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Electric Grid Resilience and Reliability for Grid Architecture

November 2017

JD Taft, PhD

U.S. DEPARTMENT OF
ENERGY

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under Contract DE-AC05-76RL01830

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1.0 Introduction: Applying the Concept of Resilience to Grid Architecture

Grid modernization activities cite resilience (sometimes called resiliency) as a key electric power grid characteristic to be improved or maximized, and so it is crucial for the development of resilient grid architectures that the concept of grid resilience be clear and quantifiable. However, attempts to define and quantify a concept of resilience for electric power grids have mostly relied upon ad hoc definitions that do not have much underlying rigor and are often closely tied to reliability, sometimes only differing in terms of scale and frequency of events. While grid reliability would seem to have strong definition given the IEEE 1366 standard, grid resilience is a term that is less clear.

A proper definition of resilience and the relationship between it and reliability will facilitate development of proper resilience metrics and the development of resilient grid architectures.

This paper addresses the resilience definition problem, and illuminates the relationship of resilience to reliability for electric power grids. As a byproduct, the nature and limitations of some existing grid reliability metrics are clarified.

2.0 What is Grid Resilience?

The EPRI definition of resilience specifies it in terms of three factors: prevention, recovery, and survivability.[2] These terms are described rather than being defined, and do not have metrics associated with them. Also, as will become clear later, we will argue that one of them (recovery) does not belong in the definition of resilience as applied to grid architecture.

ICS CERT has produced a discussion that has some similarities to the EPRI definition.[3] It uses the National Infrastructure Advisory Council 2009 definition: "…the ability to reduce the magnitude and/or duration of disruptive events." This is somewhat useful in that it represents resilience as a grid characteristic, independent of external or internal events. No metrics are provided, however. The same work defines reliability for grids as "the ability of the power system to deliver electricity in the quantity and with the quality demanded by users." This definition conflates power quality and resource adequacy with service interruption event reaction, and so creates a difficult situation in terms of defining metrics: non-orthogonality with other metrics. Some models of power quality actually include reliability as a subset.[4]

Presidential Policy Directive 21 defines resilience for the grid as "…the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions. Resilience includes the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents." This definition also conflates resilience with reliability by including recovery.

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[2] EPRI, "Grid Resiliency," available online: https://www.epri.com/#/grid_resiliency.

[3] Aaron Clark-Ginsberg, Stanford University, "What's the Difference Between Reliability and Resilience?", available online: https://ics-cert.us-cert.gov/sites/default/files/ICSJWG-Archive/QNL_MAR_16/reliability%20and%20resilience%20pdf.pdf.

[4] RE Brown, Electric Power Distribution Reliability, Marcel Dekker, Inc., 2002, p. 40.

The Smart Grid Dictionary defines resilience as "the ability to resist failure and rapidly recover from breakdown."[5] This definition starts well but then conflates utility response with a grid characteristic. The article does suggest that resilience impacts reliability, and thus suggests (perhaps inadvertently) that resilience is a grid characteristic, not an event response. This is essentially the starting point for the resilience discussion in the recently released draft National Academy of Sciences (NAS) study on electricity system resilience[6] which also combines grid characteristics with utility response to external events. Many definitions or descriptions of resilience include some aspect of ease of recovery, but do not show how to measure it as an intrinsic grid characteristic and for good reason – this approach depends on how the utility handles events, which conflates utility processes with grid characteristics and still ends up being dependent on specific events. The same NAS study indicates that there are no generally agreed-upon metrics in wide use.[7]

Some definitions or resilience attempt to position it as a characteristic that applies only after some damage has been done. For example, the Resilience Analysis Process (RAP) developed by Sandia National Laboratory[8] lists as a basic principle "…resilience metrics should be based on the performance of power systems, as opposed to relying on attributes of power systems". This is not a useful approach when it comes to grid architecture since it turns away from the very characteristics that architecture strives to define and conflates an inherent characteristic of the grid with reliability.

Some discussions attempt to use terms like security or availability to address what should be thought of as resilience (or perhaps they should be thought of as component elements of resilience) and then to push resilience into the domain of reliability. A result is that many proposed resilience metrics are in fact reliability measures of various kinds.

