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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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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

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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.

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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.

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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.

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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.

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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.

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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.

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