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Pacific Northwest NATIONAL LABORATORY

Resilience Metric Formulation Considering Transactive Systems

December 2018

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U.S. DEPARTMENT OF ENERGY

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Abstract

To help understand the effects of risk and uncertainty on power system operation, particularly during deleterious events, a model for resilience that defines four specific phases of resilience and associated activity was adopted, refined, and contextualized. Given this model, a comparison is made to the well-established field in power systems of reliability and an integrated framework is developed. The role of transactive energy systems in resilience activity is discussed and the strong alignment between properties of transactive energy systems and resilient systems is made. Finally, a scenario-based framework for risk metrics is proposed; the proposed framework allows for the direct comparison in performance between existing (business-as-usual) and transactive energy systems in improving resilience.

Executive Summary

Risk and uncertainty are inherent in the operation of power systems where known and unknown threats challenge the ability of system operators and planners to "keep the lights on." In some cases, these threats are relatively benign (e.g., vegetation-induced faults, utility pole damage from vehicle impacts, etc.) with utilities having established techniques for quickly repairing damage with little to no understanding of or specific preparation for the deleterious event. In other cases, the scope of the threat can be larger, thus affecting large portions of the system simultaneously (e.g., hurricanes, tornados, etc.) or less well-understood and harder to remediate such as cyber-attacks. This later group is of particular concern as the consequences of these events when they occur can be very high but their frequency very low, making effective corrective action difficult.

"Resilience" is the term used to describe systems that manage both anticipated and unforeseen deleterious events. Section 2 provides a discussion on resilience as it is applied to power systems. We have adopted a model proposed by Argonne National Laboratory that breaks the system activities associated with a deleterious event into four phases: 1) preparation, 2) mitigation, 3) response, and 4) recovery. This model is just one of many with similar deconstruction (and often different terminology); all of these models have the advantage of providing a holistic view of deleterious events and encouraging power system operators and planners to think broadly about how to improve resilience performance.

Traditionally, the most common measure of power system performance to deleterious events was the retrospective calculation of certain reliability metrics (e.g., System Average Interruption Duration Index, System Average Interruption Frequency Index, etc.). Power system operators have traditionally been held to certain levels of reliability as indicated by these metrics by their regulators; therefore, "reliability" has been the measure of quality for power system operation. Section 3 discusses the relationship between reliability and resilience, showing that reliability, although a more mature field, is a subset of resilience and is not sufficient to define the overall performance of the power system.

Typically, transactive energy systems (referred to as transactive systems in this report) have been proposed as means of allowing distributed energy resources to participate in meeting the technical needs of the power system and their role as a resilience tool has not been adequately explored. Section 4 discusses the general characteristics of transactive systems and shows strong alignments between the benefits that transactive systems intend to provide and the needs of a system that is trying to improve its resilience. In particular, the ability of transactive systems to provide flexibility and operate in a scalable, optimized manner can be very useful in addressing the impacts of deleterious events. An example of a simulated event and the role of a transactive system in managing it also is provided

To evaluate the improvements to resilience provided by a transactive system (or any other tool or system), we propose in Section 5 the development of a risk metric based on a suite of scenarios deemed applicable to the system in question. Each scenario would provide guidance on the construction of an analysis that would allow the measurement of the appropriate metric to evaluate the performance of a system to a specific deleterious event. These individual scores can be aggregated across the suite of scenarios to define a composite resilience score. With the analysis tools in place, it is then possible to evaluate the impacts of specific mitigation activities by determining their impact in one or more scenarios and the composite risk metric score. Thus, power system operators and planners would have the ability to estimate their resilience performance for a given set of scenarios prior to the onset of any specific event.

Contents

Figures

Tables

1.0 Introduction

The transactive systems research done by Widergren et al. (2017) has considered the treatment of uncertainty and risk within the valuation methodology. This prior work characterized two main types of uncertainty that affect valuations—probabilistic randomness and lack of knowledge ("known unknowns" and "unknown unknowns"). Randomness is intrinsic and embedded in the very nature of the physical problem whereas knowledge gaps may be reduced by eliciting expert opinion, collecting data, or borrowing experience from other domains. Irrespective of its type, uncertainty in input data propagates into the valuation model and valuation outcome supporting any decisions. The notion of risk and uncertainty arises due to the need to maintain system resiliency against deleterious events while providing reliable services. The occurrences of deleterious events in power systems cannot be precisely predicted, but the probabilities of occurrences may be estimated within an uncertainty envelope. This report harmonizes usage of the terms "reliability" and "resilience" in the context of valuation before embarking on the development of a risk-informed framework for resilience measurement. The vision is to enable development of resilience metrics for rational decision-making in the presence of uncertainties.

A resilient system results from sound risk-management practices. Integral to this management is a structured and comprehensive cause-consequence analysis. Prevention and control strategies in this cause-consequence continuum aim to alleviate the intensity and extent of cascading events and subsequent consequences. These risk analysis elements are well captured in a bowtie representation shown in Figure 1. While a manmade infrastructure strives to be resilient in a hazard- and threat-agnostic sense, motivation to implement effective strategies comes from a basic understanding of the sources of stress on the system.

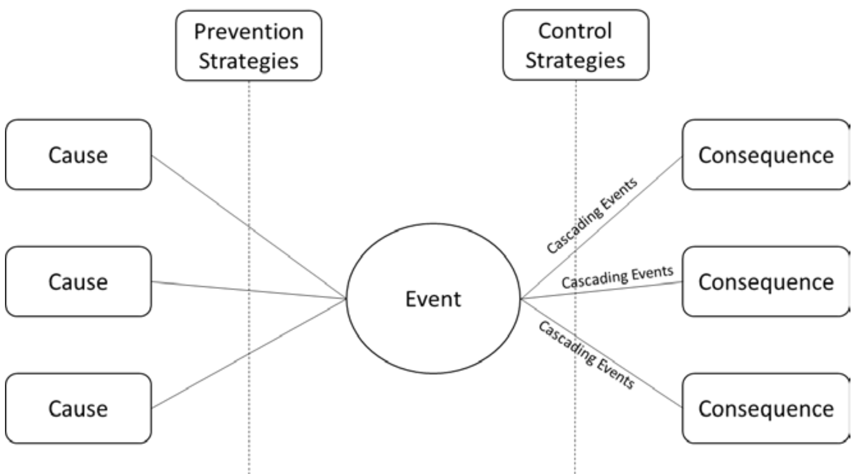

Figure 1. Bowtie Risk Assessment Diagram for a Deleterious Event

Achieving resilience through risk management is a multi-phased approach that encompasses this cause-consequence continuum. A phased approach to resilience characterization is described in Section 2. To avoid ambiguities between closely related terms of resilience and reliability, Section 3 delivers a contextual overview of reliability. A theory-based case is made in Section 4 to promote transactive systems as a means to enhance power system resilience. Section 5 proposes a framework and a methodology to risk-inform resilience strategies with the ultimate intent of developing metrics that can measure resilience in the valuation of transactive energy systems.

2.0 Resilience: Phased Approach to Characterization

Treatment of resilience with respect to power systems has evolved the following risk-based definition. A system is said to be resilient when it can manage the risk associated with both unforeseen and anticipated abnormal events (i.e., heretofore deleterious events). A firm understanding of resilience requires a compare-and-contrast approach to reliability, which will be elaborated further within Section 3.0. Reliability considerations apply to events that are operational in nature, having frequencies and magnitudes predictable with some degree of confidence. Examples include failure rates of assets or circuits and causes of common outages that can often be resolved using repair, replacement, and efficient restoration techniques achieved within a tolerable timeframe. Reliability metrics are captured through utility outage management systems. Low-probability, high-impact deleterious events (e.g., hurricanes, floods, etc.) typically are excluded in estimates of reliability metrics and hence are treated primarily within a resilience purview by the National Association of Regulatory Utility Commissioners and other organizations. Successful resilience management minimizes service disruption to customers and asset damage for owners. Such a resilient system definition is agnostic relative to the actual mechanisms or frameworks designed to achieve resilience at various intervals within the event lifecycle. A survey of efforts undertaken during the past decade affirms a phased approach is currently the most comprehensive way to characterize resilience (NIAC 2010; ANL 2013; GMI 2018).