Many proposed resilience metrics are in fact reliability measures.

3.0 Defining Resilience and the Relationship to Reliability

Figure 1 below provides a definition of grid resilience and illustrates some key issues, such as the difference between resilience and reliability, and how to determine which definition applies in the various phases of grid operation.

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[5] Christine Herzog, 'Grid Resiliency is Required for Improved Grid Reliability," available online: http://www.smartgridlibrary.com/2012/03/26/grid-resiliency-is-required-for-improved-grid-reliability/

[6] National Academy of Sciences, Enhancing the Resilience of the Nation's Electric System, The National Academies Press, p. 1-4, available online: https://www.nap.edu/catalog/24836/enhancing-the-resilience-of-the-nations-electricity-system

[7] Ibid, p. 2-28.

[8] E Vugrin, A Castillo, and C Silva-Monroy, "Resilience Metrics for the Electric Power System: A Performance-Based Approach," Sandia Report SAND2017-1493, February 2017.

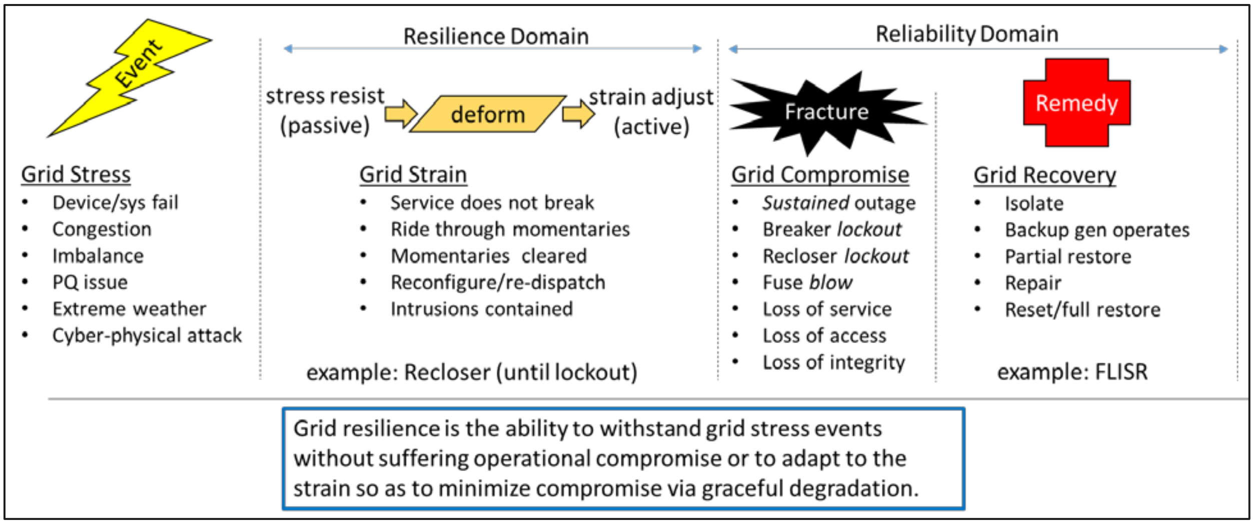

Figure 1. Resilience and Reliability Domains

A key concept here is that resilience is *an intrinsic characteristic of a grid* or portion of a grid. A perfectly resilient grid would not experience outages and so any definition or metric that is based on measuring outage frequencies, times, extents, or impacts on customers or systems does not get at the essence of resilience. Resilience applies to the grid under stress: how it resists losing capabilities or gracefully degrades is the essence of resilience. This explains why reliability measures are not useful for quantifying resilience. Resilience is in large part about what does **not** happen.

Grid resilience is the ability to withstand grid stress events without suffering operational compromise or to adapt to the strain so as to minimize compromise via graceful degradation. It is in large part about what does **not** happen to the grid or electricity consumers.

