U.S. DEPARTMENT OF ENERGY | Office of ELECTRICITY DELIVERY & ENERGY RELIABILITY

RELIABILITY DISPATCHES

FEBRUARY 14, 2024

A Systems Approach to Defining Reliability

Prologue

Electric system reliability is easy to observe, but difficult to define. The electric system is reliable if the lights come on, or stay on, as the customer desires. Unreliability of electric systems can also be observed. The most dramatic examples of un-reliability are past multi-state blackouts of the bulk power system. Electric power failures on transmission and distribution systems have different causes and affect different types of customers differently. But for each, a general sense of what it means for electrical service to be reliable is similar – the lights come on and stay on, so to speak. Reliability is a com-plex problem that spans issues of system operations, equipment availability, and customer values and behavior. Using the analytical approach of Grid Architecture, this Dispatch, produced as part of the Department of Energy Reliability Initiative, provides our working definition of reliability. The paradigm of Grid Architecture gives the definition broad applicability. The combination of definition, definition structure, context, and scope/scale, forms a comprehensive framework for reasoning about reliability in the ultra-large-scale, complex[1] environment of U.S. electric power grids.

Introduction

Electric reliability has a number of definitions, some formal, and some de facto. It could, for example, be argued that electric reliability is what electric reliability indices measure – perhaps the frequency and length of outages, some of which do not affect customers. Or it could simply refer to the customer experience. The purpose of the definition is twofold:

1. To provide a common formal foundation for this Initiative.
2. To inform those interested in the Initiative about how we use the term "reliability."

Today, the United States is moving to increased electrification, greater use of renewable resources, and widespread approaches to decarbonization. At the same time, the role of customers is shifting. Traditional approaches to reliability fail to encompass the emerging role of the grid and new technologies. The definition herein provides a framework that includes a range of common industry approaches[2], and also facilitates evaluating many new reliability considerations:

Electric reliability is the degree to which electric service that meets applicable usability standards is available to users (or customers) at any scale and over any given time period.

Within the dispatch, you will also find articulation of the definition structure, definition context, and scope and scale taxonomy. The first provides a breakdown of the definition into recognizable elements that can be related to practical views of reliability. The second shows how the definition of reliability fits into a larger set of definitions and definition relationships for systems in general and electric grids in particular. The third clarifies the extent of the definition as regards electric power systems. Finally, we discuss the relationship between electric reliability and grid resilience.

[1] Feiler, Goodenough. Northrop, et.al, *Ultra-Large-Scale Systems*, Software Engineering Institute/Carnegie Mellon University, June 2006.

[2] As part of the definition work, we reviewed 46 electric utility reliability indices covering generation, transmission, and distribution on scales as small as individual feeders and as large as whole interconnections.

Use of System Concepts and Terminology for Defining Reliability

Electric power systems have a level of complexity that vastly exceeds that of ordinary systems. The discipline of Grid Architecture provides methods for handling grid complexity based on systems concepts and terminology. Complex systems in general, and power grids specifically, have many characteristics often described by "ility" words, reliability being one of them[3]. A source of confusion in discussing system characteristics is that there are two kinds and the distinction is not always recognized or acknowledged. We label those two sets of characteristics system *properties* and system *qualities*.

System properties are intrinsic or internal characteristics that arise directly from the components and structures of the systems. Such characteristics are directly related to system operations and performance. Reliability and affordability are examples of system properties. System qualities are characteristics that are visible to the users of the system and are directly connected to the users' perceptions of the value and performance of the system. For example, a customer sees a positive quality when the lights go on with the flick of a switch.