All-hazards methodologies used to evaluate resilience imply a broader model with four phases: 1) preparation, 2) mitigation, 3) response, and 4) recovery. Deconstructing resilience into these four phases or components more holistically enables owners and operators to determine the ability of a system to withstand specific threats, minimize or mitigate potential impacts, and resume normal operations, if and when degradation occurs. A threat is a natural or manmade occurrence, individual, entity, or action that has or indicates the potential to harm life, information, operations, the environment, and/or property (DHS 2010). Originally developed by Argonne National Laboratory in 2013, the Resilience Measurement Index (RMI) described resilience as, "… the ability of an entity to anticipate, resist, absorb, respond to, adapt to, and recover from a disturbance" (Carlson et al. 2012). Refinement of resilience treatment in recent years has elaborated this RMI model via phase-dependent risk considerations. Namely, the Grid Modernization Initiative considers resilience equivalent to application of a subset of risk treatment strategies available within a risk-management framework (Widergren et al. 2018). The concepts of stress avoidance (i.e., risk avoidance), strain adjustment (i.e., risk mitigation), and stress acceptance (i.e., risk acceptance) are emphasized equally for hazards or threats. Hazards are considered manmade or naturally induced events for which occurrence can be probabilistically estimated (ANL 2013). The evolving resilience posture necessitates a phase-naming convention that seeks to align these schemas (see Table 1). The RMI schema is **bolded** for emphasis because we will continue to use this terminology throughout this report. In this report, we describe the four phases of resilience as they pertain to both traditional and transactive energy systems.

Table 1. Similar Resilience Phase Nomenclature

RMI (ANL 2013)	(NIAC 2010)	(GMI 2018)
Preparedness	Adaptability	Avoidance
Mitigation	Robustness	Adjustment
Response **Recovery**	Resourcefulness	Acceptance

The definitions and explanations provided for the four phases are extensions and refinements of what is found in (ANL 2013). These improvements have been made to remove some of the ambiguity found in that report regarding the specific definitions for when the phases begin and end. This report further contextualizes resilience phases to power system applications. Though specificity and clarity have increased, precise definitions for the boundaries of each phase are not essential for model application within this arena. This work is more general in nature and proposed clarifications are intended to fill gaps found in evaluating the model.

2.1 Preparedness

Resilience efforts or activities look different in each phase. *Preparedness* refers to activities undertaken by an entity in anticipation of threats or hazards and their associated consequences. Compared to the subsequent three resilience phases, preparedness is the most event agnostic. Utilities commonly develop plans to handle a variety of events. However, these plans need to be sufficiently general and/or flexible to apply to a host of adverse scenarios. For example, plans to mitigate substation flooding need to remain relevant whether such flooding is from a nearby river or from the ocean (e.g., storm surge from a hurricane). Details of plan execution, which vary more by event type, play a more prominent role in subsequent resilience phases. Preparedness activities can be subdivided into actions fostering awareness or planning. Specific actions that can be undertaken to enhance awareness related to an asset include:

- Development of hazard-related information, including hazard assessments and information sharing
- Implementation of various activities designed to anticipate potential natural and manmade hazards.

Planning-related activities include:

- Avoidance strategies
- Response or emergency action planning
- Actions undertaken to enhance continuity of operations.

In the absence of transactive systems (discussed more in Section 4.0), resilience is traditionally achieved through a number of mechanisms that generally require significant organizational planning and/or capital investment. Evidence suggests that clear understanding of operational objectives can facilitate phased resilience outcomes. For example, the reserve cadre of skilled specialists who regularly work power emergencies throughout the nation constitutes a resilience preparedness measure that fosters success for electric utilities when responding to emergency situations. Line workers are routinely shared among companies during emergencies through mutual assistance programs. Emergency response plans are routinely updated based upon the extensive experience and knowledge these specialists possess. Hence, employees can support distinct, articulated storm assignments. Such crew training and (n-1) contingency analysis to reduce downtime justifies emergency response strategies.[1] In the case of Mississippi Power, following Hurricane Katrina in 2005, the existence of such plans and the well-communicated mission "to get the lines back up," empowered staff to "do what it takes." The company succeeded in implementing a rapid recovery mechanism that restored power to all customers capable of accepting service within two weeks of the storm's landfall. This recovery time was approximately half what was initially estimated during initial post-Katrina assessments (Smith 2008).

[1] N-1 contingency analysis is performed to ensure secure operation of the grid while controlling the active power flow.

Resilience in the Preparation phase also manifests as considerations to anticipated but non-specific threats made during the design and implementation of a system. Such considerations take advantage of the natural upgrade, refurbishment, and expansion process that all utilities go through, giving them opportunities to prepare for easily anticipated scenarios that commonly threaten their systems. Elevating assets above expected floodplains, using water-tight connectors, building power poles with appropriate wind load ratings, installing redundant power sources for substation controls, and installing multiple communication channels all would be considered Preparation strategies. Preparation even encompasses very general strategies, such as creating redundant routing options in a contingency situation. Such actions can provide high power reliability and availability, thereby reducing the number of critical pathways for which failure could cause a system-wide loss of service (Widergren et al. 2018).

Finally, Preparation also applies to activities made immediately before a deleterious event when such an event is imminent (such as a hurricane). Mitigation activities are undertaken shortly before an event to reduce the severity or consequences of the hazard. Details of likely event impacts can be better articulated and planning steps better tailored to the hazardous conditions to come, fostering ready execution. Examples include:

- Emergency crews (i.e., first responders) dispatched to locations likely to suffer greatest impact from deleterious event.
- Hardening or maintenance activities to offset imminent deleterious events (e.g., extra vegetation trimming/removal around power lines in coastal areas of the southeastern region to withstand major hurricane sustained winds).
- Resource activities examining the reliance of an asset on key resources to support its core operations (e.g., electric power, natural gas, information technology, etc.), susceptibility of an asset to disruption of these resources, and any actions taken to diminish key resource loss. Fuel supply redundancy is a common resource Preparedness measure.

2.2 Mitigation

Mitigation activities characterize a power system's capabilities to resist a threat or to absorb the consequences from a specific given hazard. Mitigation takes place as the system first encounters a specific threat and is characterized by the properties of the system as designed and any activities it engages in as the threat is manifest. Mitigation attempts to maintain system performance at a level that is indistinguishable from that seen prior to the onset of the deleterious event. That is, when a threat is fully mitigated, the system will not report faults or failures, and there will be no loss of service. This does not necessarily mean that the state of the system is unaltered, only that the system is able to continue to perform its intended function. For example, a fault in a particular piece of distribution system equipment may be mitigated by reconfiguring several circuits, thus bypassing the fault. This new configuration may not be optimal (i.e., it forces operation closer to the specified limits of certain equipment, has a lower level of protection, etc.) but does allow the system to continue to operate and maintain service.

Mitigation occurs only during the event, and as a result, short-duration events will be managed entirely by existing autonomous systems. Thus, the success of Mitigation will often be the result of activities taken during the Preparation phase when remedial actions were designed and implemented. A well-designed system that is fault-tolerant, self-repairing, and with built-in intelligence will exhibit the ability to mitigate threats by design. An analogy commonly used to describe system behavior during a deleterious event is that of a toothpick, bending until all its flexibility has been expended. Comprehensive mitigation implies the toothpick does not break, but is able to return to its pre-event state (shape) once the threat has been removed.

Mitigation is not necessarily comprehensive; it is possible for a system to mostly or partially mitigate a threat but experience some degree of degradation or loss of service. For example, traditional distribution system protection schemes make use of fuses. These devices are a mitigation measure as they limit short-circuits in one area of the system from causing significant damage over a much broader area (or to more expensive equipment). When a fuse blows, the threat has been largely mitigated with a relatively small number of customers experiencing loss of service; this is the unmitigated portion of the threat and must be addressed by activity in the Response (see Section 2.3) or Recovery (see Section 2.4) phases.

