptable operating state and to reduce the time length of supply disturbances, after a disturbance.
Adaptability: capacity of a system to learn from previous experience and to apply new strategies to enhance robustness, resources and restauration ability after a period of crisis.

4.2. Using curves of resilience

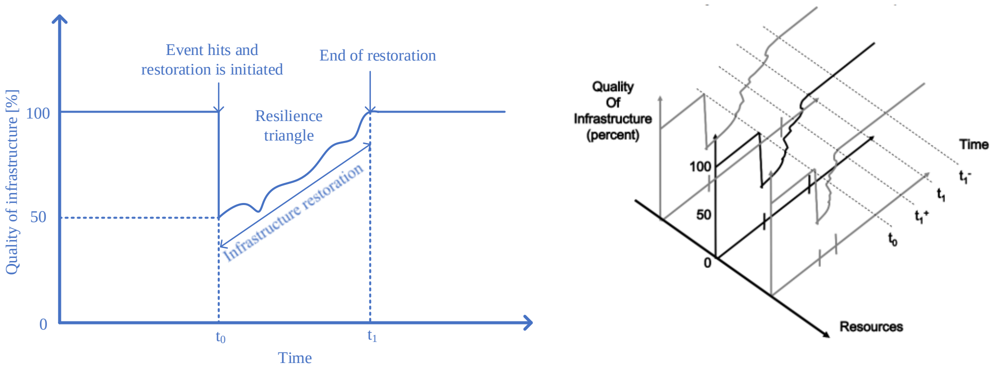
Following events like Hurricane Katrina and the September 11th, 2001, attacks, there's a growing realization that the notion of disaster resilience can be employed to describe how well an organization can restore an acceptable level of functioning following a disaster.
The disaster resilience triangle serves as a straightforward yet effective tool for illustrating the connection between the initial impact of a disaster event and the subsequent time required for recovery.

The author of the research paper [17] adopts the perspective that both the initial ability to withstand a disaster and the subsequent process of recovery are crucial factors that define an organization's capacity to return to normal operations. Evaluating and analyzing disaster resilience becomes especially vital in the context of strategically placing critical facilities like supply chain distribution hubs or network operations centers. The author proposes that disaster resilience can serve as a comprehensive measure to compare the suitability of potential facility locations, considering various potential hazards.

To support this concept, the author introduces a fresh approach to visually and analytically representing the underlying relationship between the two aspects of resilience mentioned earlier: the ability to withstand initial losses and the speed of the recovery process.

In a more detailed context, a resilient system demonstrates the following attributes [18]: (i) decreased probabilities of failure; (ii) minimized repercussions from failures, including loss of lives, damage, and adverse economic and societal effects; (iii) shortened recovery time (reinstatement of a specific system or group of systems to their regular performance level). A comprehensive gauge of resilience, encompassing these crucial aspects, can be broadly represented by the concepts visualized in Figure 10(a).

The concept of the resilience triangle was initially introduced by Bruneau et al. [18] to assess and enhance community seismic resilience. Disaster resilience is defined by the degree to which the factors of robustness, rapidity, resourcefulness, and redundancy are integrated into the physical or social system. The latter two factors, resourcefulness and redundancy, are commonly regarded as the methods through which disaster resilience can be elevated. The corresponding outcomes are typically gauged by the influence of these enhancements on the initial two factors, robustness and rapidity.



(a) (b)

Fig. 9. Concept of a curve for seismic resilience measurement (a), and (b) 3-D resilience concept (expanded in resourcefulness dimension) [18, 19].