This definition includes the ability to withstand operating excursions outside the normal operating envelope with an inherent tendency to return to operations within the normal envelope. Reliability on the other hand, is a measure of *behavior once resilience has broken*. Standard reliability metrics fall into two categories: frequency indices (CAIFI, SAIFI, etc.) and duration indices (CAIDI, SAIDI, etc.). Frequency indices are very roughly related to resilience in the sense that they reflect to some degree how often resilience is broken (but in a non-normalized fashion, making them unusable as resilience measures). Duration indices measure how well a utility responds to broken resilience (also in a non-normalized fashion). This is why recovery, as mentioned in the EPRI resilience definition, actually belongs in the reliability domain.

The dividing line is clear: for electricity delivery, the start of a sustained outage is the transition point from the domain of resilience to the domain of reliability. An understanding of this concept is necessary for the development of resilient grid architectures.

For some time, there has been a view in parts of the electric power industry that momentaries should be included in reliability metrics. The impact of momentaries on smart inverters has heightened this issue recently. In the definition and model provided here, momentaries are *power quality* issues that stress the grid. When smart inverters respond to momentaries by pulling off the grid for a period of time, this reflects a lack of resilience in the inverters (by design!) that can create a transition to a reliability domain issue.[9] Hence, changing the ride-through behavior of smart inverters can be a resilience improvement with a potential impact on reliability.

It is worth noting that FERC uses a statutory definition of reliability for bulk energy systems derived from 18 CFR Part 39[10] that pertains to some of what we here include in resilience *("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 …."))*. Given the source of this definition, it is not likely that industry definitions will change, nor is it the purpose of this document to suggest that they should.

Resilience and reliability do have a relationship but it is not simple. The Smart Grid Dictionary discussion referenced above suggests that resilience "impacts" reliability. In fact, increasing resilience *may* improve reliability, but this is not guaranteed, since reliability as measured by standard metrics depends on some set of events that result in outage and resilience is intended to avoid such outcomes. It can be the case that grid events and stress do not intersect with the resilience change, so that reliability metrics may improve, not show a change, or actually degrade. This is one of the reasons that the definition and metrics for resilience are so important – to be useful in the development of resilient grid architectures and the design of resilience tools, device, and systems, it must be possible to determine resilience directly from grid descriptions, not from reliability indices.

Note that the definitions of both resilience and reliability can be applied at various scales. This means it is possible to discuss the resilience of a whole power system, a transmission or distribution system, a single circuit, or portion of a circuit, even a single device. The choice of scale will depend on the nature of the problem being solved and is up to the engineer, operator, regulator, or other stakeholder to determine appropriately. Scale should be specified so that the extent and scope of the analysis is clear. Scale includes not just physical system extent, but also time scale. This is important for dividing certain operations into resilience vs. reliability functions. For example, recloser operation and FLISR activity can depend on time settings, which may vary from utility to utility.

Given the above definitions and clarifications, it is possible to classify devices and systems as working in either the resilience domain or the reliability domain, an understanding that is necessary for the grid architecture work. Table 1 provides some examples.

Table 1. Device Domain Examples

Device/System	Domain	Comment
Recloser	Resilience	Operates to prevent a breaker lockout
FLISR	Reliability	Operates after a breaker lockout
Battery storage	Both	Provides capacity to adjust to stress conditions; can provide backup in sustained outage
Building thermal storage	Resilience	Can be resource for gen/load balance; does not aid electric service restoration
Partial mesh feeders	Both	Support load rebalance to adjust to stress; support FLISR after lockout
Backup generation	Reliability	Operates in the event of a sustained outage

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[9] This can be taken advantage of in an IoT environment to become a cyber security vulnerability.

[10] RULES CONCERNING CERTIFICATION OF THE ELECTRIC RELIABILITY ORGANIZATION; AND PROCEDURES FOR THE ESTABLISHMENT, APPROVAL, AND ENFORCEMENT OF ELECTRIC RELIABILITY STANDARDS

Device/System	Domain	Comment
Generation reserves	Resilience	Used to adjust to gen/load stress such as in frequency regulation
Demand response	Resilience	Used for stress avoidance and strain adjustment, such as system peak limiting
Asset health monitoring	Resilience	In terms of predictive maintenance, asset monitoring can be viewed as a means to assist in preventing reliability events form occurring.
Microgrids	Resilience	Grid-directed microgrid islanding can be used as a grid strain compensation measure, whereas self-directed islanding may be a resilience measure *for the microgrid itself*, in response to a grid reliability event.
Contingency Planning	Resilience	Contingency planning deals with how to adapt to grid strains.
System Integrity Protection Schemes (SIPS)	Resilience (from the perspective of the bulk energy system)	There are a large number of individual methods known collectively as SIPS, and some but not all of them involve shedding load.[11] From the standpoint of the load that is shed, a reliability event occurs. From the standpoint of the BES, this is adaptation to protect system stability.