The Mitigation phase ends when the threat has ended. This does not necessarily mean that failures in the system stop occurring only that the inciting event has ceased to be a threat; mitigation always occurs relative to a specific threat.

2.3 Response

Response capabilities are a function of immediate and ongoing activities, tasks, programs, and systems that have been undertaken or developed to respond and adapt to the adverse effects of a deleterious event. Response focuses on containing and limiting the fallout from the threat experienced by the system during the Mitigation phase. In some cases, little to no Response activities are needed as the damage to the system stops immediately upon the removal of the threat (e.g., damage from a destructive localized storm such as a tornado). In other cases, even if the threat has been removed, the consequences of it not being fully mitigated continue to ripple through the system causing a cascade of failures. Depending on the scope of the threat and its duration, the Response to the threat may be entirely autonomous activities that were designed and implemented during the Preparation phase. In other cases, any cascading failures occurring may proceed at a rate slow enough to allow and/or require human intervention; the choices made would likely also be impacted by discussions held and decisions made during the Preparation phase.

Continuing with the toothpick analogy introduced in Section 2.2, Response takes place once the toothpick has been pushed beyond its ability to flex and begins to crack. It could be that the nature of the damage caused by the threat and/or the system design is such that even after the threat is removed (force on the toothpick), the toothpick continues to break. In these cases, those managing the system respond by adjusting system controls and dispatching crews as necessary to prevent the bad situation from getting worse.

The nature of the activities that take place in Mitigation (see Section 2.2), Response and Recovery (see Section 2.4) can be very similar, particularly for longer-duration events (e.g., during and after a hurricane). In these cases, repairs to the system begin even while the threat exists and thus would be considered Mitigation efforts. Such activities would continue once the storm had passed and would thus be classified as Response efforts as system operators seek to halt the spread of failures due to the threat. As system operators and repair crews continue working, their activities would be considered Recovery efforts. The activities of those operating and repairing the power system may be virtually identical in all three phases

2.4 Recovery

Recovery mechanisms constitute activities and programs designed to efficiently and rapidly return a given asset to an acceptable operational level. Recovery can be considered to begin when the power system has reached its lowest level of service/performance and begins to return to its pre-event state. Decisions made during this period typically have a fuller understanding of the state of the system and without the additional stress on the system of the inciting threat.

Recovery actions are subdivided into two components:

- Onsite capabilities capturing the ability of an asset to respond to an accident without needing immediate support from external first responders. If an asset can use onsite or internal resources to effectively sustain or handle stresses caused by a given event, the asset has adequately recovered from the hazard and will not need to leverage offsite capabilities.
- Offsite capabilities or activities characterize external interactions with the emergency services sector to recover from an event (e.g., power substation fire) and support the asset within its boundaries. Offsite capabilities can take various forms, including existing memoranda of understanding that link the asset to external emergency management systems.

Restoration agreements govern existing memoranda of understanding with entities other than emergency responders as well as procedures or equipment supporting asset restoration. A common example of a restoration agreement involves protocols an electric utility has established for working with contractors to restore service following a broad-scale outage. Recovery time characterizes the temporal requirements for an asset to resume full operations following significant component loss. Depending on the severity of a given event, a system may not always be able to return to its pre-event operational profile. In these instances, recovery concludes when an asset reaches a “new normal” state determined adequate by relevant stakeholders.

Recovery activities reflect the ability of a system to overcome a deleterious event and eventually returning to the pre-event level of service or some newly established “new normal.” The timescale of a specific deleterious event is generally independent of the resilience recovery impacts associated with the given event. Catastrophic earthquakes and hurricanes strike regions over the course of minutes or hours, respectively. However, recovery operations are generally measured in months or years. The adaptive capacity of the power grid reflects the ability of the system to continue service at a reduced level following a successful attack or hazardous event. The adaptive system provides a level of service deemed acceptable by stakeholders operating within the damaged environment a certain period out from the given event. In certain instances, the level of damage sustained at the system level is too great to allow a “full” recovery (Coles et al. 2011). Instead of assuming an infinite phased resilience time horizon, the period of recovery concludes when the level of service satisfies the long-term demand profile, which too may be diminished for the foreseeable future. Initially an academic exercise, the last decade has illustrated several cases where a “new normal” appears to have been established following an extended recovery phase. In the instance of the Fukushima Daiichi disaster, curtailment of the traditional reliance on nuclear power in Japan has resulted in brownouts and the population’s tolerance of limited availability of air conditioning during the summer to reduce peak demand (Duffield 2016).

In many of these real-world examples, the question remains whether an extended recovery phase continues or a new, reduced long-term state has been reached. Puerto Rico following Hurricane Maria in 2017 constitutes a recent illustration of this recovery ambiguity. The loss of power in Puerto Rico that occurred after Hurricane Maria devastated the Commonwealth in September 2017 and constitutes the biggest blackout in U.S. history in terms of customer-hours of lost electricity service. Seven months after Maria struck the island with winds that exceeded 150 miles per hour, electricity had been restored to 96% of customers and restored load was approximately 89% of pre-storm, peak load conditions (DOE 2018) (Figure 2). However, these Commonwealth-wide statistics belie the last-mile problem that has prevented roughly 20% of residents in the mountainous eastern region of Caguas from regaining grid connectivity (Task Force Power Restoration (Puerto Rico) Public Affairs 2018). In the longer run, a new system state may well develop in which different power configurations (e.g., off-grid renewables) are pursued to “island” these remote communities from the larger power grid managed by the Puerto Rico Electric Power Authority. Such new system alternatives may not offer equivalent performance as the pre-

Maria grid solution but, given future resource constraints, may be the most sustainable, viable path forward.

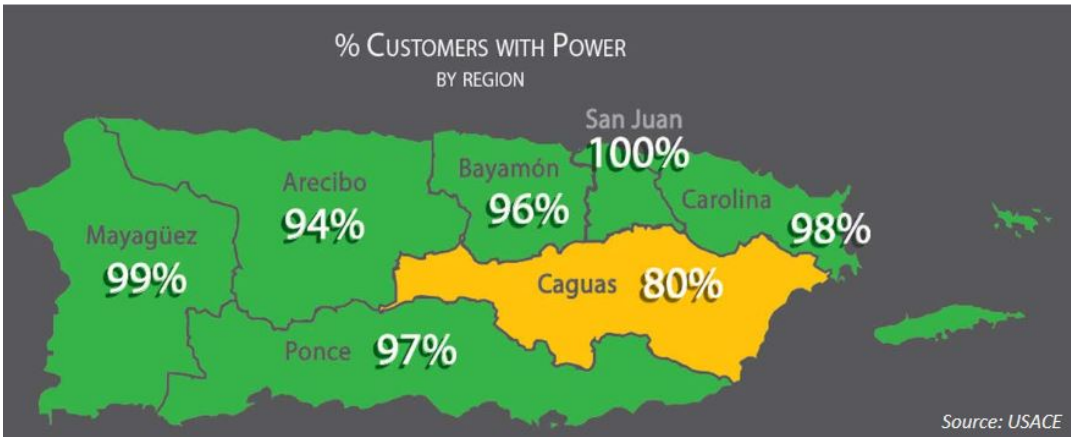

Figure 2. Percentage of Customers with Power by Puerto Rico Region as of April 2018

2.5 Linking Four Phases of Resilience

The four phases of resilience as described above are not autonomous but interrelated. A risk-informed assessment of resilience as illustrated within the deleterious event service loss diagram in Figure 3 underscores these phase linkages when considering pre-event, event, and post-event activities and behaviors.