Figure 1 illustrates the structural relationship connecting a system to its properties and qualities.[4]

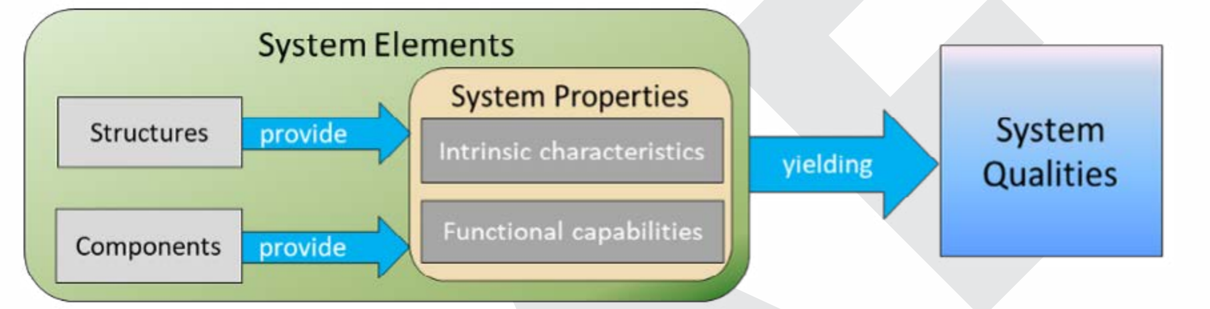

Figure 1 Basic System Relationships (Analysis View)

Three more definitions will help us to understand how different parts of a complex system are related in order to reason about reliability in the context of electric power systems:

- ***Objective*** – an aim, goal, or preferred outcome.
- ***Capability*** – the ability to perform certain actions or achieve a specific objective.
- ***Functionality*** – the sets of tasks, operations, or services that a system can supply or carry out. Functions combine to implement capabilities.

From an architectural standpoint, there is a clear relationship that traces from objectives through the implementation and operation of the system. Figure 2 illustrates the architecture closed loop concept for this relationship. Objectives for the grid arise primarily from three sources: user (customer) expectations, public policy, and emerging trends. The trends may be technological, social, environmental, or economic. Meeting these objectives leads to the specification of necessary capabilities and functions, which must be implemented by the various system elements. The system will have a set of intrinsic properties that should provide the users with the qualities they seek. If done properly, the qualities will then support the original objectives and the loop will close. Failure to close indicates problems in system design, implementation, or operation.

[3] Characteristics indicate the nature of a system. For power grids, many of the characteristics are "ility" words, that is, words ending in "ility," such as reliability, affordability, or adaptability. Not all grid characteristics are actually "ility" words (for example: resilience, responsiveness, transparency), but a great many are, so this is a convenient shorthand for the list of over 80 such terms in use to describe complex systems.

[4] Components might include the number and size of generators, the capacity of transmission lines, substations, transformers, markets, and so on. Structure is about the way things are connected or related to each other.

