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TECHNICAL REPORT

Conceptual framework of power system resilience

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CONCEPTUAL FRAMEWORK OF POWER SYSTEM RESILIENCE

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- reconfirmed,
- withdrawn, or
- revised.

CONCEPTUAL FRAMEWORK OF POWER SYSTEM RESILIENCE

1 Scope

This document provides a conceptual framework for power system resilience. It covers the definition, evaluation metrics and methods, improvement strategies and uses cases of power system resilience. This document is applicable to developing resilient power system and implementing resilience improvement strategies.

This document is not exhaustive, and it is possible to consider other aspects, such as different application scenarios, evaluation methods, and improvement measures.

2 Normative references

There are no normative references in this document.

3 Terms, definitions, and abbreviated terms

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

- IEC Electropedia: available at https://www.electropedia.org/
- ISO Online browsing platform: available at https://www.iso.org/obp

3.1 Terms and definitions

3.1.1
high-impact low-probability event
HILP event
event that occur with relatively low probability (or low frequency) but can have significant impacts when it does occur

Note 1 to entry: The term "high-impact low-frequency" (HILF) events is also used for this concept.

3.1.2
extreme event
rare and severe event that can have significant impacts in contrast with the more common conventional disturbances, including HILP events and unforeseen events

3.1.3
power system resilience
ability of a power system to perceive the operating state and potential threats, coordinate internal and external resources, identify, prepare for, actively defend and rapidly recover from disturbances caused by extreme events, and learn from events

3.1.4
resilient power system
power system with the characteristics or ability of resilience

3.1.5
resilient power grid
power grid with the characteristic or ability of resilience

3.1.6
short-term resilience
resilience performance of power systems in the short term, which mainly reflects their ability to respond to an individual extreme event

3.1.7
long-term resilience
resilience performance of power systems in response to multiple types or numbers of extreme events on a long-term scale

3.2 Abbreviated terms

The following abbreviated terms are always in capital and without dots.

AC	alternating current
AHP	analytic hierarchy process
ARERA	Autorità di Regolazione per Energia Reti e Ambiente (in Italy)
DC	direct current
DER	distributed energy resource
EENS	expected energy not supplied
EI	energy internet
FACTS	flexible AC transmission systems
FPSC	Florida Public Service Commission
GIS	geographic information system
HILF	high-impact low-frequency
HILP	high-impact low-probability
ICT	information and communication technology
IEA	International Energy Agency
IPS	integrated power supply
LNG	liquefied natural gas
MPQSS	multi-power quality supply systems
MTTF	mean operating time to failure
NEDO	New Energy and Industrial Technology Development Organization
NTT	Nippon Telegraph & Telephone
PAFC	phosphoric acid fuel cell
PV	photovoltaics
SMEPC	State Grid Shanghai Municipal Electric Power Company
UNDRR	United Nations Office for Disaster Risk Reduction
V2G	vehicle to grid

4 General

Along with climate change, the impact of extreme events on public utilities has attracted unprecedented attention. Enhancing the capabilities of infrastructure to cope with extreme events has become a consensus among countries, as has the power system.

Nowadays, the power system confronts rising threats from natural disasters, cyber-attacks, physical attacks or cascading failures. Due to global warming and climate change, weather-related events are likely to occur more frequently and severely. Extreme natural catastrophes, such as floods, storms, hurricanes, tornadoes, tsunamis, landslides, avalanches, extreme temperatures and earthquakes, have increasingly affected the power system. Furthermore, with the increasing demand for decarbonization, interconnected electric power systems are undergoing a series of changes, including the integration of more renewable energy sources, the integration of additional power electronic devices, and closer interdependence with other infrastructures. And the power system's ability to withstand extreme events has got greater attention.

Therefore, concepts and applications related to power system resilience have prevailed in academia and industry. Both power utilities and grid system operators have emphasized more on resilience during the planning, designing, and operating phases so that the power system can adapt to or recover from extreme events effectively and quickly, ensuring continuous power supply and maintaining system core functions. However, even if many global research institutions have already conducted research on power system resilience, many ambiguous aspects still require further investigation.

Hence, this document attempts to provide a comprehensive and accurate interpretation of the power system resilience conceptual framework. Clause 5 analyses the driving factors of resilience development, including various threats and the needs of power systems. Clause 6 provides an applicable definition of resilience, relevant interpretations, and comparisons with related concepts, such as reliability. Clause 7 presents short-term and long-term conceptual frameworks for power system resilience and outlines several key features. Clause 8 provides the metrics and methods for the evaluation of power system resilience. Clause 9 presents a list of common measures to improve the power system resilience. Clause 10 analyses several typical use cases of building resilient power system. Clause 11 discusses the unresolved issues and the standardization needs related to power system resilience.

5 Driving factors

5.1 Diversified threats to power system

5.1.1 General

A report recently released by the United Nations Office for Disaster Risk Reduction (UNDRR) has shown that the number of global disasters is rapidly increasing due to factors such as climate change and human behaviour. According to current development trends, the annual number of global disasters will increase to 560 in 2030 from 400 in 2015, just 90 to 100 in 1970 to 2000. Due to global warming and climate change, natural disasters like storms, floods, and tornadoes have occurred more frequently than before. Moreover, the snowstorm and frost damage caused by the extreme cold are more devastating and uncertain equally. Worse still, the trend of intensifying natural disasters will continue for a long time in the foreseeable future.

5.1.2 High wind

High wind refers to the wind whose velocity exceeds the conventional protection level, causing catastrophic damages, including super typhoons (hurricanes), high-intensity winds on a small scale (squall lines, downbursts, tornadoes, etc.), strong winter storms, severe wind vibrations and so on.

For the power grid, the high wind could induce flashovers, conductor galloping and lightning strike-induced tripping of transmission lines. In severe cases, transmission towers even collapse. Debris drifting in the air from high wind can also cause physical shocks to exposed power infrastructure.

In July 2014, Super Typhoon Rammasun landed in Southern China, causing a great deal of tower collapses and disconnections in transmission lines, extensive damage to power facilities, and severe destruction to the power grid structure. On August 10, 2019, Typhoon Lekima landed in Wenling City, China, destroying power facilities in many places. In particular, 72 substations, 3 753 lines, and 5 535 500 households suffered power failure. On October 28, 2013, the Danish power grid was hit by Hurricane Allan, and several interconnecting lines tripped, leaving the system in an unstable state.

5.1.3 Extreme heat

Extreme heat refers to exceptionally high temperatures that surpass the maximum threshold for the protection of the power system and its components. In such scenarios, climate disturbances contribute to the occurrence of heatwaves, which are characterized by prolonged periods of hot weather, reduced rainfall, and elevated average temperatures, typically experienced during the summer season. These climatic events result in abnormal operating conditions, particularly for underground cables and their joints, posing significant challenges to their functionality and performance.

For the power grid, extreme heat could cause the overload of lines, transformers, and other equipment because of increased electricity use. It also could cause sagging power lines, cable failures, shorted underground circuits and transformer overload, resulting in power outages.

In August 2020, a record heat wave in California caused a surge in power use for air conditioning that overtaxed the grid. That caused two consecutive nights of rolling blackouts due to the imbalance between supply and demand under extreme heat, affecting thousands of residential and business customers. In July 2022, nearly 50 000 New York City residents lost power on Sunday evening as the third day of an intense heat wave gripped the city, and roughly 33 000 customers in Brooklyn had their service cut in order to repair the damaged equipment.

5.1.4 Extreme cold

Extreme cold refers to extremely low temperature, icing, and snow that break through the minimum protection level of the power system, such as glazed frost, mixed frost, rime, snow, and hoarfrost, etc.

For the power grid, extreme cold, especially ice and snow disasters, could lead to the freezing and blocking of switchgear, the flashover of transmission equipment covered with ice and snow, and the breakage and damage of lines and towers. These disasters usually cause large-scale power outages due to their wide coverage, long duration, and difficulty in repairing equipment.

The ice and snow disasters in 2008 severely damaged power facilities in 13 provinces and cities in southern China, cut off 36 740 transmission lines and led to the collapse of 2 018 substations and 563 236 towers due to the imbalance between supply and demand caused by extreme cold. In mid-February 2021, extreme ice, snow, and cold weather hit Texas in the United States, causing a severe blackout in the Texas power grid, during which nearly 5 million households suffered power failure.

5.1.5 Earthquake

An earthquake refers to the vibrations caused by the rapid release of energy from the earth's crust, leading to direct damages, including building damage, landslides, mudslides, tsunamis, and earthquake light burns, as well as secondary damage like fires, floods, poisonous gas leaks, and plagues.

More than 5 million earthquakes occur on the earth every year, namely, tens of thousands of earthquakes every day. However, most are so weak that they cannot be felt. About 10 to 20 earthquakes cause serious harm to human beings every year worldwide. Earthquakes cannot be predicted easily, as they occur infrequently and randomly.

Strong earthquakes could lead to widespread power grid failures and devastating damage to grid equipment. For example, on May 12, 2008, when an earthquake of magnitude 7,8 occurred in Wenchuan County, China, the power system lost about 4 million kilowatts of load, and one 500 kV substation and twelve 220 kV substations were out of service. An earthquake of magnitude 9,0 occurred in the Northeast Pacific region of Japan on March 11, 2011, followed by a tsunami, which seriously affected Fukushima Daiichi nuclear power plant. This event profoundly changed the energy strategy of Japan and even the world.

