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Reliability and Resilience Considerations for Transactive Energy Systems

Prepared by

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About this Document

The GridWise Architecture Council was formed by the U.S. Department of Energy to promote and enable ***interoperability*** among the many entities that interact with the electric power system. This balanced team of industry representatives proposes principles for the development of interoperability concepts and standards. The Council provides industry guidance and tools that make it an available resource for smart grid implementations. In the spirit of advancing interoperability of an ecosystem of smart grid devices and systems, this document presents a Transactive Energy framework to provide the context for identifying and discussing development and application of this technology. You are expected to have a good understanding of interoperability, familiarity with the GWAC Interoperability Context-Setting Framework, and knowledge of energy markets and their business models. Those without this technical background should read the *Executive Summary* for a description of the purpose and contents of the document. Other documents, such as checklists, guides, and whitepapers, exist for targeted purposes and audiences. Please see the www.gridwiseac.org website for more products of the Council that may be of interest to you.

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Executive Summary

This paper introduces a new context for addressing reliability and resilience objectives using transactive energy systems (TESs). TESs use a combination of market-like economic and control techniques to improve grid efficiency and reliability. The GridWise® Architecture Council (GWAC) believes that both elements—efficiency and reliability—must be considered for practical development and application of TESs [1], [2]. While TESs have been developed for efficient economic operations, the application of TESs toward reliability and resilience objectives has not been so straightforward. This paper offers a model of responses that a grid system might make to avoid, resist, or recover from an event and pairs these responses with the normal, stressed, or emergency grid conditions under which such responses are planned or activated. Existing grid products and services are then reviewed. TESs may either directly harvest the monetized values of these products or services at their boundaries or allow their market transactions to dynamically value the underlying objectives to which the TESs respond. Finally, an exercise is completed to develop example use cases for six viable pairings of the paper's grid conditions and event responses. The authors compare the mitigations offered in these scenarios alternatively using existing products and services or TES approaches.

Acknowledgments

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About GridWise® and the Architecture Council

The GridWise vision rests on the premise that information technology will revolutionize planning and operation of the electric power grid, just as it has transformed business, education, and entertainment. Information technology will form the “nervous system” that integrates new distributed technologies—demand response and distributed generation and storage—with traditional grid generation, transmission, and distribution assets. Responsibility for managing the grid will be shared by a “society” of devices and system entities.

The mission of the GridWise Architecture Council (“the Council”) is to enable all elements of the electricity system to interact. We are an independent body that believes tomorrow’s electric infrastructure can be more efficient and secure by integrating information technology and e-commerce with distributed intelligent networks and devices. To achieve this vision of a transformed electric system, the Council is defining the principles for interaction among the information systems that will effectively and dynamically operate the grid. The Council, which is supported by the U.S. Department of Energy, includes 13 representatives from electric energy generation and delivery, industrial systems control, building automation, information technology and telecommunications, and economic and regulatory policy.

The GridWise Architecture Council is shaping the guiding principles of a highly intelligent and interactive electricity system—one ripe with decision-making information exchange and market-based opportunities. This high-level perspective provides guidelines for interaction between participants and interoperability between technologies and automation systems. We seek to do the following:

- Develop and promote the policies and practices that will allow electric devices, enterprise systems, and their owners to interact and adapt as full participants in system operations.
- Shape the principles of connectivity for intelligent interactions and interoperability across all automation components of the electricity system from end-use systems, such as buildings or heating, ventilation, and air-conditioning systems, to distribution, transmission, and bulk power generation.
- Address issues of open information exchange, universal grid access, distributed grid communications and control, and the use of modular and extensible technologies that are compatible with the existing infrastructure.

The Council is neither a design team nor a standards-making body. Our role is to bring the right parties together to identify actions, agreements, and standards that enable significant levels of interoperation among automation components. We act as a catalyst to outline a philosophy of inter-system operation that preserves the freedom to innovate, design, implement, and maintain each organization’s role and responsibility in the electrical system.