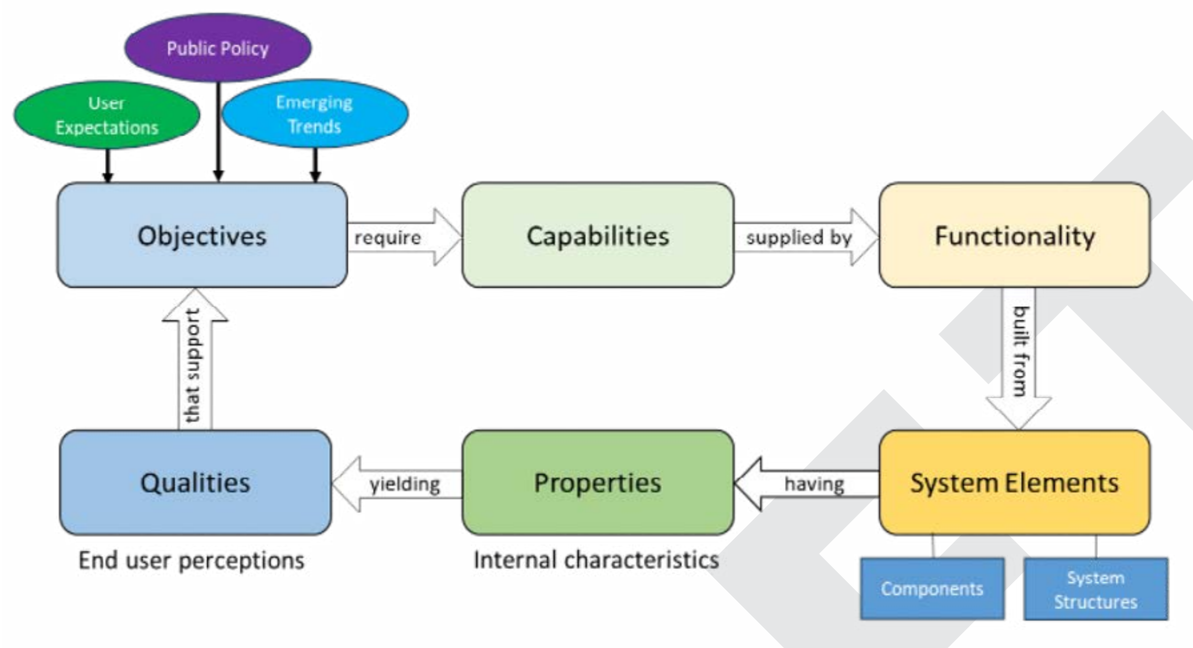

Figure 2 Architecture Loop

The architectural loop model has implications for electric reliability far beyond simple tabulation of reliability indices. Reliability has many moving parts, and therefore does not lend itself to representation by simple statistics. For example:

- Electric Reliability is not a static issue, it is a *Dynamic Issue* - Electric reliability exists in the context of a system (the power grid) which is subject to changing expectations, public policies, technologies, and other factors. Consequently, the structure and operation of the grid is continually evolving, and this requires corresponding changes in how reliability is scoped, measured, and valued.

- Electric Reliability involves multiple entities required to provide electricity[5] - Electric power systems must perform under many conditions, thus reliability considerations start with the grid architecture, and involve such processes as asset management and various levels of planning, as well as operation, mitigation, recovery, and measurement. As the use of Distributed Energy Resources (DER) increases, electric reliability considerations must expand to include the non-utility entities that operate or aggregate such resources. Reliability considerations may also expand as the roles of distribution utilities evolve.

Reliability Involves Three Necessary Points of View

To fully understand electric reliability and its implications, we must be prepared to understand different points of view. Critical among these are:

- Customer /User (external view) – the perspective of the user is primarily about how well the grid serves the customers' needs, meets expectations as seen from outside the electric system, and the cost of doing so. Consequently, the customer view is related to the system qualities that directly impact customer experience.

- Builder/operator[6] (internal view) – this view is about how the grid performs and grid organizations go about providing electric service to meet customer expectations as well as comply with public policy and regulations. This view is necessarily focused on grid properties, which are the internal characteristics as seen by the grid builders and operators, as well as the regulators to some extent. Most of the existing grid reliability indices focus on grid properties and operational behavior. This view is expanding to include DER as grid components.

[5] The entities involved in providing electricity to customers include the owners and operators of physical infrastructure including utility-scale generating facilities, transmission and distribution lines, substations, distributed generation (for example residential and commercial solar installations); local, state, regional, and federal regulators; retail service providers; distributed resource aggregators; and so forth.

[6] Operators include transmission line operators, DER aggregators, distribution operators, and system operators – i.e. people who make the grid function on real-time and longer basis.

- Policy/Regulatory view – public policy reflects societal interests with respect to electric systems. Regulation plays an important role, balancing the interests of consumers and providers while implementing policy. As such, from a reliability perspective, this point of view is concerned with both qualities and properties. Increasingly this involves making determinations about such questions as the societal value of electric reliability.

Disparity in these points of view can lead to differences in determining how much reliability to provide, how it is distributed across customer bases, and how much investment can or should be made in improving electric reliability.

Solving problems in modern electric reliability requires an integrated understanding of electric power system processes and customer, provider, and policy points of view.