The quality of the system's infrastructure at a given time *t* is defined by $Q(t)$. This quantity is expressed in percentages and measures the level of the infrastructure of a community, where 0% indicates a total loss (no service available), whereas 100% indicates no damage. For example, in Figure 10(a) it is considered that, after a disturbance, the quality of infrastructure drops from 100% to 50%, then is completely restored (by reparation) within a time interval (t_0 – t_1). The loss of resilience, denoted by *R*, is the measure of expected degradation in system's infrastructure quality (probability of failure), with respect to a specific disturbance, over the recovery time [18]. This loss of resilience, identified geometrically by a triangle, is simply evaluated by the following mathematical formula:

$$R = \int_{t_0}^{t_1} [100 - Q(t)]\mathrm{d}t \qquad (1)$$

Since the initial definition of the parameter *R*, as shown in Equation (1), essentially encompasses the region between the curve $Q(t)$ and the line $Q = 100$, we can simplify its estimation by calculating the area of the actual triangle formed by the initial decline in functionality and the corresponding recovery time. Consequently, the vertical and horizontal axes in Figure 10(a) represent the extremities of resilience, namely robustness and rapidity. Nonetheless, the depiction in Figure 10.*a* can be extended into a three-dimensional (or four-dimensional) representation, capturing the mechanisms of resilience, as depicted in Figure 10(b), with an additional axis illustrating that added resources can be employed to curtail the recovery time [19]. Subsequently, the area of this triangular representation can serve as the foundation for deriving a direct quantification of resilience, as proposed in the work of Cimellaro et al. [20]. However, it's crucial to acknowledge that if we quantify resilience as a basic parameter derived from the area of the resilience triangle, then disparate combinations of initial loss and recovery time can equate to the same resilience level. Since this definition of resilience relies on the scaled multiplication of these two factors, a facility experiencing minimal initial loss but requiring an extensive recovery period might exhibit the same quantified resilience as another facility facing substantial immediate loss but with a swift recovery time.

It can be observed that, because of an extreme event occurrence, there is a sudden degradation related to an earthquake of short duration (seconds to minutes) that does not necessarily relate to weather related events – where the time duration of hurricanes or storms can be hours to days; in this last case, degradation worsens while the event traverses the network, whose operation degrades linearly. The shape of the hypotenuse of a triangle can change depending on the effectiveness of the implemented recovery strategies. The shape can be linear, triangular, or exponential.

Moreover, it is considered that network restoration will be triggered at t_{t0} which is impossible due to organizational reasons. Besides this, the resilience triangle must be constructed separately for operational resilience and for infrastructure resilience.

Taking into consideration these limitations, another *curve of resilience level vs. time*, due to an event moving across the system, is presented in Fig. 11.[9]

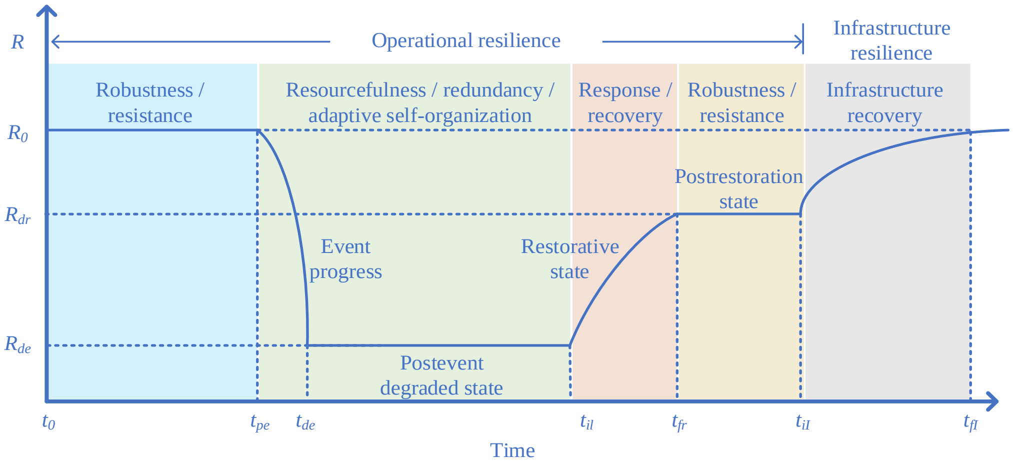


Fig. 10. Conceptual resilience curve for operational and infrastructure resilience [9].