5.1.6 Hydrological disasters

Hydrological disasters refer to heavy rainfall, floods, storms, and tsunamis that break through the conventional protection level of the power system. Over the past 20 years, the number of global floods has more than doubled, from 1 389 to 3 254, averaging 163 per year.

Hydrological disasters exert a direct impact on the power infrastructure, causing damage to transmission lines and power equipment. Moreover, tsunamis will also inflict direct physical damage on coastal or offshore wind power infrastructure and other equipment.

In late July 2015, a series of heavy rains fell in Quang Ninh Province in Northeast Vietnam, triggering the largest flood disaster in this region in 40 years. Due to the damage to many coal mines and the increased difficulty of power transportation caused by the flood, all coal-fired power plants in Quang Ninh province faced coal shortages, affecting the overall power supply across Vietnam.

5.1.7 Other natural disasters

Other natural disasters also pose threats to the power system, such as thunderstorms, wildfires, geomagnetic changes, and geological disasters. Take thunderstorms as an example. During thunderstorms, power lines are commonly struck by lightning, causing a power surge that overloads local transformers and causes major power issues.

On September 28, 2016, South Australia suffered a lightning strike once in 50 years, resulting in a large-scale power outage, with a loss of 1 826 MW of load, affecting 1,7 million people.

On March 13, 1989, a geomagnetic storm caused a blackout of the 735 kV power grid in Quebec, Canada. The power outage lasted for 9 h, and 6 million residents were directly affected.

In this context, power systems are facing increasing external and internal threats, including the aforementioned natural disasters and other threats. These events, characterized by low occurrence probability or extremely low predictability, can have significant impacts on the power system once they occur. We refer to them extreme events, including "high-impact low-probability" (HILP) events and unforeseen events. These extreme events have become the focus of research on power system resilience.

5.2 Complex characteristics of power system

5.2.1 General

In order to cope with climate change and alleviate the dependence on fossil energy, many countries have successively put forward sustainable development strategies in recent years, intending to create a new green and low-carbon power system.

A sustainable energy supply system is expected to not only ensure the security of energy supply, but also promote low-carbon energy development. However, in the process of low-carbon energy development, especially the development of a zero-carbon power system, energy security is adversely affected, especially in extreme situations.

The low-carbon power system is featured by the high proportion of renewable energy, the high proportion of power electronic devices, diversified terminal loads, and the deep integration of information and physical systems. The continuous integration of new elements promotes low-carbon energy transformation and further complicates power systems, posing severe challenges to the safe operations of power systems. On one hand, the renewable energy generation and diversified loads increase the operational uncertainty of power system. Environment changes and uncontrollable human behaviours can cause significant variation in power injections at renewable energy generation nodes and power consumption nodes. On the other hand, the vulnerability of the system is affected by power electronic devices and interconnection grid structures. The cascading failure of devices could increase the operational risk and lead to large-scale risk propagation across different systems. Therefore, it is important to clarify the complex characteristics and demands of the power system.

5.2.2 High proportion of renewable energies

The low-carbon power system emphasizes the replacement by clean energy on the power supply side. In the current technical environment, it is manifested by the rapid development of renewable sources, such as wind power and photovoltaics (PVs).

The renewable energy power generation, such as wind and PVs is random and fluctuating, posing a huge challenge to the power system steady state. That is, a high proportion of renewable energy will lead to significantly increased fluctuations in power generation. Under the operating condition that the power supply is adjusted with load changes, other conventional power sources are expected to follow new energy fluctuations and make corresponding adjustments. Introducing renewable energy into power balance in the dispatching operation is crucial yet strenuous.

A high proportion of renewable energy access will induce higher risk in the safety and stability of power systems. As many conventional power sources are replaced by renewable energy sources, the power system's moment of inertia and ability to regulate frequency and voltage continue to decrease, as well as the dynamic adjustment capabilities of power generation.

5.2.3 High proportion of power electronic devices

The continuous integration of renewable energy sources has led to the introduction of a large number of power electronics at the source end, such as the converters for direct-drive wind turbine and photovoltaic. On the grid side, DC transmission, FACTS and DC distribution networks are developing rapidly. Load-side power electronics are also emerging. Consequently, the components of energy generation, grid and loads in low-carbon power systems tend to be highly electronic, presenting numerous challenges for their operation, analysis and control.

Power electronic devices are featured by low inertia, weak disturbance resistance, and multi-time scale response. Unlike traditional synchronous units with rotational kinetic energy, power electronic converters lack inertia response. Also, interaction among power electronic devices and between power electronic devices and the AC grids can cause wideband oscillation. The diversity of control methods for intermediate power conversion interface devices poses significant challenges in conducting stability analysis and control of power systems.

5.2.4 Diversified load characteristics

The continuous increase in the proportion of power consumption and the development of multi-energy-supplemented supply systems symbolizes that the power load continues to grow through diversification. When various loads, which are featured by different power consumption needs, transient characteristics, multi-time scale response, and spatial-temporal uncertainty, are connected to the power grid. Power consumption on the load side becomes more "individualized", which increases the adjustable resources of power systems to a certain extent but poses new challenges to its safe operations.

5.2.5 Infrastructure interdependencies

Along with the development of the energy internet (EI), energy coupling has become increasingly intensified, and the electrification of various infrastructures has deepened. The interdependency between infrastructures greatly increases the overall complexity of the energy system. The power system, the water supply system, the transportation system, the natural gas system, the oil system, and the cyber system are tightly interdependent. The complex relationships among them are characterized by multiple connections, feedback, and feedforward between infrastructures, as well as complex branch topology. In that case, a holistic view takes into account the multiple coupled infrastructure systems and their interdependencies. However, the interdependence between different infrastructure systems raises the risk of cascading failures and increases the vulnerability of the infrastructure with power systems to unconventional disaster events, resulting in increasingly significant economic and social impacts stemming from power outages. Thus, risk management is required to improve the resilience of interdependent systems. Furthermore, asset management could be integrated into the operation and planning of interdependent systems. For the infrastructures, factors such as asset value and alignment affect the strategic decisions made by operators, and managing multiple assets within interdependent systems increases the regulatory complexity.

Based on the above characteristics, in order to ensure the safe operations of the low-carbon power system, it is important to acknowledge the significant impact of extreme events on power systems and to develop metrics, methods, and strategies for defining, evaluating, and improving the power system resilience.

6 Definition of power system resilience

6.1 Definition

The concept of resilience was initially introduced to measure an ecosystem's ability to withstand and absorb disturbances and maintain system stability. Over time, the concept has increasingly become integrated into other fields, such as environmental science, sociology, and industry, to evaluate the ability of individuals, groups, or systems to withstand and recover from external disruptions.

The concept of resilience has also got significant attention from academic and industrial communities in the field of electricity. Discussions and considerations regarding the planning, design, and operation of power grids by power companies and system operators have received widespread attention, enabling the power system to adapt to or recover from extreme events effectively and promptly, ensuring continuous power supply for critical loads, and restoring the system to normal as soon as possible.

Governments, businesses, and research institutions in different countries have published various research reports providing their understandings and definitions of resilience.

In the United States, "Presidential Policy Directive 21: Critical Infrastructure Security and Resilience" (PPD21) in 2013 focused on the security and resilience of critical infrastructure, and provided a definition of resilience. The primary aim of PPD21 is to coordinate and integrate government efforts in protecting and enhancing the resilience of these vital assets. Although the directive does not explicitly address power systems, it encompasses critical infrastructure sectors, including energy, making it applicable to discussions on power system resilience. However, this definition does not mention the learning and continuous improvement of system capabilities.

The Canadian government released the "Federal Policy for Emergency Management" in 2009, and updated and revised it in 2017. Although the policy does not specifically address power or energy system resilience, it does mention the definition of "resilience". The objective of this policy framework is to enhance overall Canadian resilience in response to various emergencies. And the definition does not mention the aspects of prior prevention and preparation, nor does it address post-event recovery.

The UK Energy Research Centre released a research report "Building a Resilient UK Energy System" in 2011, in which the definition of "energy system resilience" was introduced. This definition primarily adopts a user-oriented perspective, offering a functional description of the resilience concept in energy systems. However, it places greater emphasis on defensive capabilities and lacks a detailed characterization of the requirements and features of energy systems themselves during the prevention and recovery phases.

The International Energy Agency (IEA) released a report "Making the energy sector more resilient to climate change" in 2020. The report highlights the significant risks climate change poses to energy infrastructure and supply chains, emphasizing the importance of strengthening the resilience of energy systems. Additionally, the report presents a definition of the resilience of the energy sector. In IEA's definition, resilience addresses not only hazardous events but also hazardous trends, and it incorporates learning and transformation aspects. However, it does not mention preventive measures prior to such events or trends.

Due to varying development stages of power systems, types of disruptions, and focus areas, the understanding and definition of resilience differ across different countries and organizations. However, the fundamental starting point remains consistent. Resilience addresses aspects that traditional concepts, such as reliability and safety, cannot cover, thus filling a gap in one aspect of power system security.

Based on the research conducted by a group of SC C4, CIGRE provides a concise and accurate definition of resilience, and described the characteristics including anticipation, preparation, absorption, sustainment, recovery, adaptation and lessons learnt. The definition also offers several key actionable measures that are relatively comprehensive and easy to understand.