Reliability Definition and Structure

Figure 3 illustrates the definition and its structure. The definition has two components, each of which has two sub-components.

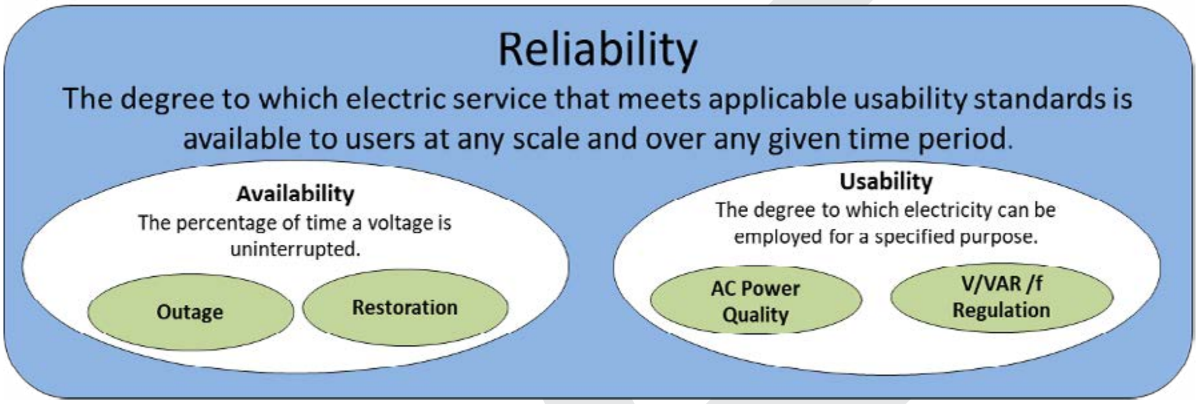

Figure 3 Reliability Definition and Structure

Several points are worth noting:

- The definition has two major parts – availability and usability.
- Availability relates closely to such distribution level indices as System Average Interruption Frequency Index (SAIFI) and System Average Interruption Duration Index (SAIDI).[7]
- The definition of usability makes power quality a subset of electric reliability. Some have that relationship reversed, but this approach serves the scope of our definition better (see below).[8]
- The essential focus of the definition is on the user of the electric service ("is available to users") since the purpose of the grid is to provide electric service to customers.
- That being said, the comments above on the importance of points of view stand.
- The definition provides that reliability is a variable characteristic ("the degree to which"), not a binary condition (reliable or not reliable). This points to the need for quantification of reliability.
- The combination of user focus and point of view with the quantification requirement implies that the "quantity" of reliability can vary from customer to customer and from time to time.

[7] System Average Interruption Frequency Index (SAIFI) and System Average Interruption Duration Index (SAIDI) (sometimes Customer Average Interruption Frequency Index (CAIFI) and Customer Average Interruption Duration Index (CAIDI)) indicate how often it breaks and how long it takes to fix it, respectively.

[8] See for example R.E Brown, Electric Power Distribution Reliability, Marcel Dekker, Inc., New York, 2002. This model relates primarily to electric distribution, where making reliability a subset of power quality is more workable than at the bulk power system level.

Reliability Definition Context

While we ordinarily think of reliability and dependability as interchangeable, for purposes of addressing reliability of power systems, they are different. In the context of power systems, reliability refers to the outages engineers try to manage and the quality of power the system provides. These are measurable elements. From a power system perspective, dependability encompasses all the elements that affect the user experience, including reliability.[9] Understanding this context is important to understanding how apparently unrelated factors affect reliability. Figure 4 provides the definition of dependability and shows the sub-component structure. Dependability includes reliability, along with safety, security, stability, and resilience.

Safety and cyber-physical security are always electric utility concerns and their relationships to dependability are clear, but outside the scope of reliability. Stability (smooth, well-behaved, controlled system operation) is more complex. While this is an operational control issue, stability has such an impact on reliability that FERC references it in the Federally mandated definition[10] of operational reliability it uses for bulk power systems (more on stability below).