4.0 What Do Reliability Metrics Really Measure?

Metrics for use in grid architecture must derive from proper system characteristics definitions. Characteristic definitions and their related metrics must have certain properties of their own in order to be useful for architecture work. These include:

- Normalization of exogenous factors
- Orthogonality with other pertinent definitions and metrics – no conflation of factors that should be understood and measured separately
- Focus on intrinsic system characteristics, not external events and responses to them
- Mathematically, measures must be norms, not metrics. The term metric is misused but all too common. Metrics measure distance; norms measure size.
- Usefulness for prediction of system behavior (i.e. not backward –looking)

Standard reliability metrics for the grid do not measure intrinsic grid properties. Consider any particular grid: over the course of a year, it experiences a set of events that cause outages. At the end of the year, various reliability metrics can be computed based primarily on outage times and extents, and recovery times. Now consider that exact same grid in a different year. A different set of events occurs, leading to different outage times and extents and recovery times. The metrics for the second year likely will not be the same as for the first year. To the extent that events are similar year on year, it can give the impression that the reliability metrics are stable and therefore measure intrinsic grid characteristics, but this is not the case.

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[11] V Madani, et. al., “Application Considerations in System Integrity Protection Schemes (SIPS),” available online: https://www.gegridsolutions.com/smartgrid/May08/3_SIPS.pdf

Standard grid reliability metrics (SAIDI, SAIFI, CAIDI, CAIFI, etc.) conflate the response of a grid and how the utility responded with the specific set of events that happen to be what actually occurred. This means that they are *non-normalized* – they do not remove the events themselves from the metric calculation and so do not represent the grid's characteristics in isolation from the events. Comparing the metrics from year to year for a single grid or comparing two grids is not actually proper (even though it is done all the time), since the events are not uniform and the metrics do not normalize out the variations in events. The frequency index metrics give some vague indication of *lack of* grid resilience (by measuring how often resilience was broken to some extent) but these metrics do not in any way measure what *did not happen*, which is a key aspect of resilience. The duration indices measure how the utility responded to some specific set of events which may or may not repeat.

Both frequency and duration indices are backwards-looking, meaning that they are computed from past events. Because they are not normalized, they are not rigorously predictive of future grid behavior unless event sets are similar, even though they are treated this way. Consequently, they cannot properly be applied to compare different time periods for a single grid or to make comparisons across different grids or to predict the response of a grid to different events. Since one of the key purposes of any grid architecture (or any system architecture) is to predict system behavior, these metrics are not very useful in developing new grid architectures or in comparing architectural alternatives. Finally, standard reliability metrics do not measure reliability; they measure unreliability (they get larger as the grid becomes more unreliable).

Despite all of the above, reliability metrics are standard and will continue to be used in the industry, so it is not a purpose of this document to attempt to change how reliability is measured but to clarify the limitations of these measures in developing resilient grids.

5.0 Relationship to Cyber-Security

In the 2014/2015 work on grid modernization, the Department of Energy's Energy Policy and Systems Analysis (EPSA) group defined cyber-security as an element of resilience. While cyber-security involves more than what is covered by resilience, cyber-security is clearly an aspect of resilience for electric grids. This means that the definition of resilience and the identification of transitions from resilience domain to reliability domain must be sufficiently general to include cyber defense failures as well as ordinary electricity delivery failures.

Inverting the paradigm provides the view that grid resilience can be a cyber-security measure. This leads to an understanding of some grid components as more than means to provide grid services.