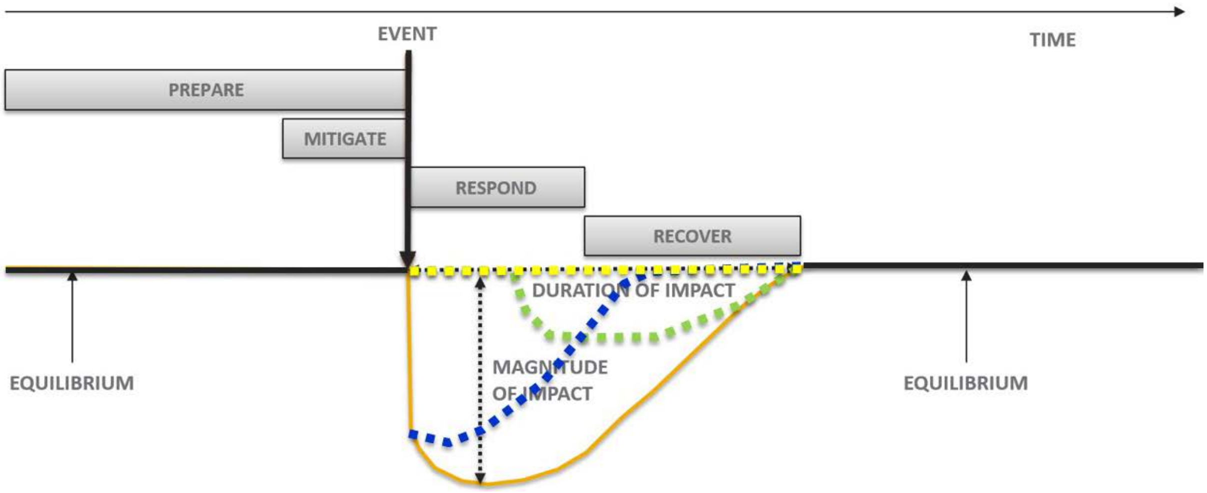

Figure 3. Components of Resilience and Timing of Adverse Events

As can be seen, the four phases are modeled as sequential in nature, though there is some degree of interaction (as previously discussed). This being said, there are many types of events that blur the transition points between the phases and introduce overlap between them. For example, a small, short-duration event such as a vegetation-induced fault may have a protection system designed and installed (Preparation) that included a blown fuse during the fault (Mitigation). The system was fully degraded when the fuse blew so there is essentially no Response phase, and Recovery takes place when a crew arrives to replace the fuse.

A counter-example would be that of a hurricane. Especially for hurricane-prone regions, significant planning takes place to adequately Prepare for the storm; some of this Preparation, such as clearing vegetation or strategically positioning work crews, may take place days before the storm hits. As the hurricane begins to impact the area in question, various faults begin to occur throughout the system; some of these faults are mostly Mitigated while others spread failures more extensively before being contained. Even before the storm ends and the damage fully incurred, Response may begin to take place with crews being deployed to make repairs. For areas on the edge of the storm, these limited repairs may be all that is needed to fully Recover. In this case, because of the long duration and wide geographic area of impact of the event, the Mitigation, Response, and Recovery phases take place simultaneously at various points in the affected system.

In addition to providing a temporal relationship linking the Preparedness, Mitigation, Response, and Recovery phases, the lines transecting the response and recovery phases in Figure 3 illustrate the adaptability of a system to a deleterious event. Such adaptability "curves" (Coles et al. 2011), which are defined below, may form the basis for metric(s) that holistically chart the overall resilience of a given system:

- *Resistance (yellow dotted line, ▪▪▪▪▪▪)* – Reflects the ability of the system to retain its service, to completely fend off the effects of a successful attack or a hazardous event so that although some system damage may occur, the system does not experience a loss of service.
- *Absorptive capacity (green dotted line,* ▪▪▪▪▪▪) – Reflects the ability of the system to mitigate the effects of a successful attack or a hazardous event by implementing contingency activities that restore all or part of the lost service. In the absorptive mode, the system is providing its service at an effective level and remains in this mode until it returns to full service.
- *Adaptive capacity (blue dotted line, ▪▪▪▪▪▪)* – Reflects the ability of the system to continue to provide service at a reduced level following a successful attack or hazardous event. In the adaptive mode, the system is providing an effective level of service and remains in this mode until it returns to full service.
- *Recoverability (orange solid line, ——)* – Reflects the ability of the system to return to full service, within an acceptable time interval. In the recovery mode, the system is not providing service at an effective level and remains in this mode until it returns to full service.

3.0 The Context of Reliability within the Resilience Model

This section examines reliability and its contextual placement within the phased resilience model. Reliability and resilience are both relevant concepts in relation to the power grid. Magnitude and duration impact both reliability and resilience but are not easily quantifiable in all cases. Reliability, with its focus on “keeping the lights on,” can be described as the end goal of the power grid.

3.1 What is Reliability?

Reliability is the probability that an item can perform its intended function for a specified interval under stated conditions (IEC 60050-192, 2015). Thus, reliability is forward-looking and probabilistic in nature. In most industries and for most assets, it is expressed in terms of metrics, such as mean time between failures. However, for the electrical grid, it is often applied retrospectively in the determination of grid reliability as a measure of “unavailability.”

Within the power systems arena, the concept, metrics, and applications of reliability constitute a relatively mature body of knowledge. The North American Electric Reliability Corporation uses seven principles that define the foundation of reliability for North American bulk electric systems (NERC 2018). Existing reliability metrics include:

- *System Average Interruption Frequency Index* – The average frequency of sustained interruptions per customer over a predefined area
- *Customer Average Interruption Duration Index* – The average time required to restore service to the average customer per sustained interruption
- *Momentary Average Interruption Frequency Index* – The average frequency of momentary interruptions.

These metrics seek to quantify impacts on relevant populations from a continuity-of-service perspective and are well defined in IEEE 1366.

As will be discussed in greater detail within Section 3.2, a working inference as to why reliability metric identification and quantification has, to date, been a more straightforward undertaking concerns the alignment of reliability within the larger resilience context. Reliability actually comprises the temporal components of resilience that exist during and immediately after the occurrence of a deleterious event. Hence, the frequencies and durations of such events tend to sufficiently characterize reliability considerations. Within the phased resilience framework described within Section 2.0, once an outage has occurred, it is not only a resilience event but also a reliability event. From an academic perspective it is logical that an outage may be considered both a reliability event and a resilience event. However, from a reporting and regulatory perspective, resilience and reliability have traditionally been considered separately (Larson 2015). This is significant as a low-frequency, high-impact event (e.g., major hurricane) may be considered a resilience event but not a reliability event. *This report treats all outages as resilience events including those that from a regulatory and investment perspective, would be considered reliability events.*

Interestingly, although reliability excludes major events for the purpose of metrics reporting, the Energy Information Administration collects System Average Interruption Duration Index and System Average Interruption Frequency Index figures that both include and exclude major events on its form EIA-861 as part of the Electricity and Renewable Power Surveys (Office of Management and Budget Control Number 1905-0129) information collection. Resilience is not mentioned anywhere in the form because no consensus on corresponding resilience measurement exists. While reliability is treated as a simple quantification of the lack of availability of a grid asset or a system, resilience includes the use of people, processes, and technology and is harder to quantify, especially before an event when deciding upon the appropriate level of preparation and/or mitigation necessary.

Recognizing differences in theoretical and practical applications of reliability and resilience is critical. Reliability and resilience are both measures of risk and carry inherent uncertainties[2] and have bearing on the objective of providing highly reliable electricity with minimized interruption duration and frequency. Both reliability and resilience are used to justify grid investments. While reliability falls within the resilience model proposed in this report, it is important that reliability and resilience be defined and measured separately for cost/benefit reasons. From a regulatory perspective, resilience is the robustness and recovery characteristics of utility infrastructure and operations, which avoid or minimize interruptions of service during an extraordinary and hazardous event (NARUC 2013). Reliability is generally used as a measure of system availability during blue-sky conditions (i.e., does not include extraordinary and hazardous events). The National Association of Regulatory Utility Commissioners argues that considering resilience as an aspect of reliability enables consideration of large-scale events and non-traditional hazards that were previously excluded. In contrast, this report considers reliability an aspect of (and favorable reliability metric values a product of) resilience but also proposes inclusion of all events (i.e., blue-sky and non-traditional hazards) when measuring resilience.