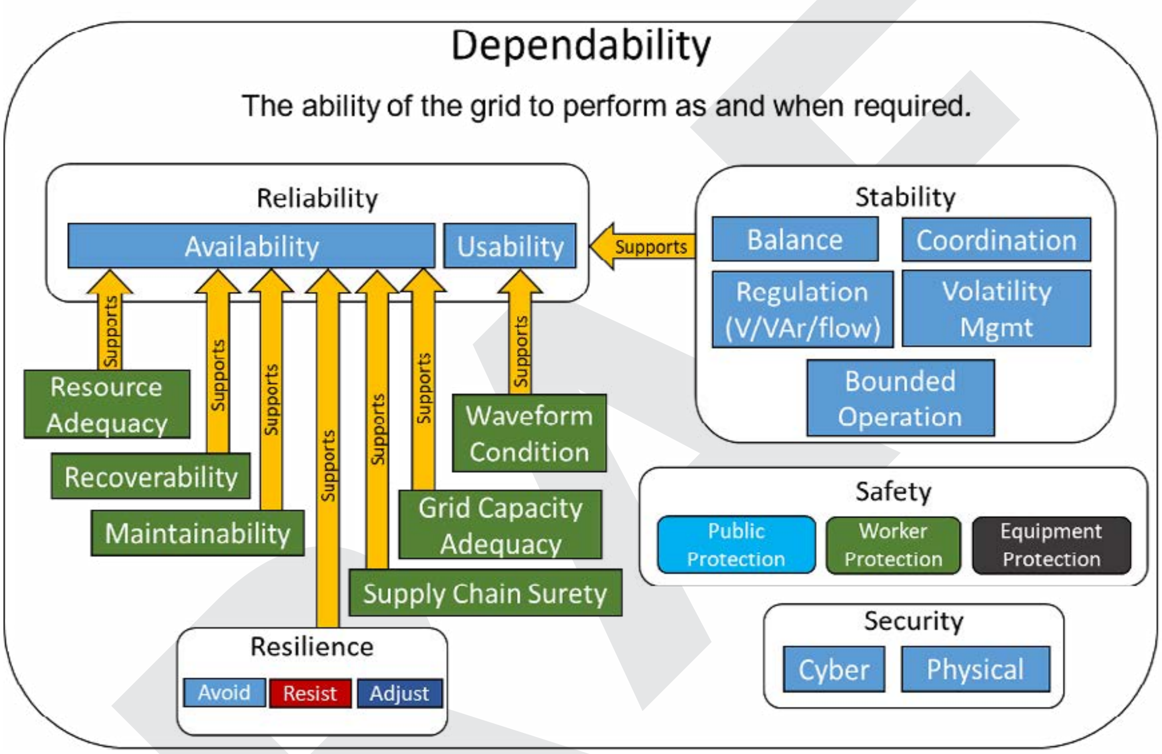

Figure 4 Dependability Context for Reliability

As Figure 4 illustrates, a number of key factors support reliability. These include:

- Resource adequacy – sufficient resource capacity and reserves to maintain supply/demand balance (in other words, enough coal, wind, falling water, sun, gas, or other energy resources are available, and enough generators operable, to meet demand with a margin of safety).
- Recoverability – ability to regain normal or usable condition.
- Maintainability – ability of an item to be retained in or restored to a specified condition.
- Supply chain surety – the ability to ensure material resources (including fuel and rare earth elements), device, system, software, auxiliary equipment, or service availability at the right time and right place.
- Grid capacity adequacy – ability of the transmission and distribution systems to transport the required amounts of

[9] While there are broad surveys of customer satisfaction, currently there is no such thing as a dependability index for electric systems.

[10] 18 CFR Part 3910: "Reliable Operations means operating the elements of the Bulk-Power System within equipment and electric system thermal, voltage, and stability limits so that instability, uncontrolled separation, or cascading failures of such system will not occur ...."

power (separate from resource adequacy).