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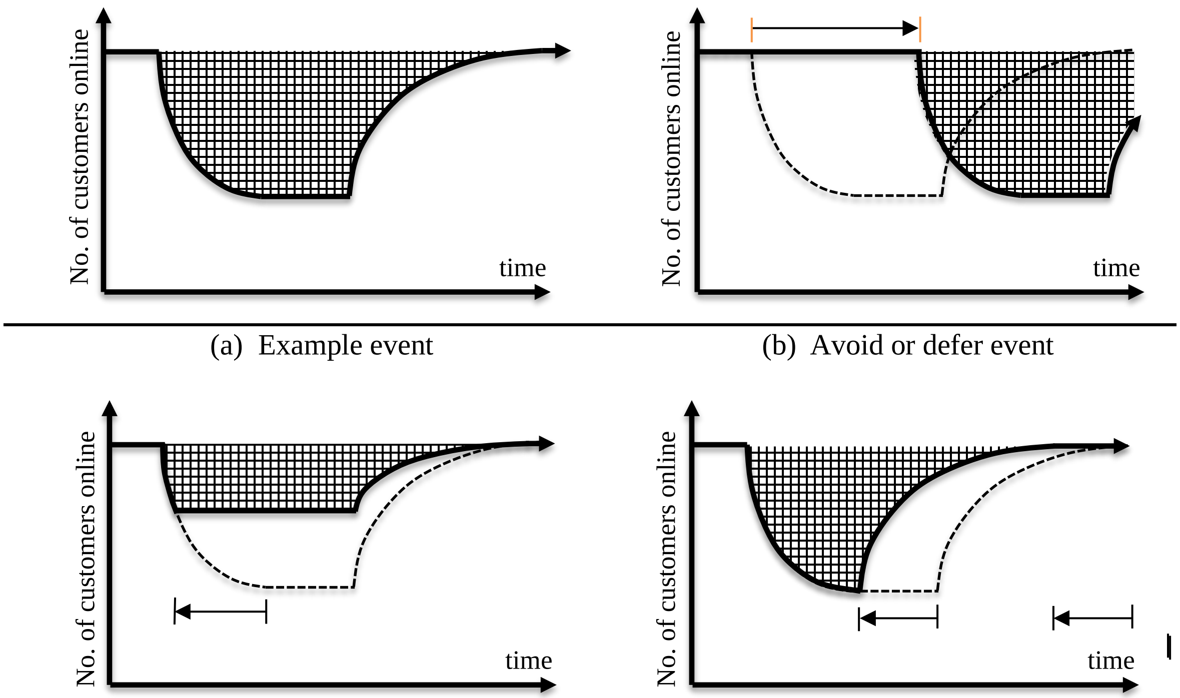
1.0 Introduction

Economic value in a transactive energy system (TES) is created when participants have a common valuation metric that represents cost and benefit of selecting from among competing alternatives, and which respects the individual values placed on those alternatives by system participants. A definition of transactive energy is maintained by the GridWise™ Architecture Council [1].

TESs have adopted useful practices and theory from existing, proven wholesale electricity markets concerning the valuation and exchange of electric energy. Applying these principles, early implementations of TESs readily discovered and responded to objectives that derive from energy availability and scarcity (e.g., supply and delivery constraints). The application of TESs to grid system resilience or reliability—also worthy objectives—has not been as straightforward. The TES community currently lacks context to evaluate the provision of resilience and reliability using TESs. This paper strives to supply such context.

However, further usage of and dependence upon the terms *resilience* and *reliability* will be avoided in this paper. These terms are overloaded. Contradictory usages of these terms abound. Instead, a simple event-response model is introduced in Figure 1. An underlying assumption of this model is that many adverse effects accompanying device or system outages are approximately proportional to an area like the shaded area of Figure 1 having units "customer-outage-time." Admittedly, there may be additional impacts that are not proportional to this area. The units of the vertical axis may differ to reflect alternative weights for the impacts of the event. For example, the vertical axis could represent supplied power, which emphasizes power value instead of customer counts.

Consider a typical system event of Figure 1a. The event has probabilistic rate of occurrences, depth or severity of outages and damages, and duration. The remaining panels of Figure 1 conceptually introduce improvements to system resilience corresponding to avoiding, resisting, and recovering from such an event. If the likelihood of events is diminished, then the average time between events increases and the events are effectively deferred as shown in Figure 1b. If system improvements resist and react to the event more rapidly, then the depth of the event may be diminished as shown in Figure 1c. The improvement in Figure 1c could have either reduced the rate of system degradation, halted the degradation earlier, as is shown by Figure 1c, or both reduced the rate of degradation and halted the degradation earlier. If system improvements are made to recover from events more rapidly, the duration of events may be shortened as shown in Figure 1d. The system improvement could have either shortened any delays that occur prior to the start of active recovery, as is shown conceptually by Figure 1d, increased the rate of active recovery, or both shortened any delay and sped the active recovery rate.



(a) Example event

(b) Avoid or defer event

(c) React to the event faster

(d) Recover from the event more rapidly

Figure 1. Event Model (modified from [3])

The customer-outage-time area may be reduced if a system, transactive or non-transactive alike, can 1) avoid or defer the event, 2) respond to or resist the impending event, or 3) recover from the event after its occurrence. If the capabilities of systems can be functionally mapped to these three responses, new system capabilities may be designed and valued on equal footing with electric energy value. Certain capabilities of systems might be argued to reduce future customer-outage-time areas in a future, probabilistic sense. A reduction in actual customer-outage-time may later confirm the effectiveness of the design, but again, only in a probabilistic sense.

Certain qualities of TESs will help the power system effectively avoid, resist, or recover from events. These qualities should be addressed at a level of abstraction that invites continued innovation. For example, system redundancy is an abstraction that could include the provision of energy reserves.