The resilience attribute and organizational resilience are defined in ISO/TS 31050:2023, 3.1 and 3.4:

> *Resilience attribute: feature or characteristic of an organization's ability to absorb and adapt to a changing context.*
>
> *Organizational resilience: ability of an organization to absorb, recover and adapt in a changing context.*

Those definitions depict the importance of organizational resilience for an organization operation in changing environment.

As various countries and research institutions delve deeper into the study of power system resilience, the definition's connotations continue to expand, and the scenarios it addresses become clearer. While there are some variations in the definitions provided by different parties across various scenarios, the general consensus is that resilience refers to the ability of a power system to prevent, resist, and recover from extreme events, including HILP events and unforeseen events, which mainly refer to the events mentioned in Clause 5. More specifically, "low-probability" indicates that the likelihood of extreme events occurring is much lower than that of traditional power system disturbances or malfunctions, or these events are unlikely to lead to large-scale impacts on the power system under conventional circumstances; "high-impact" denotes that power system which is greatly affected by the extreme events will impose a negative impact on the power supply of large areas and users, provoking huge indirect economic losses and social disorders.

Based on the definition given by CIGRE, which has provided a relatively comprehensive definition, this document integrates the key characteristics and measures of power system resilience into the definition, taking into account the functional requirements of pre-event, during-event, post-event, and long-term resilience. Additionally, it considers the coordination of internal and external resources, as well as the perception of internal and external system statuses, to form a more detailed explanation of the concept of power system resilience (see 3.1.3):

Power system resilience is the ability of a power system to perceive the operating state and potential threats, coordinate internal and external resources, identify, prepare for, actively defend and rapidly recover from disturbances caused by extreme events, and learn from events.

Resilience outlines new requirements for the power system. That is, it is important not only to enhance the defensive capability of the power system, but also to improve the effectiveness of using various resources to adapt to changing conditions, under unavoidable accidents, to maintain operational functionality and restore system performance efficiently.

6.2 Interpretation

The definition of power system resilience is further clarified from five aspects.

a) The concept of resilience is founded in preparation for extreme events. These events are characterized by HILP or unpredictable, indicating that they could yield significant impacts but have a low occurrence probability or a low predictability, such as a "black swan" event or a "perfect storm" event. The concepts of "high" and "low" here are relative to conventional events and are typically not conducive to quantitative description.

b) The extreme events could be either instantaneous shocks or continuous pressures, such as continuous wars, ongoing pandemics, incessant random disturbances, etc.

c) In relation to ongoing events affected by extreme events, the power system resilience can also be characterized from both short-term and long-term perspectives based on the duration of extreme events.

d) Recovering from extreme events, the power system has the possibility of returning to the initial state shown before the disturbance or not. The post-recovery state could be slightly worse or better than the initial state as long as core functions remain operational.

e) The power system resilience is not only related to its planning and operating strategies but also affected by external factors, such as the government's emergency management capabilities, traffic conditions, and so on.

6.3 Comparison between resilience and other related concepts

6.3.1 Reliability

Based on the definition in IEC 60050-192:2015, 192-01-24, reliability refers to the "ability to perform as required, without failure, for a given time interval, under given conditions". In power system, it represents the ability to meet the load demands. Some average indicators, including the expected energy not supplied (EENS), mean operating time to failure (MTTF), are often used to describe the satisfaction level of load demands over a time interval.

Reliability and resilience have a similar scope but different focuses. In particular, while reliability theoretically reflects the impact of all failure events, and is measured based on a long-term average value, it fails to capture the impacts of the low-probability events. Therefore, evaluating the impacts of low-probability extreme events on the power system via reliability proves challenging.

In contrast, resilience directs attention solely to extreme events rather than all failures. It emphasizes that when unavoidable failures occur, the system can leverage diverse resources promptly and efficiently to mitigate operational risks, adapt to changing environments, maintain operational functions, and restore system performance in a relatively short period.

6.3.2 Vulnerability

Vulnerability refers to the quality or state of being exposed to the possibility of being attacked or harmed. For power system, it represents the operation state changes under a given event, such as the reduction of loads, the decrease of node voltage. Both vulnerability and resilience reflect the impacts of events on the power system operation. However, resilience also reflects the system's ability for sustained operation and restoration from the resulting impacts, aspect not typically addressed by vulnerability.

6.3.3 Flexibility

Power system flexibility refers to the ability of a power system to adapt to random changes in power generation, power grid and load at a certain cost by optimizing the allocation of various available resources under a certain time scale.

Both resilience and flexibility are intrinsic properties of the power system. While both describe the ability of the system to cope with changes from different perspectives, they complement each other. Flexibility focuses on the real-time supply and demand balance capability of the power system in the face of random disturbances of source and load. It ensures sufficient power supply by coordinating flexible resources, including sources, networks, loads, and storage. In contrast, resilience focuses on the impacts of extreme events on the power system and reflects the ability of the power system to perceive the state, coordinate resources, actively defend and rapidly recover and learn from extreme events, including but not limited to the coordination of flexible resources. A highly flexible power grid can coordinate resources more flexibly in the face of disturbances. Therefore, increasing flexibility also facilitates the enhancement of power system resilience.

6.3.4 Security

Security refers to the ability of an electric power system to operate in such a way that credible events do not give rise to loss of load, stresses of system components beyond their ratings, bus voltages or system frequency outside tolerances, instability, voltage collapse, or cascading. The major difference between resilience and security is whether to conduct security assessments for the system associated with the credited contingencies. Resilience assessment focuses on the impacts of extreme events, while the security assessment mainly studies the safe operation with system constraints, such as the voltage magnitude constraint under a set of specific contingency events. In other words, when a system operates securely, it does not necessarily exhibit resilience because resilience is specifically linked to extreme events.

6.3.5 Strength

Strength is an important part of resilience, especially within the backbone of the power system. Strength refers to the ability of a system to withstand shocks and even maintain its original state as stably as possible. Conversely, resilience emphasizes more on the overall ability to maintain core functions, regardless of the consistency of initial and restored states. While it is possible for a resilient system to lack strength during a shock, it possesses the capability for self-recovery, potentially leading to a new state that either closely resembles or differs from the original state.

The comparison between resilience and other related concepts are given in Table 1.

Table 1 – Comparison between resilience and other related concepts

Concepts	Characteristics and application scenarios
Resilience	Resilience focuses on the extreme events and reflects the ability of the power system to perceive the state, coordinate resources, actively defend and rapidly recover from events.
Vulnerability	Vulnerability refers to the quality or state of being exposed to the possibility of being attacked or harmed. It reflects the impacts of events on the system operation whilst it ignores the sustained state or the restoration process.
Reliability	Reliability reflects the impacts of failure events with predictable probabilistic characteristics in power system operation.
Flexibility	Flexibility refers to the ability maintaining the power balance by optimizing the allocation of various available resources under a certain time scale.
Security	Security reflects the operational state of the power system within a range of secure constraints and is usually used in the normal operation scenarios.
Strength	Strength refers to the ability of a system to withstand shocks and even maintain its original state as stably as possible.

7 Models and features

7.1 Short-term resilience model

Short-term resilience refers to the power system's ability to respond to a single extreme event. The resilience curve is widely used for describing the short-term resilience process, as shown in Figure 1. It shows the level of the system operating state as a function of time during the disturbance of a single event. Before the extreme event occurs at t_e, the system's operating state maintains at the normal level Q_1. After the extreme event occurs, the operating state is reduced from Q_1 to Q_{pe}. Due to flexibility and adaptability, the power system will be stabilized at a certain derated state Q_{pe} for a certain period of time. At the time t_r, the power system starts to self-restore. Once the restoration is completed, the operating state Q_{pr} have potential to be as high as the pre-event operating state Q_1 or not, i.e., $Q_{pr} < Q_1$, because relevant infrastructures possibly be damaged and require a long time to be repaired. Subsequently, as the infrastructure is repaired, the system gradually returns to a normal operating state Q_n. It is possible that this state Q_n differs from the pre-event state Q_1.

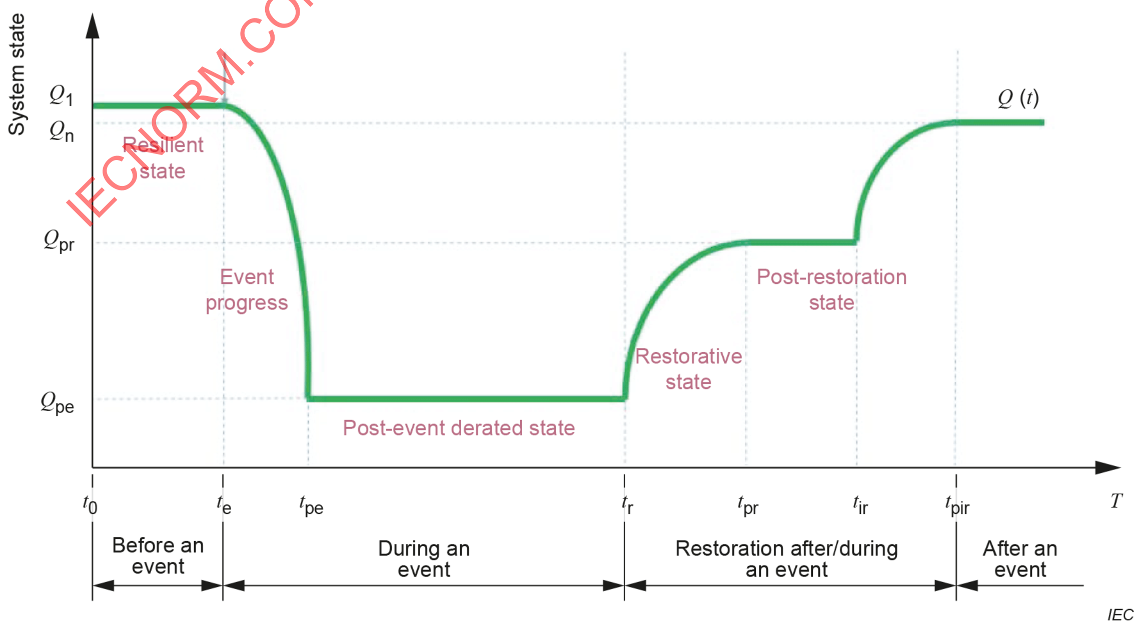

Figure 1 – Function curve of short-term resilience

7.2 Long-term resilience model

Long-term resilience refers to the resilience performance of power systems in multiple types or numbers of extreme events on a long-term scale. Long-term resilience mainly involves the ability of the system to learn and improve on a long-term scale, combined with economic efficiency.