3.2 Reliability within the Resilience Model

Utilities are required to provide electricity within acceptable levels of unavailability during blue-sky deleterious events. Such events include equipment failures and environmental factors related to wildlife and vegetation. When deleterious events that do produce outages occur, their impacts can be measured and used to calculate annual, utility-wide reliability metrics scores. IEEE 1366 defines metrics for calculating the frequency of momentary and sustained outages, the duration of sustained outages, impacts to customers, etc. Because an outage reflects the impact of an event during the Response and Recovery phases, the reliability metrics in IEEE 1366 could be used to contribute to the calculation of resilience metric(s) within those two phases. Figure 4 provides a graphical representation of reliability's contextual placement within the broader resilience phase framework.

Figure 4. The Position of Reliability within the Resilience Phase Model

Leveraging agreed upon reliability metrics to define corresponding resilience metric(s) and applying said metrics are entirely different in nature. Utilities exclude large-scale deleterious events from reliability calculations as these extreme, black-sky events would completely overwhelm the utilities blue-sky reliability performance. Nevertheless, these excluded events are what many people consider when

[2] Risk (ISO 31000) is the impact of uncertainty on objectives

discussing resilience. It is not that IEEE 1366 cannot be applied to these excluded events, it is simply not industry practice (tacitly or otherwise approved by utility commissions) when calculating reliability metric values. Thus, the definition of a metric and how it is applied are different.

The above rationale suggests reliability and its associated metrics can be applied to better delineate select phases within the broader resilience purview. However, a clear gap exists in terms of technical thresholds at which each stage leads into the next stage. While each phase is distinct, it is likely each phase will differ for each resilience event experienced, although of similar magnitude and consequence. While real events can help us understand distinctiveness, simulation can be of greater use in generating a variety of test-case scenarios.

4.0 Role of Transactive Energy in Aiding Resilience

4.1 Power Grid Resilience through Transactive Systems

Previous sections have described a framework for resilience by breaking the topic into four phases. These phases are different in nature and how transactive energy systems impact resilience in each phase will vary. The grid is an ultra large-scale system of systems but it is still a system. How that system behaves in each phase can be used to characterizes its resilience. If, generally speaking, transactive energy systems exhibit resilient qualities, then it is possible to examine how transactive energy systems can help improve resilience. That is, if transactive systems are resilient by nature then adding transactive systems to the power system will alter the systems response to deleterious events in one or more phases of resilience and improve the resilience characteristics of the power system.

This section discusses the role of transactive systems in facilitating resilience. Transactive energy has the potential to further enhance power grid resilience for select events. In a situation during which supply is limited and cannot support all the load on a feeder, a transactive system could theoretically provide limits to the amount of load available to be traded based on operational characteristics. This would increase the price of power but could allow the feeder to maintain power to customers under a low-power condition. Clearly this provides resilience following the loss of a small generator. Without a transactive system in place the utility might have to open a substation breaker, which would result in a reliability event because opening the breaker would cause an outage for the customers on the line and for the line itself. Resilient abilities that could benefit from transactive systems and are elaborated in this section include: respond, monitor, learn, and anticipate activities.

Hollnagel describes a system as being resilient if it can adjust its functioning prior to, during, or following events (“changes,” “disturbances,” and “opportunities”), and thereby sustain required operations under both expected and unexpected conditions. The capabilities of systems to take these actions are determined by their characteristics; that is, their ability to perform specific actions. The adjustment that Hollnagel describes reflects the inherent ability of resilient systems to absorb changes and adapt to them. By examining the characteristics of resilient systems, how they can be applied to each phase of resilience, and the characteristics of transactive energy systems, it is possible to describe scenarios in which transactive energy systems may improve resilience and compare the operation with non-transactive systems.

Transactive energy refers to the use of a combination of economic and control techniques to improve grid reliability and efficiency. Transactive energy thus involves not only economic aspects, but also the operational reliability and related control objectives and technology within the electric power infrastructure. The GridWise Architecture Council (GWAC) (TEF 2015) believes that both elements must be considered to move forward with the practical development and application of transactive energy. Further, GWAC states that the scope of the conceptual architecture for transactive systems must address resilience and anti-fragility (TEF 4.3.2). Fundamentally, transactive energy systems provide flexibility to power system planners and operators and this flexibility can be leveraged to aid in improving power system resilience.

To examine the potential resilience benefits of transactive systems it is necessary to look at not only how these systems behave in each phase of resilience but to assess the qualities they offer that can improve resilience. There are qualities of the power system that by their nature improve the resilience of the system and these qualities may be provided by transactive or non-transactive systems. These qualities (and others as well) also can be encompassed by scenarios that describe resilient performance within a single phase of resilience or which span multiple phases.

Hollnagel describes four interdependent resilient capabilities ("potentials") for the behavior of resilient systems. (These four characteristics are not directly related to the four phases of resilience response.) This approach lends itself to measuring performance in general as opposed to focusing on actions within a specific phase. These capabilities are:

- *The ability to* ***respond***. Knowing what to do or being able to respond to regular and irregular changes, disturbances, and opportunities by activating prepared actions or by adjusting the current mode of functioning.
- *The ability to* ***monitor***. Knowing what to look for or being able to monitor that which is or could seriously affect system performance, either positively or negatively, in the near term. Monitoring must cover the performance of the system and what happens in the environment. For the grid, this means monitoring the performance of both the cyber network and the physical network.
- *The ability to* ***learn***. Knowing what has happened, or being able to learn from experience, especially to learn the right lessons from the right experience.
- *The ability to* ***anticipate***. Knowing what to expect or being able to anticipate developments further into the future, such as possible disruptions, novel demands or constraints, new opportunities, or changing operating conditions.

Hollnagel's capabilities describe the capabilities required of a resilient system irrespective of the resilience phase. These capabilities can be compared to the properties of transactive systems. The capabilities described by Hollnagel reflect intelligence in the system. Intelligent systems can learn, anticipate, and respond as long as they have the information required, which is provided by monitoring. Transactive systems are distributed systems with distributed intelligence that require knowledge of the system to operate. Thus transactive systems are inherently well suited to improving resilience.

The GridWise Architecture Council (GWAC 2015) defined a set of six high-level principles that apply to transactive systems and that are statements of high-level requirements for such systems. Two of the principles relate specifically to market-based capabilities, but four of the principles describe desirable operational characteristics that can be applied to resilience:

- "Transactive energy systems implement some form of highly coordinated self-optimization."
- "Transactive energy systems should maintain system reliability and control while enabling optimal integration of renewable and distributed energy resources."
- "Transactive energy systems should be observable and auditable at interfaces."
- "Transactive energy systems should be scalable, adaptable, and extensible across a number of devices, participants, and geographic extents."

These four characteristics can be mapped to Hollnagel's capabilities as shown in Table 1 with 1 representing a high degree of fit and 2 representing a weaker fit.

Table 2. Resilient Characteristics of Transactive Systems

GWAC Principles	Respond	Monitor	Learn	Anticipate
Highly coordinated self-optimization	1	1	1	2
System reliability and control	1*	2	2	1
Scalable, adaptable, and extensible	1	2	1	1
Observable and auditable	2	1	1	2

The admittedly subjective scores in the cells of Table 2 show that there is good reason to believe that the desirable characteristics of a resilient system can be created or enhanced by widespread implementation of transactive systems. For example, the inherent scalability and extensibility of a transactive system allows to it to respond well to deleterious events by having the existing infrastructure, protocols, and control systems in place to respond to dramatic changes in load or generation.

Each cell in the table could be also represented by a scenario that could be used to describe a resilience event. For example, the cell with the asterisk in Table 2 might be represented by a scenario in which total generation resources are inadequate, the peak demand may exceed available resources and planned and unplanned demand curtailments ensue until system stability is re-established. In this example, transactive systems might play a direct role in planning, but it is more likely that a transactive system would inform the need (or value) for building new generation or further engaging more responsive demand. The ability to assess the performance of transactive and non-transactive systems for this scenario could be simulated and compared. For each scenario the uncertainties can be listed, and their impacts quantified.

By creating multiple scenarios for each cell in Table 2, it becomes possible to evaluate scenarios that exist within one or multiple resilience phases and define appropriate performance metrics that are intended to indicate the resilience of the system. An example of such a matrix is provided in Table 3. This matrix could be completed and a limited number of scenarios evaluated to compare the impacts of transactive versus non-transactive systems. Thus, the performance of transactive and non-transactive systems can be compared. Generalizations about the benefits of the contributions of transactive systems to resilience may be made where the number of scenarios overall spans all resilience phases and examples of representative threats and consequences.