- Waveform condition – the degree to which AC voltage[11] on the power lines is affected by sags, surges, harmonic distortion, flicker, transients, noise, and frequency variations.[12]
- Grid resilience – supports reliability by providing means to manage grid stresses to avoid or mitigate outages (see discussion below).

Stability supports dependability but also has reliability implications (courtesy of the FERC definition):

- Balance – management of power injected into the grid via generation or storage so as to match demand on short and long-time cycles. System frequency is used as a proxy for balance and so system frequency regulation is part of stability.
- System Regulation – control of system frequency, voltage, and real and reactive power flows.
- Coordination – systematic operational alignment of utility and non-utility assets to provide electricity delivery – increasingly important as usage of DER increases.
- Volatility management – limiting the propagation of power flow volatility injected into the grid by variable energy resources such as wind and solar generation.
- Bounded operation – operation of the grid so as to keep operating parameters within system thermal, voltage, and stability limits.

Different users view reliability differently. For example, commercial and industrial users often are able to analyze and understand the components of dependability at a technical level, while residential users are more likely to equate dependability and reliability with their perceptions of the quality of electric service. Quantification of dependability would allow for a fuller understanding of reliability for all types of users.

Reliability Scope and Scale

A necessary aspect of the definition of electric reliability is a taxonomy of the scope of the definition and of the scales at which it applies. The taxonomy of scope and scale is a classification system. Here we represent taxonomy as a tree structure to provide visual clarity of how different aspects of electrification fall under the definition. The scope deals with which components of the system are addressed. From investors in generation to system planners to grid operators to retail power providers, reliability is of concern. All these market participants reflect the broad scope of this definition of reliability. The scale represents proportional dimensions of components and subsystems. The role of the elements of the physical infrastructure, from items as small as a residential EV charging station to as large as the entire grid, reflects the scale. Many definitions focus on one tier of the electric power system, such as distribution, or on delimited aspects of the grid such as individual components. For the purposes of this initiative, the scope and scale are set broadly. Figure 5 diagrams the scope and scale in terms of three major categories: the physical system, utility processes, and third parties.

[11] Usable electricity flows as either alternating current (AC) or direct current (DC). DC flows in one direction. AC flows back and forth at a very high speed, measured in Herz (HZ). In North America, nearly all components of power systems use AC at 60 Hz.

[12] Here this means frequency fluctuations. For analog electric clocks and electric motors, line frequency quality was a more significant issue than it is now with the rise of digital clocks, network time distribution protocols, and motors with power electronics and digital control. System frequency has large significance in another context – see the discussion on stability.

