IEC TR 63515

Edition 1.0 2025-03

TECHNICAL REPORT

Conceptual framework of power system resilience

IEC TR 63515:2025-03(en)

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INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

ICS 33.200 ISBN 978-2-8327-0255-0

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CONCEPTUAL FRAMEWORK OF POWER SYSTEM RESILIENCE

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The text of this Technical Report is based on the following documents:

Draft	Report on voting
8C/117/DTR	8C/126A/RVDTR

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this Technical Report is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/publications.

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- reconfirmed,
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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

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.