This time, the curve is divided in five different states, proposed by MCEER (Multidisciplinary Center for Earthquake Engineering Research of the State University of New York at Buffalo), which corresponds to the states of anticipation, robustness, redundancy, resourcefulness, and rapidity. The first resilience state is between ($t_0 - t_{pe}$), where t_{pe} is the moment in which the event occurs. During this state, preventive measures are recommended, while the system will remain robust and resilient to demonstrate resilience sufficiency. Contrary to the representation in the resilience triangle, electric network resilience degradation ($R_0 - R_{de}$) is marked by the curve drawn during ($t_{pe} - t_{de}$). In order to take into account planned reconfiguration of electric networks through resourcefulness and redundancy for operational flexibility, a second state related to post-event degraded state has been introduced (during $t_{de} - t_{ir}$), where the resilience of system is significantly compromised (R_{de}). During the restorative state $t_{ir} - t_{fr}$, the electric network is restored to the level of resilience R_{dr} by considering a linear restorative process. Post-restoration state, during t_{fr} - t_{iI}, considers the duration for recover and the time required to repair the infrastructure, while the network remains at a level of resilience R_{dr} or may not be as high as the pre-event resilient level R_0, i.e. $R_{dr} < R_0$. During the repair state $t_{iI} - t_{fI}$ infrastructure is completely restored and the electric network is recovered to the level of resilience R_0 before the event.

Figure 11 illustrates both operational and infrastructure resilience, each of which is assessed using distinct indicators. Operational resilience pertains to the attributes that would guarantee robust operational performance for a power system. This encompasses aspects such as ensuring continuous power supply to customers or maintaining available generation capacity, even in the event of a disaster. On the other hand, infrastructure resilience relates to the physical durability of a power system, serving to alleviate the sections of the system that have incurred damage, experienced collapse, or generally ceased functioning [21].

The curves from Fig. 11 reveal the importance of operational measures, besides actions related to infrastructure strengthening: the first are efficient because operational recovery take less time that infrastructure recovery actions ($t_{ir} – t_{fr} < t_{iI} – t_{fI}$). Furthermore, even though operational resilience (t_0 - t_{iI}) and infrastructure resilience ($t_{iI} – t_{fI}$) are clearly marked on the curve, the curve is helpless in isolating operational degradation from infrastructure degradation during event occurrence. Additionally, post restoration state ($t_{fr} – t_{iI}$) is considered together with operational resilience, even at the same level, although its state is associated with infrastructure recovery planning which is accounted for infrastructure resilience.

Resilience trapezoid. During settling of a system performance level vs. time, to evaluate resilience of a transport system against a hurricane, the authors of [22] have developed a curve of performance in three phases. Subsequently, this curve has been restructured by the authors of [23] as a resilience trapezoid, by drawing the curve of resilience level vs. time of a system during extreme events, as well as the temporal sequence corresponding to these situations and the types of associated strategies. The event division in phases (I, II and III) enables dynamic and multi-phase resilience assessment (Fig. 12).

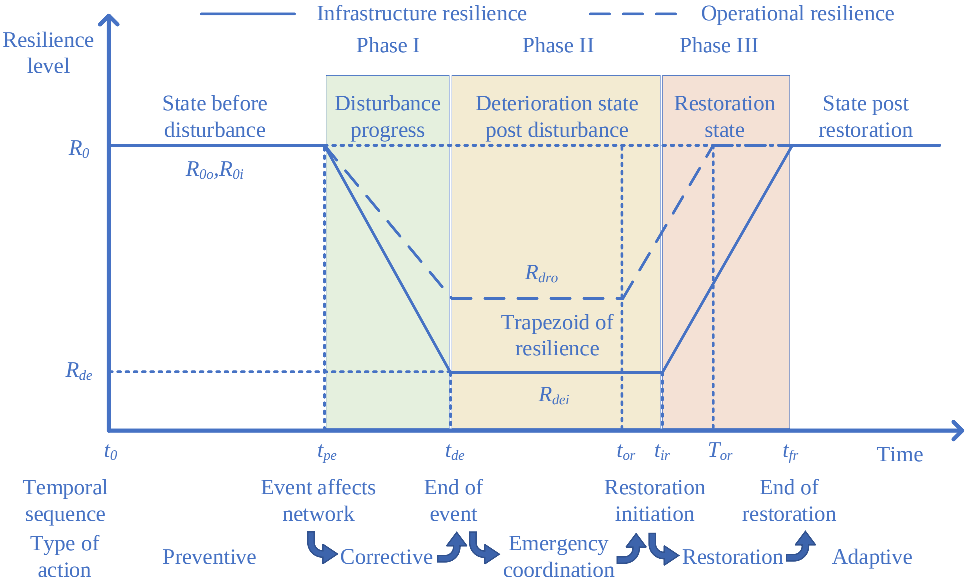


Fig. 11. Multi-phase trapezoidal diagram for resilience associated to an event [23].