Table 3. Resilience Scenarios to Explore with Transactive Systems

GWAC Principles	Respond	Monitor	Learn	Anticipate
Highly coordinated self-optimization	Malicious cyber event	Available transmission is inadequate	Transmission conductor or transformer failure event	
System reliability and control	Total available generation resources are inadequate			Solar intermittency—diurnal pattern
Scalable, adaptable, and extensible	Wind intermittency event		Distribution conductor adequacy	Solar intermittency—cloud event
Observable and auditable		Communication delay	Generation resource outage contingency event	

4.2 Challenges for a Transactive System as a Resilience-Improvement Mechanism

Although it is clear from Section 4.1 that there is a mutually beneficial fit between the flexibility, scalability, and coordination that transactive systems provide and the resilience needs of a power system during deleterious events, there are key challenges for measuring how transactive systems function in this role. Because there are no generally accepted metrics for measuring resilience, it is necessary to examine how transactive energy systems function in each of the four phases of resilience and how the characteristics of transactive systems relate to the characteristics of resilient systems.

In the preparedness phase, the system is running normally, and the system should be preparing for potential disruptions. By establishing transactive systems and implementing them under normal system conditions, the strengths and weaknesses may be identified and resolved. Examining how transactive systems adapt to include flexible resources in local balancing provides the ability to plan how they might behave and contribute to continued operation under stressed conditions.

In the mitigation phase, stressors for impending potential events may be detected and acted upon. This involves the system resisting and absorbing the stain until, if unsuccessful, the stress increases to a level at which disruption occurs. Because transactive systems are a hybrid blend of economic and control mechanisms, they need to monitor the system and may offer the capability to react to stress by adjusting inventive mechanisms to reflect new control priorities and incent behavior from flexible devices to adjust to and mitigate the threat.

In the response phase, an event that resulted in a negative impact on the system has occurred. During this phase, the system responds to the immediate and cascading impacts of the event but the situation is dynamic and new impacts are being felt. Because potential threats differ in nature, this phase may last from seconds to hours. During this phase, the system is in a state of flux because fixes are being made while new impacts are felt. This stage is largely reactionary (even if using prepared actions), but the system must be able to adapt continuously to changes as they occur. Transactive systems may be significantly beneficial during this phase if local loads and generation can be incented to create balance. Pockets of balanced energy can provide a strong foundation for recovery.

In the recovery phase, the state of flux is over and the system is stabilized but uncorrected impacts endure and operation is at potentially low functionality. In the recovery phase, enough is known about the current and desired (normal) states to create and initiate a plan to restore normal operations. Although less dynamic than the response phase, the recovery phase potentially includes many changes that occur over possibly significant (log) timescales.

Clearly the characteristics of each phase of resilience are different. This creates challenges for developing of a way to measure resilience. Hollnagel's characteristics provide a basis for measurement. If the ability of a transactive system to monitor, respond, learn, and anticipate can be measured, quantifying resilience is possible. The value of each of these characteristics may vary from phase to phase, and the grid characteristics that enable these measurements may also vary. Thus, the development of metrics will likely be conceptually similar from phases to phase but will differ in how they are actually calculated.

5.0 Proposed Resilience Metric Development

5.1 Risk Metric as a Resilience Metric

Metrics form the basis of valuation; they are the specific quantified assessments of system performance in the dimensions or characteristics of interest. To improve the resilience of a system, there must be a method of quantifying resilience performance of a power system, and unlike reliability metrics, it is highly preferable that this quantification be possible prior to the event. Measuring the resilience performance of a power system after recovery is complete is much less useful than a resilience assessment that estimates the values of the appropriate metrics prior to the event.

Generic resilience metrics available in the literature are described in Appendix A. These metrics are generic in the sense that they are applicable to both traditional and transactive systems. A valuation analyst must perform a mapping between such generic metrics and power system metrics. Such generic metrics would address issues of sustainability, adaptability, and flexibility (Roege 2014). These metrics may or may not be specific enough to the deleterious events a given power system may experience to provide that meaningful a priori estimate.

A single metric that transcends all resilience phases may be helpful in relative understanding of readiness or effectiveness with respect to each phase, but it also must be general by nature and thus more abstract. Metrics built around specific scenarios offer another approach and avoid the problems of abstraction.

Alternatively, we propose the definition of a scenario-based risk metric to more comprehensively and universally provide a measure of a given systems performance in response to a set of deleterious events. A set or collection of standardized scenarios could be defined and assembled that would support the analysis and quantitative assessment of the performance of a given system prior to the onset of any given deleterious event. The total or composite resilience score would be an aggregation of the scenario-specific scores based on scenario-specific metrics, which are not necessarily uniform across scenarios (e.g., a flood scenario may have different key metrics than a tornado) although some of them may be similar. For example, the traditional reliability metrics (System Average Interruption Duration Index, System Average Interruption Frequency Index, etc.) offer good general assessments of how well the power system was able to meet its primary mission of serving load and potentially could be estimated as part of the analysis.

Scenario-based resilience scoring offers several advantages. First, it allows a given utility and/or utility commission to identify the scenarios they deem most pertinent or applicable to their power system. This customization allows for utilities to focus on their most pressing concerns while not putting unnecessary effort into evaluating and planning for deleterious events that are unlikely to occur (e.g., a tsunami in Kansas).

Relatedly, standardized scenarios require the utility in question to customize or realize the specifics of the scenario in a meaningful way. If the scenario calls for the loss of 10% of overhead assets, it would be the responsibility of those executing the analysis to determine which 10% are affected. This is necessary as no standardized scenario could define in a generic way which specific assets would be lost, and it relies on the integrity of the analyst to determine in a fair and realistic manner which assets to remove from operation. Such flexibility also provides the opportunity for manipulation and unrealistic interpretation of the scenarios on the part of the analyst and may require the intervention of a third party to perform or validate the analysis.

Given the broad nature of the assessment of the response to a deleterious event, the analysis of events would almost certainly extend beyond the domain of traditional power system operation simulators and tools. Damage estimation from the deleterious event would need to be made in some manner, and logistics and planning simulators would likely be necessary to estimate repair times and equipment needed. Communication system simulators would be needed for evaluating systems with and without transactive systems.

5.2 Risk Metric Definition

Resilience is better understood in the context of risk when supported by a risk metric. Risk to the power grid owing to a deleterious event can be expressed as a triad of 1) the scenario during a resilience event, 2) the probability of the scenario happening, and 3) the consequence of the occurrence (Veeramany et al. 2016; Kaplan and Garrick 1981). The consequence is quantified as the product of magnitude and duration of the event. When put in perspective, risk is the product of these measureable quantities for the given scenario. A potential risk metric, then, is measured in terms of energy unserved in megawatt-hours, and when further extended, it can become an economic risk metric (Veeramany et al. 2018). An example scenario is a 120% increase in demand in excess of available margins on a peak load day. The probability of this scenario happening (anticipation) can be obtained from a combination of weather records (monitoring), forecast algorithms, and engineering judgment (learning).

The value of resilience is in the ability to reduce risk over a baseline, where baseline risk refers to resilience offered in the absence of transactive systems. The implementation and quantification of transactive services can have profound impacts on power system resilience when measured using a risk metric. While the probability of occurrence of a causal scenario (e.g., peak heat day) does not change due to transactive services, the magnitude and duration of the event can be influenced. For example, if successful deployment of a demand-response program can reduce duration of an abnormal event by half, then the resulting risk is halved, denoting an increase in resilience.

A risk-informed approach to resource allocation often warrants the use of probabilities and estimation of consequences, and the availability of probabilities depends on the maturity of domain models under consideration (Veeramany 2017, 2016). Estimation of probabilities for certain high-impact, low frequency type events such as Carrington type geomagnetic storm events (NAS 2017) and electromagnetic pulse attacks is challenging. Where the maturity is high (e.g., seismicity), models can use high-resolution information.

