CIGRE Reference Paper : Defining power system resilience

By E. CIAPESSONI (IT), D. CIRIO (IT), A. PITTO (IT), M. PANTELI (UK), M. VAN HARTE (SA), C. MAK (CA) on behalf of C4.47 WG Members

The term *resilience* has been used in very different fields of knowledge for many decades. In the electricity sector, the adverse impact of natural and man-made hazards on critical infrastructures has resulted in governments, regulators, utilities, and other interested stakeholders seeking to formalise a framework to oversee and enhance resilience. In essence, such formalisation aims to define strategies to improve the ability of a critical infrastructure to anticipate and prepare for critical situations, to absorb impacts of hazards, prevent deterioration in service to the point of failure, to respond to and recover rapidly from disruptions, and to make adaptations that strive to provide continued essential services under a new condition.
Despite several attempts by organisations worldwide in the power and energy engineering communities to define resilience, there is not as yet a universally accepted definition because resilience is a multi-dimensional and dynamic concept. Resilience is more than simply "the ability to bounce back" after a failure; an organisation seeking to be highly resilient also needs to continuously focus on aspects related to the potential for multiple failures at all levels of the organization, to find opportunities to improve its emergency preparedness and operational practices prior to, during, and following major disturbances, and service interruptions, as well as improvements based on lessons learnt from past events.

CIGRE WG C4.47 – Power System Resilience

Given these challenges facing the electricity sector, CIGRE SC C4, in 2017, has established a Working Group to provide guidance on these challenges and attempt to set a standardised approach to resilience thinking and practices in the electricity sector. WG C4.47 – Power System Resilience comprises a large number of international experts from 19 countries. This worldwide perspective has formed the expertise foundation for the development of an industry-accepted resilience definition and framework in the electricity sector.
The need for a standardised approach is further confirmed by an international survey conducted by the WG in 2018 with results highlighting the pressing need and elevated interest of utilities worldwide in evaluating the impact of extreme events that could potentially cause widespread disruptions of critical infrastructures. The survey suggested that utilities require measures to contain and/or respond to the effects of such extreme events.
The purpose of this reference paper is to present the CIGRE WG C4.47 definition of power system resilience in the electricity sector.
This will assist utilities to better understand the concept of resilience and how it differs from the well-established concept of reliability. The WG conducted a comprehensive review of resilience literature leading to the final definition of power system resilience that is discussed in this paper.

From reliability to resilience

The concept of *reliability* was introduced in order to assess the performance of the power system in providing energy to users even in the case of disturbances. This property has been defined by several well-recognised institutions, such as CIGRE, IEEE, IEC, NERC, and ENTSO-E, in terms of adequacy and security. The definition of reliability has recently been updated in TB 715 on the "Future of reliability" and in the corresponding article in Electra No 296 (February 2018).
All these definitions agree that *reliability* refers to the probability of the satisfactory provision of power and energy to meet load demands and ability to withstand disturbances. The performance and degree of reliability of a power system can be generally measured and benchmarked through the frequency, duration, and intensity of service degradation due to grid disturbances.
Resilience, as a concept, adds a new dimension to system management and reliability. The concept discussed below is intended to assist utilities and regulators to encourage prudent investments to enhance resilience capabilities of the interconnected power system in case of extreme events that are characterised by their low frequency of occurrence but with significant consequences.
These extreme and disruptive events are normally initiated by multiple contingencies resulting in significantly deteriorated operational capabilities, possibly leading to widespread cascading impacts that could also affect interdependent critical infrastructures with catastrophic consequences.

Therefore, resilience assessments may require a multi-dimensional evaluation of the response of an interconnected power system to these extreme and disruptive events. Furthermore, achieving resilience may require multiple strategies with due consideration of utility response objectives for planning and/or response efforts. These undertakings can be very complex and challenging due to the interdependence and relationship with essential services and mission-critical loads.

Definition within the electricity sector

Ecologist CS Holling is considered by many to be the first to provide a foundational definition of resilience, in 1973. This definition of resilience has been adopted by numerous researchers from different disciplinary perspectives and evolved into different resilience definitions. The key capabilities in the definition of resilience can be tailored to support particular applications for enhancing utility strategies against extreme events.

To adapt the definition of resilience to the electricity sector, CIGRE WG C4.47 performed a comprehensive review of the applicable resilience definitions, provided by different stakeholders (academia, government, engineering societies, regulators, infrastructure operators), some of whom are generic on critical infrastructures while others are specific on electricity infrastructures. The goal of the WG was to compare their merits and appropriateness so that the key features can be incorporated into a comprehensive resilience definition that is suitable for power system application.

The review of the WG has culminated in the following concept of *resilience* that:

- *requires a comprehensive evaluation of system response to disturbances, including not only the system degradation but also the system behaviour during the restoration phase, as well as all the measures taken to preventively improve system performance;*
- *supports the characterization and design of actionable measures aimed at improving the performances of the power system response following extreme events triggered by adverse weather conditions, malicious acts, cyber-attacks, etc. with due consideration to past extreme events.*

CIGRE WG C4.47 definition for power system resilience

The new definition is intended to be different from the existing definitions in separating the **resilience** *properties (or abilities)* from *the key actionable measures* that collectively contribute to the achievement of enhanced power system resilience.