Based on the conceptual framework of long-term resilience, the power system continuously learns from the impact of extreme historical events and integrates new technologies for self-improvement. It is important to combine historical information and actual engineering experience to evaluate a power system, and regularly update strategies and decisions related to the power system resilience.

On the other hand, economic efficiency emphasizes the cost-benefit analysis in the process of improving the power system resilience. It is helpful to deeply understand the costs and benefits of each resilience improvement measure to guide the long-term planning and investment of power system infrastructure. In this process, it is important to take into account the principles of asset management (see ISO 55000, ISO 55001) for power grid, which involves the balancing of costs, opportunities and risks in various extreme events to achieve high-resilience power system. As shown in Figure 2, the power system operators learn the resilience enhancement measures from the historical events. Then, the costs and benefits of different measures are evaluated, in which the value of each asset for improving the system resilience is determined by the operators. By asset alignment, the resilience enhancement objective would translate into technical and financial decisions, plans and activities in long-term resilience model. Finally, the model and evaluation results guide the priority application of resilience enhancement measures considering the requirements of asset management.

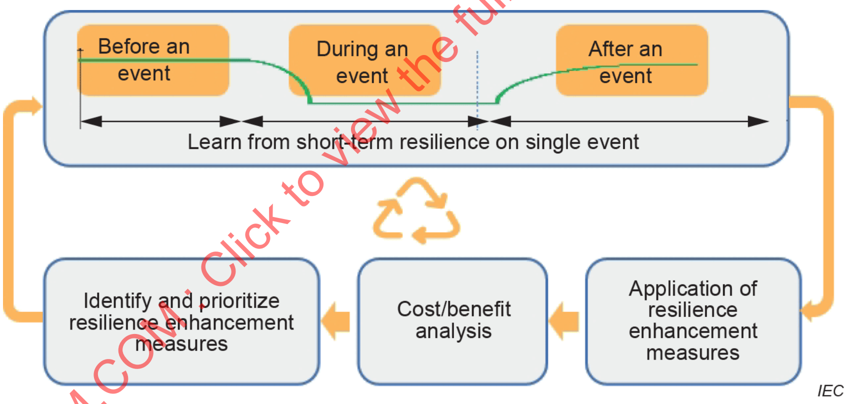

Figure 2 – Framework of long-term power system resilience

7.3 Features of power system resilience

7.3.1 General

Based on the definition and models showed in 7.1 and 7.2, the power system resilience could be characterized by abilities of preparation, resistance, adaption, restoration, perception, coordination, and learning (see Figure 3). In particular, preparation, resistance, adaption, and restoration are core features of short-term resilience, which describe the coping capabilities of the power grid before, during, and after a disturbance event. Perception and coordination are important in both normal operating state and throughout the disturbance event, supporting the enhancement of preparation, resistance, adaption, and restoration capabilities. Learning ability refers to the ability of a power system to learn from accidents and make improvements afterward, strengthening the abilities of the other six key features.

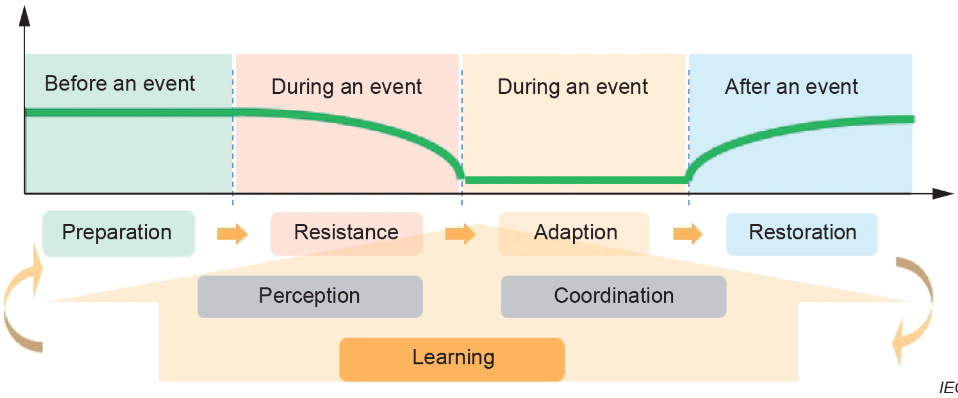

Figure 3 – Features of power system resilience

7.3.2 Preparation

Preparation refers to the ability of a power system to proactively predict the possibility of an event and its anticipated impact before the occurrence, formulate plans, and take targeted preparatory measures to minimize or avoid the adverse impact caused by disturbances. A resilient power system is capable of implementing targeted preventive measures to enhance its preparedness for disturbances, despite the challenges in predicting extreme events.

7.3.3 Resistance

Resistance (or defensive) refers to the ability of a power system to resist extreme scenarios, protect its core functions from being damaged or minimize possible damages as much as possible, and reduce the adverse impact of these events after a disturbance event occurs.

7.3.4 Adaption

Adaption emphasizes the ability of a power system to make prompt moves to reduce the negative impact of extreme events on the power system and even maintain the derating operation of core functions for a certain period during the disturbance. For example, the system is supposed to have enough flexibility to change its operation mode or topology and take certain proactive measures (such as load shedding) to reduce the impact of the event.

7.3.5 Restoration

Restoration (or recovery) emphasizes the ability of a power system to activate the emergency recovery mechanism in time, to ensure the continuous power supply of important loads, and to quickly return to a normal state (which can be different from the initial state). A resilient power system could prioritize and coordinate resources, activate emergency mechanisms, and apply measures to restore power supply for important loads as soon as possible.

7.3.6 Perception

Perception emphasizes the ability of a power system to perceive the current operating state and predict future operating state comprehensively, quickly, and accurately. Predicting the future operating state includes assessing the risks in the current operating state and perceiving external risks. By collecting, interpreting, and forecasting various factors involved in the operation changes of the power system over an extended period of time and space, the security situation of the power system can be accurately and effectively grasped, leading to the active security management of the power system.

7.3.7 Coordination

Coordination (or synergy) emphasizes the ability of a power system to coordinate internal and external resources to deal with disturbances, including mutual coordination among power plants, power grids, and users, among public infrastructures like power systems, gas systems, transportation networks, telecommunication network and so on, and among utilities, governments, and societies. Internal and external resources of the power system could be coordinated flexibly and intelligently to prevent power outages for key users and guarantee public infrastructure stability.

7.3.8 Learning

Learning emphasizes the ability of a power system to gain experience from historical events encountered by itself or other power systems, and to integrate emerging technologies for self-improvement continuously. That is, a resilient power system can learn from its accumulated experience or other power systems with similar structures and characteristics, identify its potential risks and take corresponding measures for self-improvement. Through incessant learning, feedback, and improvement, it is possible for the power system to continuously enhance its coping ability under disturbances and improve its resilience.

8 Evaluation metrics and guidelines

8.1 General

In the existing literature, numerous evaluation metrics and methods for power system resilience are available, as various organizations need to consider their own situations when evaluating power system resilience. In light of this phenomenon, this document offers two types of recommended metrics for reference: quantitative metrics based on resilience curves and qualitative metrics based on resilience features. In practical application, those quantitative and qualitative metrics are coordinated to evaluate the power system resilience from different perspectives.

8.2 Evaluation metrics

8.2.1 Quantitative metrics

Quantitative resilience metrics are mainly based on short-term resilience curves and the extent of damage to the system before the recovery. The concepts of resilience triangle and resilience trapezoid are commonly used for evaluation. Figure 4 presents the resilience triangle curve. The area above the resilience curve and below the normal operating state represents the power system resilience, as shown in the shaded area. Hence, to improve power system resilience means reducing the area of the shadow part. It is worth noting that the resilience curve in the resilience triangle could be either a linear function or a nonlinear function.