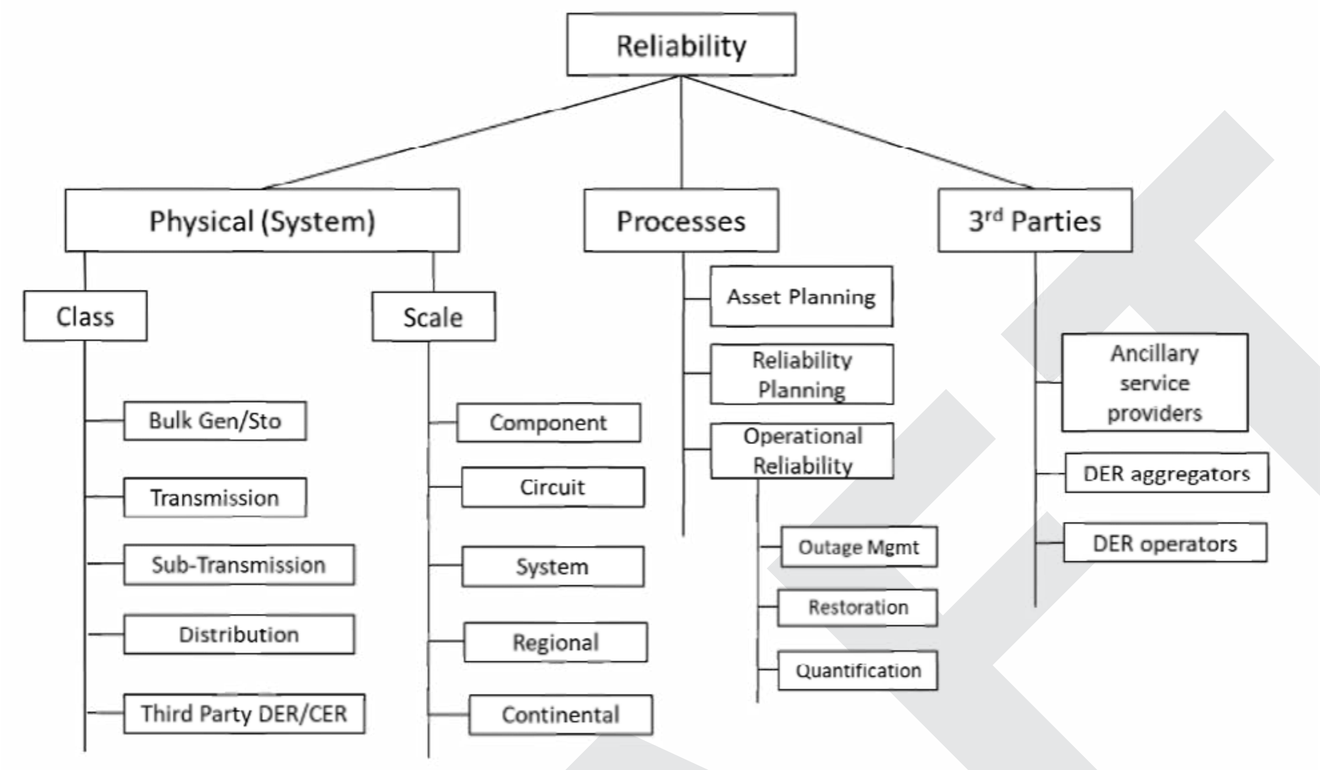

Figure 5. Grid Reliability Definition Scope and Scale

The process scope includes more than just operational reliability. Electric reliability management starts long before real time operations and includes asset planning (identification of assets that minimize costs and provide the resources necessary to reliably operate the system at risk) and reliability planning in addition to outage management, restoration, and reliability data collection for quantification.

Importantly for the future of the evolving grid, the scope of electric reliability covers more than what are thought of as the traditional roles of the electric power providers. Ancillary services providers are clearly crucial, but increasingly so are DER aggregators and DER operators (which may be separate entities). When traditional electricity providers rely upon DER for electricity delivery, then reliability considerations must include these entities and their systems and processes. This points to the need to develop appropriate measures of the impact of these entities on reliability, as well as standards for their reliable performance.

Relationship to Resilience

While resilience is not the focus of this document, it is important to address here due to the amount of ambiguity in grid resilience discussions and frequent conflation of resilience with reliability. The following brief discussion is based on extensive work done on the topic of grid resilience in the context of Grid Architecture.[13]

Figure 6 defines grid resilience and illustrates the relationship to electric reliability. Briefly, reliability is about understanding at what level things will break and what you do to recover. Resilience is about raising the level at which things will break. Outage mitigation is categorized here as the third level of resilience[14], whereas recovery is part of reliability.

[13] See several of the papers at *https://gridarchitecture.pnnl.gov/advanced-concepts.aspx*

[14] Outage mitigation includes active strain adjustment, microgrid islanding, and Fault Location, Isolation, and Service Restoration (FLISR).