As seen in Fig. 12, the pre-disturbance resilience state indicators are R_{0o} and R_{oi}. In this situation, all transmission lines are online and in normal operation. After event initiation at t_{pe}, three stages can be observed, as defined by [23]:

- Phase I, *disturbance progress* ($t \in [t_{pe}, t_{de}]$), reflects the period between the initiation of the occurrence t_{pe} and disturbance end t_{de};
- Phase II, *post- disturbance degraded state*, describes the period next to disturbance end and up to restoration initiation ($t \in [t_{de}, t_{or}]$ and $t \in [t_{ed}, t_{ir}]$ for the operation and infrastructure resilience respectively);
- Phase III, *restorative state* ($t \in [t_{or}, T_{\mathrm{or}}]$ and $[t_{ir}, t_{ir}]$ for both the operational and infrastructure recovery).

During Phase I, there is a change in resilience level, which drops from the pre-disturbance resilience R_{o0} and R_{oi} to the post-disturbance infrastructure resilience R_{dei} and to the post-disturbance operational resilience R_{dr0} respectively. However, there are some aspects which depend on the analyzed system and the severity of the disturbance. More specifically, R_{dr0} may be lower or higher than R_{dei}.

In Phase II, the system is in a post-disturbance degraded operational and infrastructure state (i.e., R_{dro} and R_{dei} respectively) and remains in this condition for a while prior to operational and infrastructure restoration initiation (at t_{or} and t_{ir}). The duration of this phase can vary for infrastructure and operational resilience, contingent upon the resilience solutions that have been implemented. For instance, the presence of intelligent operational solutions could expedite the restoration of loads (an aspect of operational resilience) more rapidly compared to infrastructure recovery. This scenario is advantageous, as it promotes a situation where the system's operational functionality is reinstated sooner than the complete recovery of its physical infrastructure.

In Phase III, there can be two sub-phases: the operational recovery, $t \in [t_{or}, T_{or}]$, and the infrastructure recovery $t \in [t_{ir}, t_{ir}]$. In many instances, operational resilience is regained more swiftly compared to the complete restoration of infrastructure components (such as collapsed transmission lines, towers, flooded substations, etc.). This discrepancy highlights the importance of differentiating between operational and infrastructure resilience. It underscores the need to assess these concepts separately and employ distinct indicators that effectively capture their unique attributes. This distinction is pivotal due to the varying dynamics involved in restoring the ability to function (operational resilience) versus rebuilding the physical components of the system (infrastructure resilience). The use of different indicators facilitates a comprehensive understanding of how these two facets of resilience respond to disruptive events and contribute to the overall system's recovery.

It can be mentioned that the level of resilience before fault Ro_0, and the resilience level post-fault, R_{oi} are not necessarily equal. However, the lowest level of resilience R_{dei} is reached during a fault. The state of resilience before the disturbance, the state of development of a disturbance, the state of degradation after a disturbance and the state of restoration are marked by the time durations $t_0 - t_{pe}$, $t_{pe} - t_{de}$, $t_{de} - t_{ir}$, $t_{ir} - t_{fr}$, as shown in Fig. 12. Additionally, a state after restauration was introduced and can be considered as a state of resilience before a new event.

The resilience trapezoid considers pre-restoration delays of weather events, where repair work cannot be started immediately for safety reasons. Such delays are successfully recorded in a degraded post-perturbation state such as the bottom of the trapezoid. In the case of events where part of the electrical network is restored immediately, while other parts are still exposed to an event causing a recovery delay, multiple delays can be marked with different t_{de} and t_{ir}. These features are differences between the trapezoid of resilience and the triangle of resilience, but the degradation and restoration of the electrical network are considered linear, although this is not always the case. In addition, the resilience trapezoid will be drawn separately for operational and infrastructure resilience, similar to the case of the resilience triangle.