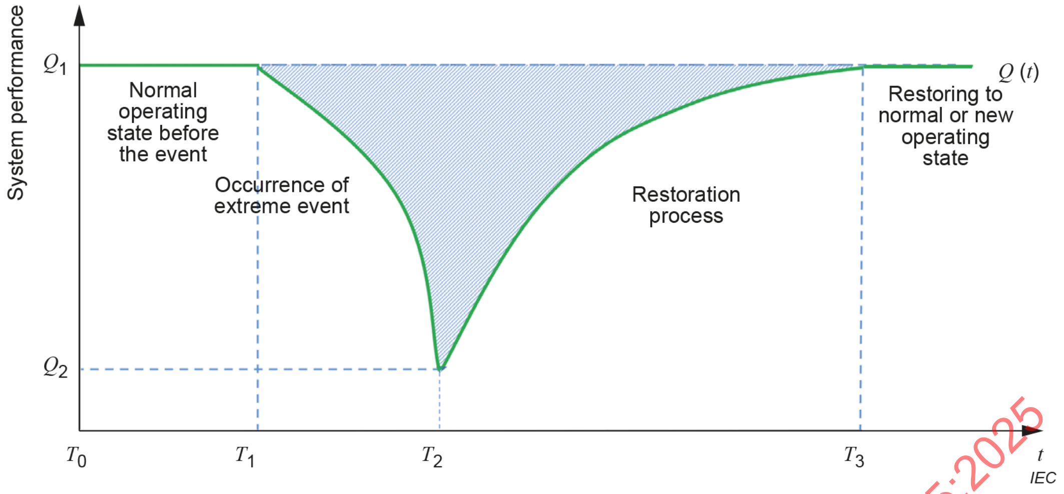

Figure 4 – The resilience triangle in the resilience curve

Considering the derated operation of the system lasting for a period after the occurrence of extreme events, the concept of resilience trapezoid has also been widely used. Figure 5 shows the resilience trapezoid curve of the power system's performance over time during extreme events. Specifically, T_0 refers to the time before the disturbance occurs; T_1 represents the moment when system performance begins to degrade; T_2 and T_3 are the start and end of the derated state of the system, respectively; T_4 is the moment when the extreme event stops affecting the power system; T_5 represents the moment when the system restores to its original normal state or reach a new stable state. Meanwhile, Q_1 refers to the system performance before the extreme event; Q_2 represents the derated performance of the system derated operation; Q_3 denotes the performance after the system returns to a normal operating state (Q_3 and Q_1 possibly differ).

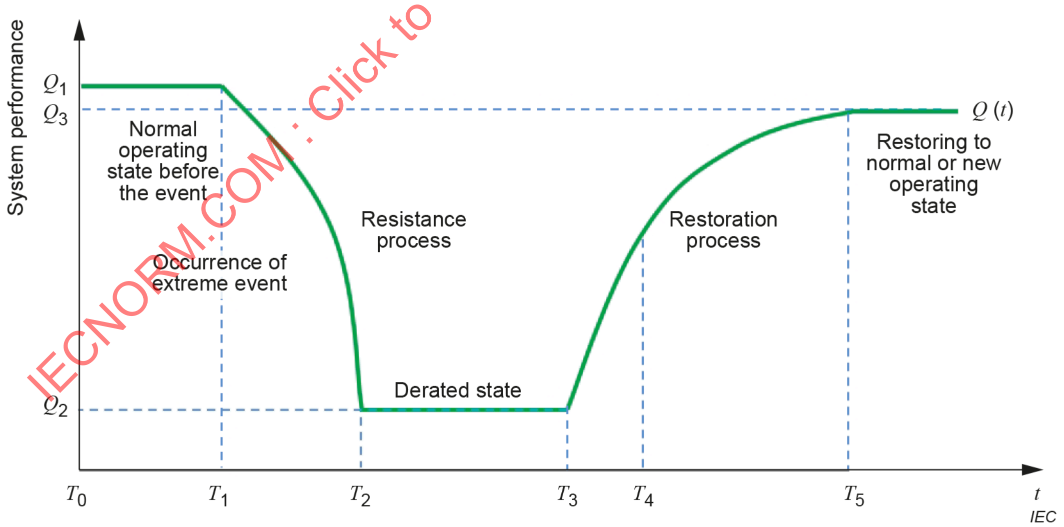

Figure 5 – Resilience curve of the power system under extreme events

Based on the above curves, the power system resilience can be evaluated through a set of quantitative metrics, including the following.

1) Degree of degradation

The degree of system performance degradation can be expressed by the ratio of the worst performance after being affected by extreme events to the initial performance. The following expression can be obtained:

$$R_1 = \frac{Q(T_2)}{Q(T_1)} = \frac{Q_2}{Q_1}$$

Obviously, the higher the degree of degradation is, the stronger the system's adaptive and defensive capabilities will be, and the more resilient the system will be.

2) Rate of degradation

The rate of system performance degradation can be obtained by the following expression:

$$R_2 = \frac{Q(T_1) - Q(T_2)}{T_2 - T_1} = \frac{Q_1 - Q_2}{T_2 - T_1}$$

The rate at which system performance degrades reflects the level of responsive and defensive capabilities of system resilience. After extreme events occur, redundant design and preventive control operations can protect the power system from huge performance decline within a short period after exposure to external disturbances.

3) Duration of degradation

The duration of degradation is used to reveal the length of time during which the system's performance undergoes degradation, from the moment it is subjected to extreme events until it reaches a derated state:

$$R_3 = T_2 - T_1$$

Before T_2, the system adapts to the impact of extreme events through passive adjustment and response. However, after T_2, the system starts to halt further performance degradation by implementing a series of proactive measures. This indicator reflects the rate at which the system responds to extreme events. The lower the indicator value, the quicker the system's active measures will be.

4) Duration of derated state

The duration of the derated state is used to reveal the time during which the system's performance remains derated after experiencing system degradation:

$$R_4 = T_3 - T_2$$

After T_2, the system halts further performance degradation, but the system restoration has not yet been initiated. Following T_3, the system begins the restoration process and recovery commences. The lower the indicator value, the more rapidly the system's recovery measures are implemented.

5) Duration of restoration

The duration of restoration refers to the time elapsed between the moment the system begins to restore and when it returns to its normal operating state:

$$R_5 = T_5 - T_3$$

After T_3, the system initiates the restoration process, and recovery begins; by T_5, the system returns to its original normal state or reaches a new stable state. Consequently, this indicator reflects the speed of the system's recovery. A smaller indicator value implies a faster recovery rate for the system.

6) Rate of restoration

The rate of system performance returns to normal operation can be obtained by the following expression:

$$R_6 = \frac{Q(T_5) - Q(T_3)}{T_5 - T_3} = \frac{Q_3 - Q_2}{T_5 - T_3}$$

This indicator reflects the restoration or recovery ability of a power system. The larger the indicator value is, the stronger the restoration ability of the power system and the more resilient the power system will be. In addition, since the restored performance level Q_3 is possibly not the same as the initial performance level Q_1, a correction factor r is constructed to correct the indicator:

$$r = \frac{Q_3}{Q_1}$$

When $r < 1$, the system has not recovered to the initial performance; when $r > 1$, the recovered system performance exceeds the initial performance.

7) Overall performance

The overall performance of the power system in a single extreme event can be represented by the area of the resilience trapezoid, which can not only reflect the performance of the power grid after encountering extreme events, but also measure the resilience level of the power system from the time scale. Considering the normalization of the indicator, the indicator can be calculated by the following expression:

$$R_7 = \frac{\int_{T_1}^{T_5} \left(Q_1 - Q(t)\right) \mathrm{d}t}{\int_{T_1}^{T_5} Q_1 \mathrm{d}t} = \frac{\int_{T_1}^{T_5} \left(Q_1 - Q(t)\right) \mathrm{d}t}{Q_1 \left(T_5 - T_1\right)}$$

The area of the resilience trapezoid represents the cumulative performance loss of the power system caused by extreme events. Obviously, the smaller the area is, the less the power system performance loss and the more resilient the power system will be.

In order to compare the resilience levels of different power systems, the measurements of the above basic indicators could be combined, such as obtaining new resilience indicators through simple multiplication and division to achieve quantitative evaluation and comparison of the resilience levels of power systems.

The metrics mentioned in 8.2.1 serve as illustrations of frequently used quantitative indicators and is not universally suitable for all power systems. Considering the characteristics of different regions and power grids, as well as the specific concerns of various stakeholders, alternative quantitative indicators could be formulated.

8.2.2 Qualitative metrics

It is difficult for many metrics to be quantified when evaluating power system resilience. In this case, qualitative or semi-quantitative metrics can be used. There are many feasible methods to construct qualitative metrics. 8.2.2 provides a method based on seven resilience features described in 7.3, describes the categories of resilience metrics and gives some exemplary indicators.

1) Preparation

The evaluation metrics for preparation mainly examine whether the system is able to proactively predict the occurrence probability of an extreme event and its impact, formulate feasible plans, and take preparatory measures to deal with it.

Here are five exemplary indicators.

- Risk assessment capability: the ability to predict the occurrence probability of an extreme event, forecast the degree of potential damage to the power system, and judge the tolerability of the expected risks.
- Event prediction capability: the ability to perceive extreme events as early as possible, which is conducive to arranging preventive measures in advance and coordinating emergency resources.
- Emergency resource allocation capability: the ability to mobilize resources promptly before extreme events to minimize expected risks.
- Network optimization capability: the ability to reconfigure and optimize the network before extreme events to minimize the expected risks.
- Operational scenario optimization capability: the ability to supply consumers' electric power and energy requirements in different scenarios when extreme events occur, such as adjusting transmission power or optimizing output regulation of generation units.

2) Resistance

The evaluation metrics for resistance mainly examine whether the system is able to resist the negative impact of an extreme event during the development of the event.

Here are seven exemplary indicators.