6.0 Metrics for Resilience

Figure 2 provides taxonomy diagrams for both resilience and some reliability metrics. Resilience was defined in Figure 1 as having two primary components (resistance and adjustment or compensation). Resistance is further subdivided into an element called grid hardness and one called asset health. Note that the traditional "ility" words (availability, flexibility, etc.) have been avoided.

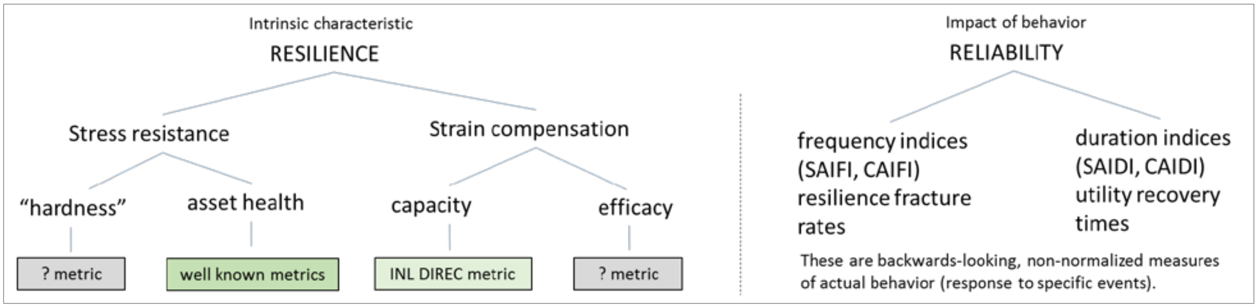

Figure 2. Resilience and Reliability Metrics Taxonomies

The asset health element is needed to address asset failures such as transformer burnouts that are sources of grid stress. Consequently, it is reasonable to consider asset monitoring as a resilience measure. The hardness element is needed to address how the grid resists stress (consider a steel utility pole vs. a wooden one for example or a network access control service that prevents a hacker intrusion). Adjustment capacity is being formalized using the concept of the Disturbance Impact Resilience Evaluation Curve (DIREC) in work done at Idaho National Laboratory (INL) under the US Department of Energy Grid Modernization Initiative.[12,13] The INL work presumes that any available adjustment capacity can actually be employed. Note that this is not a limitation for the development of resilient grid architectures, where this assumption can be used without loss of general validity. For any specific grid, it would be necessary to consider how well the grid and the utility can make use of any existing adjustment capacity – hence the need for a way to measure the efficacy[14] of its adjustment capacity.

Work remains to be done in defining proper measures of hardness and strain compensation efficacy. It would also be helpful to be able to aggregate individual device health measures into ensemble measures that apply at various scales from a circuit section all the way to a full grid. Since individual device health measures tend to be as diverse and heterogeneous as the devices themselves, this will take some effort.

7.0 Final Comments

A proper definition of grid resilience is crucial to the development of architectures for resilient grids but the traditional definitions are not very useful for this purpose. This paper has provided a new rationale for how to define grid resilience and has clarified the relationship between this definition of resilience and reliability.

The definition provided in this document casts grid resilience as an intrinsic grid characteristic comprised of stress resistance and strain compensation elements and shows where some metrics exist now and where more work is needed. Given that work is underway on metrics for adjustment capacity (part of strain compensation), and that asset health metrics (part of stress resistance) are reasonably well-understood, it is clear that effort should be applied to defining metrics for grid hardness and adjustment efficacy.

The same properties that make good grid resilience definitions and metrics for Grid Architecture are also likely to be useful for more general use. In particular, tools that implement real time or near real time

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[12] Tim McJunkin and Craig Rieger, "Resilient Metric Concepts for Control Systems for Electricity Distribution," Idaho National Laboratory, August, 2016.

[13] C. Rieger, "Resilient Control Systems Practical Metrics Basis for Defining Mission Impact," INL, August 2014, available online: https://inldigitallibrary.inl.gov/sites/sti/sti/6269308.pdf

[14] ability to produce a desired result or effect

visualization of adjustment capacity would be useful in grid operations, whereas metrics for grid hardness would be useful for grid planning and the development of resilience technologies and standards.

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