In a study carried out for the US Department of Energy [24], *a more detailed curve of the resilience trapezoid* is presented (Fig. 13), which shows the performance indicator of the system, $P(t)$, at different moments t: t_0 is the moment at the state of origin; t_{pe} - the moment of occurrence of the devastating event; the devastating transition phase is between t_{pe} and t_{de} (the end of the impact of the event); the interruption phase - the one in which the system is degraded, between t_{de} and t_{ir}, that is, until the restoration actions begin; t_{r*} - initiating system recovery; t_{r**} - the beginning of infrastructure restoration; t_{fr} – state of the totally redone system.

So, increasing the resilience of the network during these phases implies the implementation of *preventive, corrective and restoration actions*.

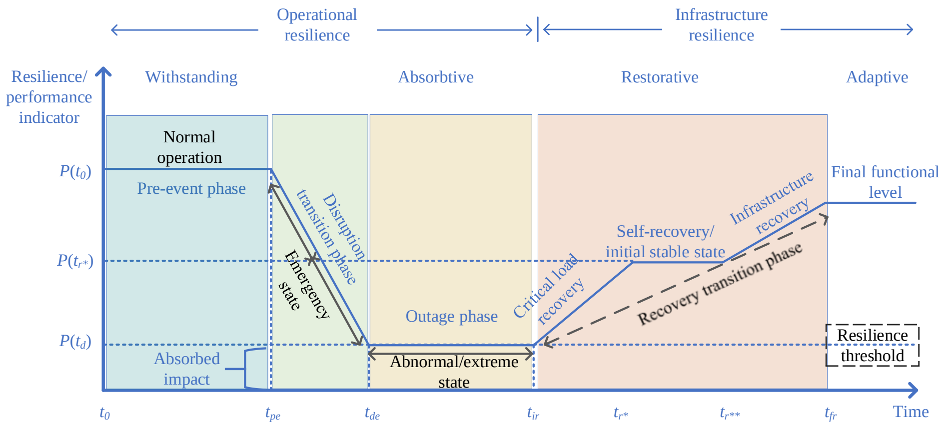


Fig. 12. A trapezoidal curve of resilience with system performance P(t) at different times [24].

As depicted in Figure 13, during the pre-disruptive event phase, the system functions under standard conditions. Upon impact of the disruptive event, the system absorbs a portion of the impact and transitions into an alert state, progressing towards an emergency condition marked by heightened degradation. This phase, termed the interruption phase, represents an atypical state. Within this phase, the system deploys corrective measures and introduces emergency resources to reinstate the provision of essential services—this process is referred to as self-restoration. Subsequent to the prioritized reestablishment of critical functions, restoration endeavors persist, involving the repair and recovery of the impacted infrastructure.

A possibility to include such actions - preventive, corrective, and restoration - in the operation of energy systems is through smart grid technologies, such as telecommunications and advanced control techniques, which will increase operational flexibility in prevention and actions correction, as well as distributed PV/wind energy resources and energy storage, for restoration actions. Also, reconfiguration options can be used to support restoration and thus optimize system resilience, while transportable energy storage systems have been proposed to reduce the effects of blackouts on large areas and planned generation within microgrids.

The capabilities and dimensions of resilience

It is noted that the phases within the resilience trapezoid described in Fig. 13 can be directly associated with the different capabilities of the resilience of a system, which are resistance, absorption, adaptation and restoration capacity (Fig. 14):