- Component anti-strike capability: the ability of the power system's components to withstand extreme events without failure.
- Grid structure toughness: the ability of the overall network structure of the power system to remain intact during extreme events.
- Power system redundancy: Redundancy refers to an excess quantity kept from the security perspective to ensure that the power system can operate normally during abnormal conditions.
- Frequency emergency response capability: the ability to regulate the frequency of a power system. Good frequency regulation is an important feature of a resilient power system.
- Dynamic voltage regulation capability: the ability to regulate the voltage of a power system. Good voltage regulation ability is another important feature of a resilient power system.
- Failure spreading limiting capability: the ability to prevent failure spreading and to implement system decoupling, including rapid action of relay protection.
- System security defensive capability: the ability to improve the security and stability of system operation through device relay protection or system stability control.

3) Adaption

The evaluation metrics for adaption mainly examine whether the system is able to take measures in time to reduce or adapt to the adverse impact of extreme events during their dynamic development.

Here are four exemplary indicators.

- Extreme disaster emergency response capability: the ability to direct, communicate, and allocate emergency response resources after an extreme event.
- Key load power supply capability: the ability to maintain power supply to key users and ensure multiple safeguards of power supply, because when a severe disturbance occurs, it is important to ensure the continuous power supply for important users, or fast recovery of power supply to the key load in the recovery stage.
- Load transfer capability: the ability to formulate long-term, short-term, and temporary transitional power supply plans to meet the needs of different users and enhance the power supply of the distribution network, based on load transfer approaches.
- Autonomous operation capability: the ability of decomposed small-area grids to operate independently and autonomously after grid decoupling in extreme events.

4) Restoration

The evaluation metrics for restoration mainly examine whether the system is able to activate the emergency recovery and repair mechanisms in time and ensure the continuous power supply of important loads after an extreme event occurs.

Here are four exemplary indicators.

- Load recovery capability: the ability to restore load as fast as possible after extreme events. The recovery time can directly reflect the load restoration of the system. A short recovery time is an important manifestation of the strong restoration ability of a resilient power system.
- Component reparability: the ability to locate the faulty components, isolate the faulty area, and fix the failures. The ability to repair components under extreme meteorological disaster conditions such as thunder, typhoon, ice and snow weather reflects the resilience level of power systems.
- Grid reconfiguration capability: the ability to restore power plants, key substations, and important lines after extreme events. A stable skeleton grid is gradually built to restore power generation on a large scale and provides a good foundation for the subsequent full recovery of the system load.
- Black start capability: Most generation facilities require electricity for operation. If the generators are off-line, the restoration plans would be performed utilizing the selected black-start generators that do not require power supply from the main grid.

5) Perception

The evaluation metrics for perception mainly examine the system's perception of its own operating status and external risks and threats.

Here are five exemplary indicators.

- Information monitoring capability: the ability to monitor and manage the status of equipment and collect information on user electricity consumption.
- Anomaly event locating capability: the ability to accurately locate vulnerable and abnormal sections of power systems to ensure that vulnerable lines are protected before events and avoid cascading failures after an event occurs.

- Threats screening capability: the ability to early screening potential threats. In the face of increasingly complex and vast power systems, it is often difficult to detect threats, thus leading to tremendous damage. Therefore, pre-screening is also an important indicator of perception.
- Weakness warning capability: the ability to provide dynamic warnings regarding the vulnerable parts of source-grid-load. Based on the dynamic warning indicators of weakness, it is possible to form a dynamic early warning and prevention network for weakness covering the entire network and various operating entities through regular inspection, prevention, and timely processing.
- Information transmission and warning accessibility: the ability to inform government, users, and related power system equipment promptly and automatically about perceived disturbances and help to formulate and implement an emergency plan in order to ensure the linkage between the power grid and the external environment.

6) Coordination

The evaluation metrics for coordination mainly examine whether the system is able to cooperate with internal and external resources to respond to the extreme event after it occurs.

Here are six exemplary indicators.

- Transmission and distribution coordination capability: the ability to evaluate real-time operational risks and handle failures. In particular, real-time operation risk evaluation relies on topology analysis, state estimation, power flow calculation, and safety verification of the integrated transmission and distribution network to obtain the real-time operating state of the entire grid. Failure handling relies on the topology analysis, reconfiguration and load transfer, power flow calculation, and safety verification of the integrated transmission and distribution network to obtain the failure scope in time and develop a safe, reasonable, and highly optimized power supply recovery strategy as soon as possible in the failure recovery stage for implementation.
- Inter-distribution network coordination capability: the ability to collaborate operations within different distribution networks and allocate power supply among distribution networks based on predetermined goals, thus ensuring normal power supply to different users.
- Source-grid-load-storage coordination capability: the ability to coordinate and interact among source, grid, load, and storage sides. By strengthening the coordinated source-grid-load-storage control, the coordination and interaction of new energy-consuming equipment on the demand side, such as distributed power sources, electric vehicles, energy storage, micro-grids, thermal storage and electric heating, can be realized, which is conducive to the coordination of adjustable and controllable resources across the entire network. A new multi-level scheduling collaborative control mode of unified decision-making and decentralized control is adopted; coupled with flexible, accurate, intelligent, and automatic source, grid, load, and storage control methods, coordinated prevention and control of global risks, rapid coordinated handling of complex failures, and normal-state adaptive cruise are achieved, thus ensuring the safe and stable operations of the power grid in an all-round way.
- Multi-energy supplementation capability: the ability to coordinate and monitor multiple systems and control them holistically. In a multi-energy flow system, different systems are coupled and influenced by each other. The failure and disturbance of a certain part will affect other parts within the multi-energy flow system, possibly leading to a chain reaction. So, it is important to analyse the possibility of cascading failures caused by the interaction between the systems after the disturbance of the coupled system, as well as the different characteristics and influence subjects of the disturbance or action at different time scales of the integrated energy system, and fully exploit the flexibility of slow dynamic systems such as heat and gas systems. Thus, a control strategy is provided for eliminating the potential safety hazards of fast dynamic systems (power systems) and achieving coordinated safety control.
- Infrastructure coordination capability: the ability to collaborate with different infrastructures to promptly respond to disturbance, including deriving feasible solutions, and eventually implementing an optimal plan, to minimize the adverse impact of disturbance.

- Inter-organizations coordination capability: the ability to notify various organizations, such as government and relevant enterprises, of the occurrence of the disturbance, the current state of the power system and possible outcomes and assist in developing and implementing an emergency plan to guarantee its operation and cut the losses of these organizations.

7) Learning

The evaluation metrics for learning ability mainly examine whether the system is able to gain experience from extreme events and realize self-improvement through continuous integration of emerging technologies after the event occurs.

Here are three exemplary indicators.

- Accident analysis capability: the ability to absorb experience from extreme events, and fix vulnerabilities to minimize the adverse impact when the same extreme event occurs. Specifically, it includes power facility repair, communication system repair, network environment repair, employee training, etc.
- Emerging technology application capability: the ability to carry out systematic analysis of accident data by using emerging technologies and power system models to guarantee safe, reliable, economical, and efficient power system operations.
- Economic rationality: by analysing the importance and economy of various resilience improvement measures, and confirming the priority of each measure, the power system resilience can be maximized at a certain cost.

8.3 Evaluation guidelines

8.3.1 Evaluation criteria

Considering the characteristics of extreme events, relevant criteria for the evaluation of power system resilience are proposed as follows.

a) The impact of extreme events on both short-term and long-term scales needs to be considered simultaneously. On the one hand, it is important to evaluate the power system resilience within a period when an extreme event occurs, to make judgments on the degree of damage and recovery strategy of the power system as soon as possible, and then take measures to maximize the power supply capacity promptly. On the other hand, the measures used in a single extreme event do not apply to all situations. In order to comprehensively improve the power system resilience, it is important to evaluate the power system resilience by considering the operations of the power system within multiple extreme events on a long-term scale.
b) To evaluate the power system resilience, it is important to pay attention to both its own conditions (such as power loss of loads, duration of power outages, etc.) and the impact of such outages on other infrastructure and even economic and social impacts (such as communications, water supply, transportation, etc.).
c) Different types of resilient power system have different priorities. The main task of a large-scale interconnected power grid is to ensure that the power grid is strong enough in the face of disturbances to prevent large-scale power outages or to achieve rapid recovery. For distribution networks, it is essential to ensure a continuous and stable power supply to important users.
d) Different power systems are found with different types of extreme events. For example, power systems located in earthquake zones need to cope with earthquakes; power systems in coastal areas need to consider the impact of typhoons; power systems in high latitudes need to be capable of dealing with ice and snow disasters; power systems in densely forested areas need to be ready to prevent wildfires.

e) Both quantitative and qualitative metrics need to be considered simultaneously for a comprehensive evaluation of power system resilience. Due to the complexity of the power system structure, many power equipment, transmission circuits, and user data are involved, and the impact of extreme events on power systems cannot all be quantitatively calculated to obtain quantitative metrics. Meanwhile, the development, duration, and impact scope of extreme events remain unknown, which leads to a large deviation in the process of calculating quantitative metrics. Therefore, a more comprehensive evaluation plan needs to be developed by integrating quantitative and qualitative metrics, to evaluate the power system resilience.

8.3.2 Evaluation methods

Considering quantitative and qualitative evaluation metrics of power system resilience, the evaluation methods of power system resilience can also be categorized into two types. Annex A provides two example evaluation methods, respectively.