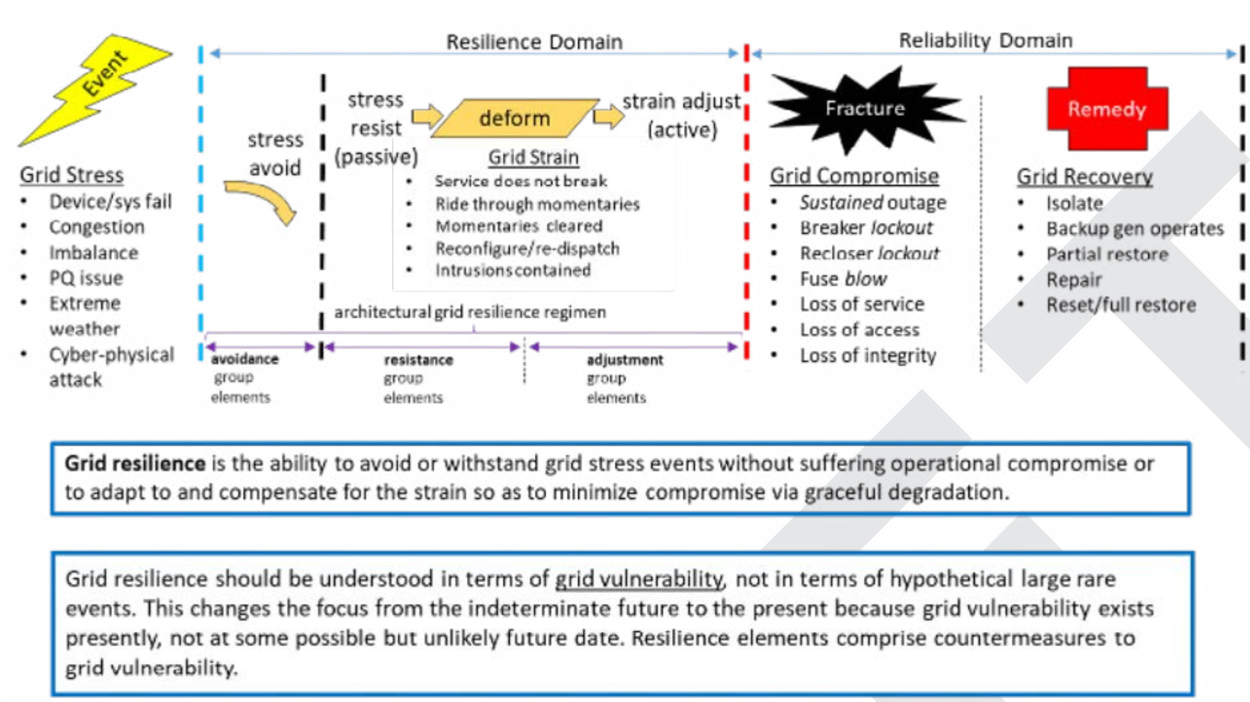

Figure 6 Resilience Definition and Relationship to Reliability

Final Comments

The definition of electric reliability in this dispatch provides a basis for understanding the past and present approaches to reliability as well as the future of reliability in the 21st Century.

For example, this framework illuminates the relationship of system frequency to reliability. Due to the FERC definition of operational reliability (incorporated into our definition), system stability supports reliability as shown in Figure 4. System frequency is a proxy or metric, if you will, for balance, which is a significant component of system stability. So, within our framework it makes sense to understand system frequency regulation as being related to electric reliability.

The inclusion of power industry processes in the scope (Figure 5) is important because reliability management goes far beyond simple, measurable indices. Using this framework, it is possible to map the various processes back to the definition framework and to identify gaps and future directions of development of reliability theory and practice. This is already evident in the consideration of DER, where appropriate quantification methods, planning methods, and standards do not currently exist.

The concepts of multiple points of view and of separating grid characteristics into two groups (internal properties and external qualities) provide additional clarity when thinking about reliability. When used well they help to avoid the confusion that comes from conflating these two superficially similar but fundamentally different groups of characteristics or misinterpreting priorities due to unstated assumptions about points of view. This will be very useful when sorting out the public policy debate about treating a high level of reliability as a right vs. as a privilege.

This definition document is the basis and framework for reasoning about reliability of electric power systems in the Reliability Initiative.

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