- **Resistance**: This pertains to the system's capacity to uphold an acceptable operational state during a disaster. It is evaluated by contrasting the system's normal functioning with its state during disaster scenarios.
- **Absorption Capacity**: This refers to a system's ability to absorb the impact of a disruptive event, minimizing resultant damage. This capacity considers a predefined minimum acceptable operational level and is active during the disruptive transition phase, evaluated within the interruption phase. Notably, absorption capacity is only evident over the short span of the transition phase, unlike resilience which encompasses prolonged exposure to disasters.
- **Restoration Capacity**: This signifies a system's rapid return to normal or satisfactory operation post-disruption. Speed is pivotal during this phase, with efficient resource allocation being crucial for system restoration. The velocity of damage identification also significantly influences the restoration process.
- **Adaptability**: This denotes a system's aptitude to learn from disastrous events, leading to adjustments in system configuration, staff training, and functions. This enhances the system's flexibility against future disasters. Evaluation involves comparing resilience indicators post-disturbance and post-restoration to those before the event. Furthermore, planning capability, tied to the pre-event phase, encompasses the user's ability to implement measures that mitigate potential hazards' impact on network operation.

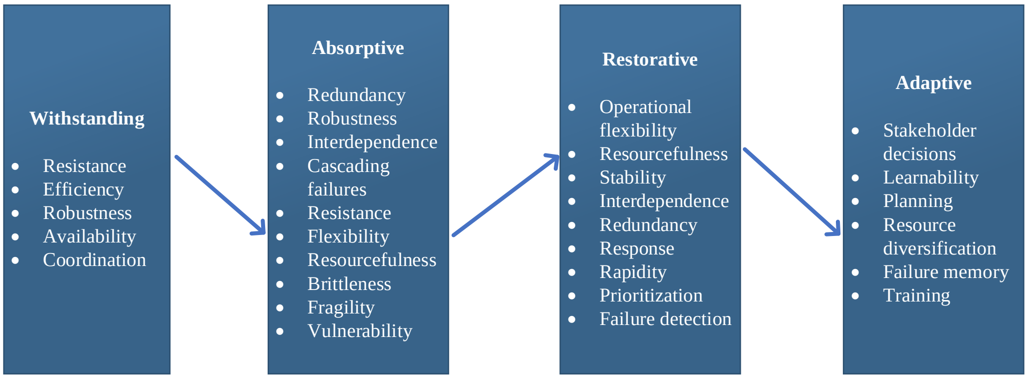


Fig. 13. Common terms associated with resilience (adapted after [23]).

In addition to these capabilities, there are *the 4R dimensions of resilience*:

Robustness: The ability to withstand disasters up to a certain level without functional loss, associated with the pre-event phase.

Redundancy: The degree to which components and subsystems can be substituted to compensate for functional loss, linked to the disruptive transition and interruption phases.

Resourcefulness: The system's knack for identifying defects, prioritizing, and mobilizing resources during threatening conditions or for recovery efforts. It's connected to absorption and restoration capacities, typically assessed between the disaster and restoration phases.

Rapidity: The capability to promptly address recovery priorities, encompassing loss management and functional continuity.

To effectively quantify resilience, quantitative metrics gauge these capabilities and dimensions. These measurements assess how diverse strategies aimed at bolstering operational and infrastructure resilience impact the system across its various performance phases outlined above.

Conclusions

Designing an electric power infrastructure that can be capable of withstanding known and credible threats, while also demonstrating resilience against infrequent yet high-impact events, presents a significant challenge. Resilience is not a fixed notion; rather, it constitutes an evolving and continuous process that involves adjusting and potentially reshaping the design and functioning of power systems to enhance their readiness to withstand unexpected external disturbances.

A resilient network must possess two characteristics: robustness and operational flexibility. Besides, it must also exhibit the capability to adapt. This requires formulating, facilitating, and executing the necessary actions and strategies to prepare for comparable or novel events that may arise in the future.

Although the extreme weather events (e.g. floods, high temperatures, strong winds), earthquakes, fires, and the presence of large birds are considered the main causes of power system natural threats. The number of climate change originated system damages will gradually increase. However, many instability problems occurring in the power systems are still due to human errors.

All these proves that the power systems are vulnerable, and the energy supply service should be regarded in a less classical way. System decentralization, distributed generation, use of power electronics, energy consumption self-education, and others, are solutions to improve the power system resilience. However, their appropriateness requires a good understanding of the system vulnerabilities. Digitalization is another technical solution, but it comes with cyber-security problems. These solutions will be treated in a further work.

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