1) Evaluation method based on quantitative evaluation metrics

Evaluation metrics are defined based on the resilience curve to quantitatively characterize the power system performance changes during specific extreme events. By the evaluation results, it is possible to quantify the degree of the power system resilience during these extreme events, and to determine which extreme event exerts the most significant impact on the power system, thus taking measures to upgrade and optimize the grid to better cope with the possible extreme events. Clause A.1 further presents the details of evaluation method for power system resilience based on Monte Carlo simulation.

2) Evaluation method based on qualitative evaluation metrics

This evaluation method examines the power system on a long-term scale, with its results serving to assess resilience-related capabilities within the power system. The evaluation results can guide the power system to strengthen one or several distinctive capabilities, thereby improving the power system resilience.

In general, in the actual evaluation process, two evaluation methods are combined for resilience evaluation and analysis of the power system, thus obtaining information that fully reflects the resilience level of the power system, verifying the effectiveness and rationality of the resilience improvement measures, and proving a theoretical basis for the safe and reliable operations of the power system. See Clause A.2 for an exemplary evaluation method of power system resilience based on the analytic hierarchy process (AHP).

9 Improvement strategies

9.1 General

In practical application, the resilience improvement strategies are necessary for reliable electricity transmission and supply in extreme events. However, these improvement strategies are likely to result in higher infrastructure investments and operation costs. Striking a balance among various factors is crucial, and the following aspects could be taken into account when devising resilience enhancement strategies:

– requirements of the operators and stakeholders for resilience improvement;
– nature of the improvement strategies;
– application stage of the improvement strategies;
– investments of assets in the improvement strategies;
– power system operation costs of the improvement strategies;
– effects for enhancing resilience.

9.2 Preventive strategies

Preventive strategies include power system planning and optimized decision-making to prevent adverse outcomes. The nature of power system planning for resilience improvement is to add more infrastructures or devices in the gird to guarantee the power supply for users in extreme events. These planning initiatives usually serve as preventive measures against such events. Resilience-oriented power system planning mainly entails infrastructure reinforcement, power source planning, energy storage device planning, and so on.

– Infrastructure reinforcement refers to creating reliable and secure components, investing in system hardening, and pursuing damage prevention activities. The strategies could improve the power system resilience and play a role in preventing the extent of large-area and long-duration outages.
– Power source planning is an essential measurement for enhancing power system resilience. The planning of power sources with different locations and capacities can provide more reserve power for grid operation. It also helps promote the coordinated utilization of heterogeneous energy sources in different regions to guarantee power supply of important loads under extreme scenarios.
– Energy storage planning is an important tool to improve the system resilience. The energy storage devices can prevent the propagation of system outages and provide additional flexibility for power supply in extreme events.

The power system planning strategies for resilience improvement introduce amounts of infrastructures and devices. Thus, the costs on those assets and the benefits on resilience improvement need to be balanced in practical application.

Preventive decision-making optimization helps to optimize the allocation of pre-event emergency resources and to enhance the restoration ability of the disaster-affected grid by formulating coordinated preventive strategies. Resilience-oriented preventive decision-making optimization techniques include coordinated preventive strategies, optimal allocation of emergency repair personnel and materials, and optimal deployment of emergency power supply equipment under extreme events.

– Regarding coordinated preventive strategies, relevant personnel take daily maintenance measures, such as risk monitoring and assessment for potential extreme events that could occur. Also, operational scenario optimization to minimize potential losses to the system is developed. For example, the personnel adjust the transmission power and unit combination in advance to reduce the impacts of extreme events on practical power grid operations.
– Emergency repair personnel and material allocation are the core of emergency response activities. The nature is emergency material allocation based on maximum material utility. Also, it is important to consider the interdependencies among different systems, as well as road network constraints.
– In the optimal deployment of emergency power supply equipment, many methods already exist to establish on-site power systems – often using components that are patched together. Most backup power systems rely on small gasoline, natural gas, and diesel-fired generators that are relatively easy to operate. And it is important to consider the feasibility of emergency power supply participation, the system load recovery, and the path constraints of power supply recovery. In addition, decision-makers need to prioritize restoring distribution for important users and areas with a large number of users.

9.3 Sustained operation strategies

During the events, the operators need to take sustained operation strategies to guarantee the power supply and meet the power demands of users. The nature of sustained operation strategies is to maintain the performance of the power system as much as possible and prevent further cascading outages. Typical sustained operation strategies include emergency frequency control technology, self-healing technology for distribution network, micro-grid group control technology for resilience improvement, and resilience defense technology against information intrusion.

– The emergency frequency control technology coordinates multiple control resources to enhance the defense capability of large power grids. For example, mobile energy storage could be rapidly applied to enhance the power supply and provide frequency support in the sustained operation stage of the power system.

– The distribution network self-healing technology aims to optimize the power system structure and improve the self-healing ability of the power system to deal with failures. The intelligent distributed feeder automation for core urban areas and the self-healing technology for the special grid structure are used to improve the resilience of power supply in core urban areas.

– The control technology of microgrids for resilience improvement combines distributed generators, energy storage, and multiple microgrids in the distribution network. It is possible to achieve self-configuring operations through the smoothing and off-grid control of multiple microgrids. During this process, the stable voltage control technology is very crucial. Furthermore, the emergency power supply technology of microgrids would rapidly build a power supply lifeline for important loads and maintain sustained operation of the power system.

While sustained operation strategies have the potential to increase operational costs, they enhance power system resilience and ensure the provision of power to critical loads. Additionally, it is essential to assess the effectiveness of sustained operation strategies during their implementation period.

9.4 Recovery strategies

The goal of post-event recovery strategies is to minimize unserved loads in extreme events, highlighting the characteristics of power system with high resilience. In this process, the degree of load recovery will be determined based on the response rate of accessible generators, taking into account the performance and value of those assets. Post-event recovery strategies include technologies, such as black-start technology, micro-grid emergency power supply technology, and emergency repair technology for accelerated recovery.

– Black start refers to that after the entire power grid collapses in extreme events, the power system is in a completely "black" state. At this moment, through the start-up of the units with self-start capability and external power supply, the units without self-start capability are restarted to gradually expand the recovery scope of the system, and finally realize the recovery and power supply of the entire system.

– The microgrid emergency power supply technology enables rapid recovery of power supply for critical loads by comprehensively utilizing microgrids or distributed energy resources (DER). With appropriate system upgrades and asset management, they could provide local generation for utilities to restore from the impacts of extreme events.

– The emergency repair technology for accelerated recovery of power systems considers the coupling of the power-communication system, speeds up the repair progress, and reduces power outage losses by optimizing the dispatching of repair resources. Considering the coupling and supporting relationship of infrastructure networks, a wider range of resilience could be achieved. For example, vehicle-to-grid (V2G) technology could help the system carry out emergency control for large-scale power failure accidents.

Also, utilities and operators need to have comprehensive programs and be well-practiced at recovering from localized damage to the grid and helping to restore the system outside their service areas. In the recovery stage, the operation costs is huge while the power restoration is more important. And it is essential to help prioritize and expedite the dispatch of line crews and resources with a comprehensive understanding of damages and restoration efforts.

9.5 Long-term resilience strategies

Considering the long-term adaptability, the resilient power system needs to continuously optimize its construction and structure to adapt to the impact of multiple extreme events in a long-term scale. To improve the long-term adaptability of resilient power systems, measures such as optimizing the grid structure, increasing emergency allocation resources, and adjusting the operation mode could be adopted. The risk management and asset management also need to be considered in the long-term resilience strategies.

– By continuously optimizing the structure of the transmission grid and connecting emergency power sources, the stable power supply of the grid is enhanced to minimize the probability of load loss, shorten the emergency recovery time of the system, and rationally optimize the operation mode. Thus, the grid becomes more adaptable to the long-term operating environment and could effectively respond to extreme events.

– Emergency power supply configuration is an effective way to improve the long-term resilience of the grid. In the event of extreme events, access to the emergency power supply could stabilize the power supply capacity of the grid, reduce the probability of load loss as much as possible, and effectively shorten the emergency recovery time of the grid. In particular, when users could not fully access the main power grid, a mobile emergency power supply is a key resource for the distribution system to restore power services quickly. When continuous damage causes long-term power failure of the distribution system, it would become one of the most effective response resources. In addition, compared with fixed energy storage equipment, mobile energy storage equipment has flexible scheduling capability. However, the cost of emergency power supply configuration is often very high, but the occurrence probability of extreme natural disasters is low. Therefore, it is also necessary to balance the economy of emergency power supply configuration under long-term scale operation.

Moreover, considering the long-term learning needs, it is crucial for the resilient power system to continuously learn, strengthen, and adapt itself. Three emerging technologies, including wireless sensor network technology, artificial intelligence technology, and digital twin technology, hold great application significance to the improvement of long-term power system resilience.

– Wireless sensor network technology is used in power equipment status monitoring, power system operating status monitoring, and power system operating environment monitoring. Data is acquired by the sensor and then processed to obtain effective information, thus achieving the monitoring purpose, and improving the perception of the power system.

– Artificial intelligence is used in power outage prediction, stability assessment, stability control and failure recovery. Through the analysis of massive data, the hidden pattern in the data is revealed and effective information is obtained to make faster and more informed decisions.

– The power system digital twin technology is still under development. Based on the digital twin technology, the results can be sent back to the grid through simulation to guide and optimize decisions for the planning and operation of the system.

10 Use cases

10.1 General

Nowadays, engineering practices of the resilient power system have been implemented in various countries and regions. In Clause 10, the construction of resilient power systems is introduced, and the current developments of actual projects in terms of power system resilience assessment and features are described. Particularly, various resilience improvement strategies applied to different countries and regions are elaborated in Clause 10.