Furthermore, uncertainties associated with these probabilities challenge decision-making process because of inherent randomness (variability), lack of knowledge or data insufficiency in the input variables, or the modeling process (Veeramany et al., 2017, 2018). Uncertainties in these variables and the model propagate through the modeling process resulting in uncertainty in the estimated metric for the purposes of valuation. Uncertainties associated with probabilities and model parameters should be characterized and treated as part of risk management and should not be avoided. For example, the quantity by which to increase capacity depends on a how the growth in demand of the system is modeled. This growth model may have uncertain inputs like growth rate, demand forecast, and a planning horizon. Specific scenarios as described in Section 4.1 not only provide natural boundaries for measurement but also help focus the identification of relevant uncertainties, thus a scenario-based approach to resilience measurement appears to have merit.

5.3 Risk Metric Development Process

An outline of the steps involved in calculating the risk metric as a part of the valuation of a system in the resilience context is provided in this section. These steps fit nicely into the valuation framework first proposed Hammerstrom et al. (2016), providing a natural extension into this suite of scenarios, each of which is evaluated as a single instance of valuation experiment.

The flowchart in Figure 5 shows the process by which the risk metric is calculated. Starting in the upper left, various scenarios are defined, and for each scenario, estimates are made (through some form of analysis) of the likelihood of the event and the consequence or impact of the event (as defined by the duration and magnitude of the consequences) if it were to occur. The analysis of the consequences is made with the base (or business-as-usual) case as well as with the implementation of a test case (such as a transactive system). This allows for a clear comparison between the two strategies and an estimate of the difference in performance. The remainder of this section defines the process in detail.

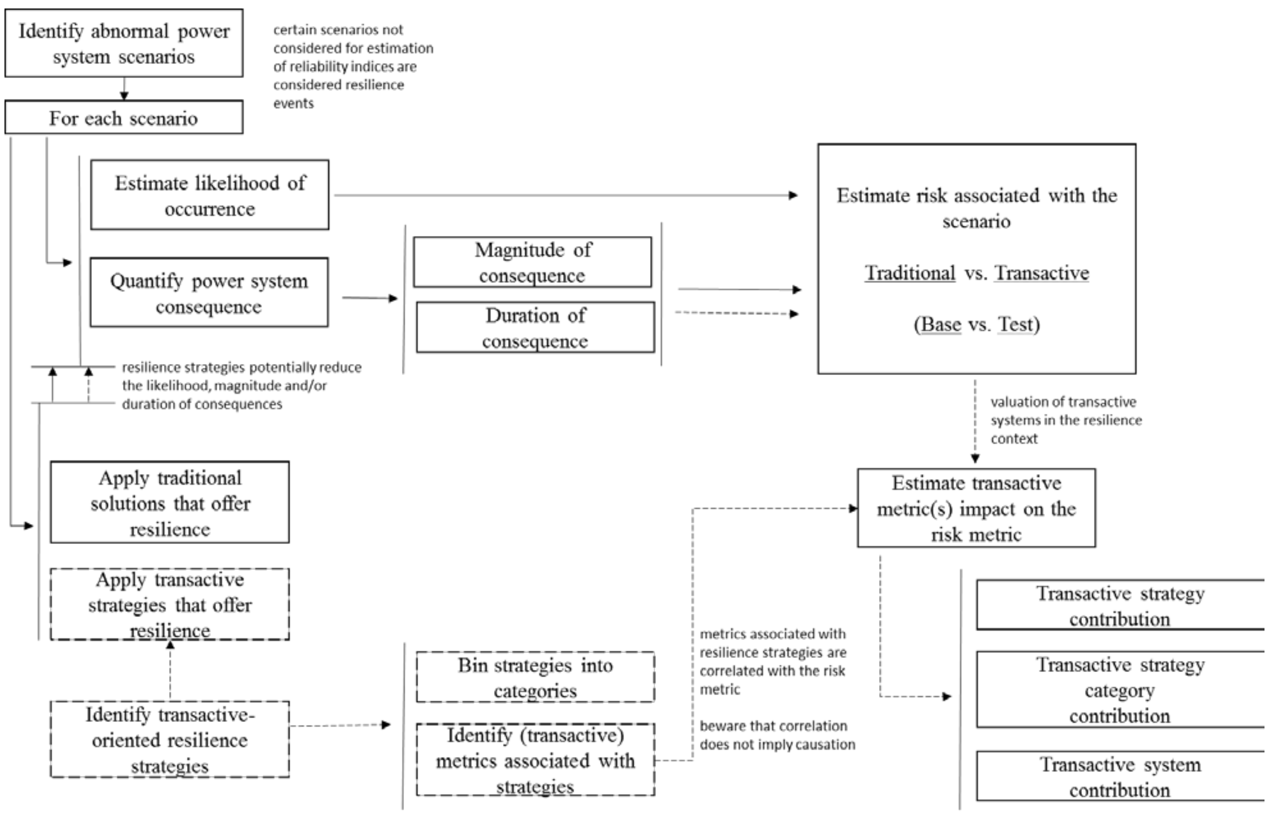

Figure 5. Measurement of Resilience in the Valuation of Transactive Systems

1. Identify abnormal power system scenarios

There exist certain classes of abnormal power system scenarios generally documented by utilities but not considered for estimating reliability metrics. A list of these scenarios should be identified and vetted for resilience consideration and are termed as “resilience events”. Although a comprehensive list can be generated, it is possible to build sets of scenarios that are sufficient to serve as a starting point in evaluating resilience of the utility. Each scenario would define a sequence of events with an initial triggering event called an “initiating event” or “initiator” and then followed by subsequent cascading events. An example is the Self-Generation Incentive Program-1 scenario in which the grid is severely strained by hot weather occurring over an extended period and leading to curtailment of services (Holmberg 2016). Note that initiator likelihoods may not be influenced in all cases, especially when they deal with natural events. However, the likelihood of events occurring in response to the initiator (e.g., cascading events) can be moderated through the deployment of mitigating mechanisms (e.g., special protection systems or remedial action schemes described by Samaan et al. [2015]).

2. Estimate likelihood of occurrence for each scenario

The likelihood of some initiators in some scenarios can be inferred from actuarial data (damage from hurricanes, flooding, tornados, etc.) while others have little to no such data available (e.g., a terrorist or cyber-attack). As an alternative, the likelihood of events can be graded qualitatively as “unlikely,” “extremely rare,” “rare,” “likely,”or “certain,” A correspondence can be drawn in terms of frequencies such as “once in fifty years” or “once a year.” Manmade threat events must be considered imminent unless a detailed analysis of threat factors is warranted. These include the value of the target, motivation of the adversary, and their access to sophisticated tools.

3. Quantify power system consequences

Occurrence of a deleterious event can potentially lead to a disruption of power grid service. The consequences of this disruption will depend on the systems (including transactive systems) in place to manage the event. Consequence quantification often warrants the need for one or more simulation tools to capture the after effects of the event. In the absence of such tools, analytical methods and expert judgment are used to grade the consequences (e.g., high, medium, and low). Resilience strategies are able to alleviate the magnitude and duration of consequences due to disruptions. These strategies are captured in Steps 4 and 5.

4. Apply traditional (base case) solutions that offer resilience

Curtailment, demand-response in the non-transactive context, and other relevant traditional strategies to reduce the likelihood, magnitude and/or duration of resilience events are identified. The impact of applying these strategies are reflected in consequence outcomes described in Step 3. In some cases, these traditional activities may be directly incorporated into the analysis taking place in Step 3 and consequentially removed when implementing the analysis for the transactive system.

5. Identify transactive strategies

For a given deleterious event, not all types of transactive systems or transactive system designs may apply. Nevertheless, a comprehensive list of transactive strategies would be documented in this step so that specific features could be invoked for a given deleterious event as described in Step 6.