WG C4.47 defines ***power system resilience*** as follows:

Power system resilience is *the ability to limit the* ***extent, severity****, and* ***duration*** *of* ***system degradation*** *following an* ***extreme event****.*

As an integral part of the definition, it includes the following key actionable measures:

Power system resilience is achieved through a set of ***key actionable measures*** *to be* ***taken before****,* ***during, and after extreme events****, such as:*

- *anticipation*
- *preparation*
- *absorption*
- *sustainment of critical system operations*
- *rapid recovery; and*
- *adaptation*

including the application of lessons learnt.

Resilience properties of new definition:

- *Almost all of the definitions describe resilience as an "****ability****" of the power system or system or infrastructure. However, most of them are "operationally oriented definitions," that is, they define resilience by using those measures (such as fast recovery, shock absorption) that make the system resilient. Some of the definitions also describe resilience as a contingency-withstanding capability, which does not help clarify the salient characteristics of resilience in response to extreme events resulting in multiple contingencies on the system.*
- *The terms "****extent and severity****" in the WG definition respectively refer to the geographical extent and the intensity of the effects of the event on the interconnected power system. This assures a more focused characterization of the dimensions of system degradation while keeping the definition concise and informative. Note that the term "****severity****" of system degradation must be kept separate from the "severity of the event," which in general does not imply any system degradation. "Severity" also depends on the (inter)dependence between essential or mission-critical loads and the disrupted and/or impaired system.*
- *The term "****duration****" refers to the time period of the negative effects on system performance with respect to the normal situation.*
- *The term "****degradation****" is intended as a deviation from specified target performances. This term refers to the criteria used to apply the resilience concept in system planning and operation and it also refers to both infrastructural and operational resilience. As is commonly known, the costs to assure power system reliability in case of multiple contingencies can be*

*unacceptably high and unsustainable; thus, the rationale is to provide a **resilience-centric** criterion of not exceeding maximum specified deviations of system performances (degradation) in case of extreme events.*

- *The term "**extreme event**" refers to an event with a large impact in terms of degraded system performance, damaged components, and reduction of component operational capabilities, as well as unsupplied customers. With this specification, WG C4.47 intends to link the definition of resilience properties with the application criteria (that is, extreme events). Due to the physical nature of large synchronously interconnected transmission systems, extreme events can be accompanied by the loss of multiple components, cascading outages, or loss of stability followed by widespread interruption to electricity users and, in the worst-case scenario, a total system blackout.*

Key measures of the WG definition

The new definition clearly separates the definition of the properties from the ***key actionable measures*** that can be deployed [Before (**B**), During (**D**) and After (**A**) events] to achieve or enhance resilience, considering the utility's objectives and the lack of an international standardised framework to support decision-making for resilience enhancement investments:

- *The process of "**anticipation**"* **(B)** *refers to evaluating and/or monitoring the onset of foreseeable scenarios that could have disastrous outcomes. It assists power system engineers to enumerate plausible disaster scenarios and proposed mitigation plans and allows decision-makers to envisage the "multiple" future states and strategies required to contain, avoid, and/or respond to an emergent threat to the power system.*
- *"**Preparation**"* **(B)** *is the process required by decision-makers to advance the knowledge gained during the anticipation phase from the resilience strategies to clear objectives to guide the deployment of measures considering tolerance to the possible adverse consequences, with emphasis on maintaining mission-critical loads and the minimum system load level to sustain a reduced but acceptable functioning of everyday life and importantly orderly functioning of a modern society.*
- *The process of "**absorption**"* (**D**) *is to meet defined objectives by means of which a system can absorb the impacts of extreme events and can minimise or avoid consequences. The outcomes are represented by the slope and the amount of the power system performance degradation after the shock has occurred or been avoided.*
- *The "**sustainment of critical system operations**"* **(D, A)** *refers to the process of maintaining the operational capability of the impaired power system to supply the mission-critical loads and a minimum system load level to maintain a reduced but acceptable functioning of everyday life and, importantly, orderly functioning of a modern society that are dependent on so many critical and interdependent infrastructures driven by electricity. This may require the deployment of additional components (for example, mobile generator), systems (for example, uninterruptible power supplies), and distributed energy resources to sustain operations until the power system is restored to a normal or near-normal state.*
- *The "**rapid recovery**"* **(D, A)** *process requires the operational response to the initial shock to contain or limit the consequence to the disruptive events, by focusing on mission-critical or essential loads that are required to support the restoration efforts. This requires integrated planning to develop efficient and effective response plans in a co-ordinated manner to recover the system operation to a normal or near-normal state.*
- *In the "**adaptation**"* (**A**) *process, changes are carried out in the power system management, defence and operational regimes, on the basis of past disruptions, in order to contain and/or limit the undesirable situations. This process includes the upgrades of prevention barriers, operational regimes, and maintenance procedures on the basis of lessons learnt from past disruptive events.*

Concluding remarks

This reference paper is a summary of the outcomes of CIGRE WG C4.47 activities on the definition of resilience within the electricity sector. It should be read in conjunction with the technical papers and/or brochures to be published by the WG.
In consideration of the scope and technical complexity of the topic, resilience assessments and enhancements require analyses on the interactions between humans, environment, power systems, and other interdependent critical infrastructures evolving over the planning and operation horizons, with due consideration to lessons learnt from past events and projected future scenarios.
In this context, the present paper attempts to emphasize the foundational definition for power system resilience.

Download this Reference Paper here