10.2 Resilience assessment and improvement against ice sleeves in Italy

In recent years, extreme events have been significantly increasing in Italy and often lead to power supply interruptions. These extreme events include those that occurred in February 2015 in Emilia Romagna and Lombardy, which left nearly 360 000 users without power for more than 8 h. In Abruzzo and Marche, power outages lasted over 72 h, affecting 39 000 customers due to extreme weather. The Energy Authority in Italy (ARERA, Autorità di Regolazione per Energia Reti e Ambiente) has observed that the frequent failures in the power grid are related to the phenomenon known as the "ice sleeve," which occurs on exposed conductors of overhead power lines in wet snow and windy conditions. Furthermore, other phenomena involve power lines that get weighed down by wet snow.

To enhance the resilience of the power system, the Energy Authority in Italy proposed a method for evaluating resilience, which quantifies the impacts of extreme events. This method can assess the infrastructural capacity of the grid under extreme stresses. Additionally, various resilience improvement measures have been implemented, such as line refurbishment aimed at mitigating outage risks stemming from ice and snow accumulation. With these improvement measures, the system's capability can be restored to acceptable working conditions, even by means of temporary arrangements. This underscores the importance of preventive strategies in enhancing power grid resilience.

To enhance the resilience of the power system and assess its economic viability, ARERA has introduced an assessment method for resilience against ice-related disasters. This method quantifies the impacts of extreme events, considering factors such as conductor types at installation sites, expected growth of ice sleeves, wind intensity, and altitude. It evaluates the maximum mechanical load caused by ice sleeves and wind, comparing it with the tension on conductors corresponding to the maximum load induced by ice sleeves and wind. Thus, it calculates the outage risk for each substation and implements targeted measures accordingly.

For instance, strategies include enhancing the design limits to withstand extreme stress on the power grid infrastructure, refurbishing lines, strengthening grid meshing, substituting bare conductors of overhead lines with insulated conductors, replacing or upgrading network components, improving protection, control, and automation systems, redesigning the network to enable intentional islanded operation, and more. Through these improvement measures, even though temporary arrangements, the system's capacity can be restored to an acceptable working state. This underscores the significance of preventive strategies in enhancing the resilience of the power grid.

10.3 Sustained operation strategies during earthquakes applied in Japan

Due to frequent natural disasters in Japan, disaster prevention and mitigation have always been a focal point of their national policies. Traditional Japanese policies have emphasized disaster prevention, but in recent years, the focus has shifted towards enhancing the resilience, disaster response, and recovery capabilities of the power grid. The Fukushima earthquake in 2011 caused severe damage to power plants, substations, and transmission lines of Tokyo and Tohoku Electric Power Companies, leading to widespread power outages. Japan set the overall goal of building a "strong and resilient nation and economy," with ensuring the continuity of critical national and societal functions and operations being one of its key objectives.

A typical approach adopted by Japan's power system is the use of microgrids to sustain sustainable power supply. The effects of projects in Japan indicate that the island operation mode of the power grid is a crucial sustained operation strategy during extreme events and can significantly improve the resilience of the power system.

The Sendai micro-grid named Experimental Research on Multi-Power Quality Supply Systems (MPQSS), was originally designed in 2004 as an experimental project for the New Energy and Industrial Technology Development Organization (NEDO), and later managed by Nippon Telegraph & Telephone (NTT). The Sendai micro-grid had several sources of power generation: two gas engines, one phosphoric acid fuel cell (PAFC), and one photovoltaic array. It could provide various levels of power quality within the micro-grid, with DC power as well as Class A and Class B1 loads powered by an integrated power supply (IPS). The primary energy source for the Sendai micro-grid was gas engine fuel. The Sendai City Natural Gas Bureau procured LNG imported from overseas and natural gas imported from Niigata Prefecture through wide-area pipelines. Fuel for the gas engine was supplied via medium-pressure piping. On March 11, 2011, the devastating East Japan Earthquake struck the Tohoku region, causing several days of catastrophic damage to the region's energy supply system. The Sendai micro-grid continued to supply power and heat to users, proving the effectiveness of the micro-grid demonstration project in dealing with extreme event impacts and significantly improving the resilience of the power supply.

After the Fukushima nuclear accident in 2011, Higashi Matsushima built Japan's first micro-grid community. All energy supply came from distributed clean energy, including a solar system with a total installed capacity of 470 kW, a biodiesel power generation system with a total installed capacity of 500 kW, and a large-scale energy storage system with an installed capacity of 500 kWh. This ensures that the community energy supply system can operate independently in case of an accident with the centralized power system. When the traditional grid was disconnected, the smart eco-town could still provide residents and buildings with power to satisfy their daily energy needs for up to 3 days. In the event of a prolonged power outage, hospitals and auditorium cities could still receive minimal energy demand, effectively increasing the short-term resilience of the grid.

10.4 Resilience improvement strategies against hurricanes applied in Florida

Florida has been facing significant and persistent climate change risks, including hurricanes and tropical storms, which are among the most economically destructive natural disasters nationwide, and the power sector is no exception. The Florida Public Service Commission (FPSC) and the power companies under its regulation are experienced in developing policies for storm preparation. Since 1992, the FPSC has initiated the first plan to mitigate storm cost risks for utilities, providing recommendations to power companies and enabling them to apply the latest forecasts and data in infrastructure fortification efforts, thereby enhancing the long-term resilience of the power grid.

In 2006, affected by the 2004 and 2005 hurricanes, the FPSC asked power companies to assess the effectiveness of investments in infrastructure fortification and other storm prevention measures by collecting and monitoring outage data during storms, which effectively improved the long-term adaptability of resilient grids and considered the economic efficiency of long-term operations of resilient grids. Some of the measures included the following:

1) developing a 6-year transmission network inspection plan;
2) reinforcing existing transmission networks;
3) developing transmission and distribution geographic information systems (GIS);
4) collecting post-storm data and conducting corresponding analyses;
5) gathering detailed outage data and comparing reliability performance between overhead and underground systems;
6) collaborating with relevant agencies to study the impact of hurricanes and storms;
7) establishing natural disaster preparedness and recovery plans.

Through these initiatives, the Commission has enabled utilities to understand better the impact of infrastructure hardening on storm preparedness, which encouraged the utilities to increase investment further. For example, since the 2004 and 2005 hurricanes, Florida Power & Light has invested $4 billion in grid resilience improvements, including strengthening transmission lines, replacing utility poles, and clearing vegetation on more than 150 000 miles of transmission lines. In addition, by comparing post-disaster conditions after storms before and after fortifying infrastructure, power companies also found that outages and recovery time were significantly reduced. For example, during Hurricane Irma in 2017, the company took one day to restore power to 50 % of users who suffered power outages, while during Hurricane Wilma in 2005, the company took up to five days to restore power to 50 % of affected users. Other power companies also drew similar conclusions. Those measures indicate that these long-term resilience strategies are critical for resilience improvement.

10.5 Construction of the resilient city power grid in Shanghai

As the most economically active area in China, Shanghai is committed to building a resilient city, with a resilient power grid being a pivotal component. To improve the resilience of the power grid, State Grid Shanghai Municipal Electric Power Company (SMEPC) has implemented various improvement strategies.

Shanghai is situated at the eastern end of the Asian continent, along the western coast of the Pacific Ocean. The natural disaster impacts it faces primarily include typhoons, lightning strikes, urban flooding, and extreme cold wave disasters. On August 7, 2012, Typhoon Haikui struck Shanghai, causing 79 instances of power line tripping in a short period, including a 500 kV line tripping, and leading to the collapse of a significant number of transmission towers. On September 23, 2014, Typhoon Chaba hit Shanghai, resulting in 28 instances of 10 kV power line tripping and the need for repairs in 578 cases of various low-voltage faults. The repeated occurrences of typhoons and their associated effects, such as heavy rain, have significantly impacted Shanghai's power grid.

In terms of preventive measures, SMEPC primarily enhances the resilience of the city power grid through grid planning and perception ability improving. The diamond-shaped resilient distribution network has been implemented in Shanghai as an important grid planning strategy. Diamond-shaped distribution network refers to the dual-ring network structure with self-healing function. The traditional distribution automation systems with the self-healing system are replaced by the diamond-shaped resilient distribution network, which could collect local information and automatically implementing the self-healing strategy remotely. The special structure significantly modifies the preparation and coordination features of the power system. Also, power supply reliability and load transfer capability are improved through the operation of the diamond-shaped distribution network. Due to the use of a two-sided power supply method in different substations, its load transfer capacity reached 100 %. With this flexible and controllable load transfer performance, the diamond-shaped resilient distribution network is able to satisfy the N-1 security check. The preventive strategy effectively reduces the impacts of extreme events on the power grid. To enhance perception ability of city power grid, SMEPC has deployed a typhoon monitoring and early warning system, as well as a lightning location and monitoring system. The typhoon monitoring and early warning system provides precise monitoring and predictive data on wind speed and rainfall for each transmission tower. By comparing this information with the tower's design specifications, it accurately identifies towers susceptible to typhoon-related disasters among all 110 kV and higher voltage level lines. Meanwhile, the lightning location and monitoring system achieves spatial accuracy in lightning positioning within a range of tens of meters. It promptly delivers information on lightning activities, including distribution and lightning current amplitude, to operators on a daily basis.