6. Apply transactive (test case) strategies that offer resilience

Beneficial transactive system features identified from Step 5, such as market-based pricing, managed distributed energy resources, and fully engaged demand-side loads, are implemented in the test system and an analysis is conducted. The impact of applying these strategies will be reflected in consequence outcomes described in Step 3. Note that a single strategy is not likely to be adequate for all phases of resilience. Pre-event strategies (Preparedness) can reduce likelihood of occurrence of some deleterious events. When cascading events occur, invocation of protective steps during the Mitigation phase can reduce the relative severity of what would be high-consequence scenarios. Effective Response (ad hoc rapid action) and Recovery strategies (long-term) can also reduce the severity of consequences.

7. Bin strategies into categories (optional)

Transactive strategies identified in Step 5 are categorized in this step. Categorization lends itself to attribution of resilience benefits to a bin of related strategies. In the absence of this categorization, benefits leveraged from transactive strategies are directly attributed to the list populated in Step 5.

8. Identify metrics associated with strategies

A detailed description of transactive-oriented resilience strategies identified in Step 5 helps in identifying associated metrics for each respective strategy. In this step, a list of these metrics is tabulated whose quantification supports correlation with the risk metric to be estimated in Step 9. While the objective of the base and test cases is to achieve resilience, the mechanisms used to achieve this objective can be quite different; hence, the metrics associated with these mechanisms are anticipated to be different.

9. Estimate risk associated with the scenario

Risk in this context is measured as the product of likelihood, and magnitude and duration of event of interest. An increase in resilience is measured by the relative decrease in the risk metric in the presence and absence of transactive system. The individual scenario risks can then be aggregated across a collection of scenarios to form a total composite risk metric. As new scenarios are identified, they can be added to the collection, and the risk metric can be updated.

10. Estimate transactive metrics impact on risk metric

Transactive metrics associated with a resilience strategy identified in Step 8 are correlated with the risk metric estimated in Step 9. This relation is many-to-one; that is, a set of transactive metrics has a directional (increase/decrease) impact on risk. The effort required to achieve the desired level of risk as reflected by the correlation between these metrics amounts to the contribution of transactive systems in the resilience context. The value is further attributable to strategies applied in Step 6, the binned categories identified in Step 7, and the entire transactive system across a wide variety of scenarios. It should be noted that correlation does not always imply causation. Careful engineering judgment is recommended.

6.0 Conclusions and Future Work

Given the broad range of deleterious events that impact the resilience performance of the system and the competing definitions of and frameworks for the concept of resilience, we feel that the scenario-based risk metric proposed here provides a meaningful technique for systematically evaluating the resilience performance of a power system. Scenario development, particularly for the purpose of calculating specific performance metrics, will be a challenging task and will likely require defining not only the scenario but also guidelines about how to reasonably and generally interpret and implement the scenarios. Experience in this process will be essential in defining meaningful and useful scenarios.

As mentioned previously, many of these scenarios will require analysis tools beyond those traditionally used for power system simulations. Many of the challenges faced during restoration efforts for large-scale deleterious events are logistical—forming work crews, providing the necessary equipment and spare parts, feeding and housing work crews, dealing with access to work sites, surveying damage, forming the work plans, etc. At this time, we do not know if such tools are available and, if so, could they be applied to these kinds of events. As a means of facilitating scenario analysis, an effort will need to focus on determining what tools may exist and how they might be applied towards a resilience analysis.

Traditionally, transactive systems have not been designed with resilience applications in mind. As was described in Section 4.2, some existing transactive mechanisms may be able to provide meaningful improvements to risk metrics in some scenarios. Development of more transactive mechanisms specifically designed to address resilience more broadly (across all phases) and to evaluate them in the appropriate scenarios would demonstrate and quantify the impact transactive systems could provide during these deleterious events.

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Appendix A − Review of Resilience Metrics in the Literature

(Panteli and Mancarella 2015) provide a conceptual framework for power grid resilience with exemplary references to Hurricane Sandy and widespread flooding in Queensland, Australia. Reliability and resilience characteristics are briefly differentiated. Events affecting reliability are considered as high-probability, low-impact events while those affecting resilience are considered low-probability, high-impact events. The authors also distinguish between operational recovery (i.e., minimizing customer interruption time) and long-term recovery (i.e., minimizing customer interruption and promoting infrastructure recovery). The idea of fragility curves is proposed to quantify resilience with an illustration wherein components are designed to higher stress intensities than those induced by observed events. Distributed energy resources and decentralized control are presented as ways to enhance resilience while microgrids, protection and control schemes, and situational awareness being other valid mechanisms. The authors recommend boosting resilience through resilience engineering (i.e., activities before and after an event) and disaster recovery and risk management (i.e., during an event). While the idea of fragility curves is very appealing in a framework setting, it is often challenging to develop fragility curves to characterize response of power grid elements to a wide variety of catastrophic events.

(Wang et al. 2016) surveyed a number of models for forecasting power system impacts due to natural disasters. They provide clear distinction between operational outages and catastrophic outages attributed to natural disasters. These can be categorized as differences in number of faults, levels of uncertainty, spatiotemporal correlations, generating unit outages, topological impacts, interdependent losses, and time to restoration. The authors claim restoration through conventional strategies is challenging and acknowledge the need for new resilience-boosting techniques such as distributed generation, microgrids with storage, electric vehicles, decentralized restoration, and distribution automation through automatic switches.

(Chanda et al. 2016) developed quantifiable time-dependent resilience metrics for distribution systems to aid cost-benefit analysis and justify investment decisions. They illustrate the concepts with case studies assuming totally renewable or conventional generating units while acknowledging the presence of their mix in the real world. The authors also compiled a list of challenges in proactive resilience investment including requirements for high-volume, low-probability event data; computational intensity; and uncertainties. They consider the resilience metric to be a function of outage duration and fraction of load unaffected.

(Roege et al. 2014) propose a matrix-based approach to evaluating energy-resilience metrics. The matrix cuts across a comprehensive list of interacting domains (i.e., physical, information, cognitive, and social) and stages of change (i.e., plan, absorb, recover, and adapt). A qualitative resilience scoring system is then illustrated on the matrix cells. They believe certain technological aspects can be analyzed quantitatively but complex interactions and subsequent responses may warrant qualitative evaluation.

(Coles et al. 2011) develop resilience metrics within a risk assessment framework using concepts of "loss of service" and "normally provided service" as resilience factors. They define analytical expressions for quantitative characterization of resilience terms defined by National Infrastructure Protection Plan and National Infrastructure Advisory Council. For example, recovery resilience is estimated as the ratio of normally provided service to loss of service weighted by the probability of an attack and the probability of attack success given the attack. The ratio ensures that normally provided service is relatively higher for a resilient system.

(Ingram and Martin 2017) differentiate between reliability and resilience in the context of small-scale utilities. The former is regarded as the ability to resist interruptions whereas the latter as the ability to recover and respond with the intent of minimizing the magnitude and duration of disruptions. Common guidance documents such as the IEEE 1366, "Guide for Electric Power Distribution Reliability Indices," for reliability and ANSI/ASIS SPC.1-2009, "Organizational Resilience: Security, Preparedness, and Continuity Management Systems," for resilience have been listed as prominent references.

(Chanda and Srivastava 2015) propose a unified resilience metric for smart power distribution systems synthesized using multi-criteria decision-making from a "5 × 5" decision matrix. The five factors include 1) connectivity of the network before and after an event, 2) loads, 3) failure rate of distribution system events, and 5) weather related factors. The synthesis is done by assigning weights to the factors and then performing a linear transformation to arrive at a single metric. The metrics are quantified and demonstrated using Consortium for Electric Reliability Technology Solutions and IEEE-13 distribution feeders.

(Finster et al. 2016) identified a number of threats and vulnerabilities, and the associated resilience enhancement options at generation, transmission, and distribution levels of the electric power grid. They acknowledge it is a challenge to justify resilience investments as threat events are anticipatory in nature involving large uncertainties.

(Petit et al. 2013) describe components of a Resilience Measurement Index contributing to a group of four components of resilience: 1) preparedness, 2) mitigation, 3) response and 4) recovery. Each component is investigated further in the form of nested levels. At the last sublevel, components are ranked and weighted semi-quantitatively based on expert elicitation. These are then rolled up to aggregate at the top index level. The tnis one of three measurement indices depicted in a bowtie diagram, the other two being protective measurement index and corrective measurement index.

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