This paper will address the provision of avoidance, resistance, and recovery under three grid conditions—normal, stressed, and emergency—under which actions might be taken to provide these event responses. Section 2 discusses the implications of this exercise for TESs using a matrix of intersections between the paper’s three grid conditions and three event responses. Section 3 discusses sources of value in a grid that can incentivize the performance of TESs toward the purposes of resilience and reliability. In Section 4.0, use cases are introduced to exemplify provisions of the event responses by a TES under the three grid conditions. A summary is provided in Section 5.0.

2.0 The Interplay between Current Grid Conditions and Event Responses

Based on the above discussion, a TES can facilitate the avoidance of, resistance to, and recovery from grid outages by taking actions during normal, stressed, and emergency grid conditions as explained in sections 2.1 and 2.2 below. The objective of this exercise is to examine the resulting six combinations of event responses and grid operating conditions to explore the potential impact of TESs within those classifications by exploring potential scenarios associated with each combination. The scenarios of interest can be visualized as a three-by-three matrix of event responses and grid conditions (Table 1). In the following subsections, the row and column headings of the table are elaborated.

Table 1. Interplay between Grid Conditions and Event Responses

Grid Condition	Event Response: **Avoid**	Event Response: **Resist**	Event Response: **Recover**
Normal	No event is currently foreseen. Preparations are made to avoid or defer a system event.	No event is currently foreseen. Preparations are made to resist grid stresses and thereby diminish the severity of an event.	No event is currently foreseen. Preparations are made to facilitate or hasten recovery should parts of the grid fail.
Stressed		Stressed grid conditions have been detected. The system resists the stresses and thereby diminishes the severity of an event.	Stressed grid conditions have been detected. The system facilitates or hastens recovery should parts of the grid fail.
Emergency			Parts of the grid have failed. The system facilitates or hastens recovery from the failures.

2.1 Event Responses

Systems may be designed to reduce potential costs of grid events through avoidance, resistance, and recovery. These objectives are not necessarily unique to TESs. Manual and automated systems exist today and could be described in the context of this simple grid-event model. However, the purpose of this paper is twofold. The first purpose is to provide a context under which novel TESs might be designed to mitigate grid events. The second purpose is to provide a method to evaluate a TES's capabilities for mitigating grid events.

2.1.1 Avoidance

A system either defers or entirely prevents an event from occurring. Grid system stresses are made inconsequential, and failures are averted.

2.1.2 Resistance

A system is resistant if, once grid stresses begin to occur, the system retards or counteracts the stresses. If successful, the cost impact of a grid event may be lessened because less equipment becomes damaged or fewer electricity customers incur outages or become inconvenienced. Grid “flexibility” can increase the ability of the grid to “absorb” stress. In this respect, “flexibility reserves” provided by distributed energy resources (DERs) and amenable to transactive exchanges are particularly relevant to enhancing grid resistance to stress.

2.1.3 Recovery

Recovery refers to actions taken after the depth of an event’s effects has already occurred. Equipment has been damaged, or electricity customers are without power. The cost of the event may be lessened if damaged equipment can be replaced or repaired rapidly or if electricity customers can be returned to partial and full electric service.

2.2 Grid Conditions

The current condition of the grid can be represented as normal, stressed, or emergency, as described below. A TES may be designed to act under each of these conditions to avoid, resist, or recover from grid events as applicable.

2.2.1 Normal Grid Condition

The grid system is operating normally in this condition. A system might take actions to avoid, resist, or recover from events while under normal operating conditions, but events are not anticipated while the system is operating normally.

2.2.2 Stressed Grid Condition

Under stressed conditions, the grid is operating outside of normal conditions. Operating reserves are becoming partially or completely depleted. Equipment may be becoming damaged, and customer service outages may have begun to occur. However, the full depth of the event has not yet been realized. This condition may be due to equipment failures, limited generation, or an inability to transport power to where it is needed. While under stress, a system might take multiple actions to resist the stress and thereby lessen the severity of the event outcomes, and it might take actions to hasten recovery from the impending event, as well.

2.2.3 Emergency Grid Condition

Under emergency conditions, the full depth of an event has been realized. Generally, emergency conditions are accompanied by equipment damage, loss of service, and the need for restorative actions. While in an emergency grid condition, a system might take actions to recover more rapidly from the failures that have already occurred. Stated differently, under stressed conditions some equipment may be operating outside normal operating ranges, but not damaged to cause an outage; under emergency conditions operating outside normal operating ranges has resulted in equipment damage and outage.

3.0 Sources of Value for Existing Grids and TESs

Responsiveness to value is fundamental to TESs. Over many years, power grid operators have developed products and services that codify the policies and practices and rules by which necessary and valuable operations occur at various levels of the power grid. The accepted practices and rules thereby provide entities mechanisms to solicit and supply the fundamental operational requirements that underlie grid operations. If the products and services have further been assigned monetary value or price, different entities can collaborate to provide and consume the product or service. TESs can directly respond to some of these products and services because such prices are clear indicators of value at the boundaries of the TESs. Alternatively, TESs might directly target the underlying objectives for which the products and services were developed and let market principles—also fundamental to TESs—dynamically value and select from among such actions.

In this section, existing grid products and services and the value they are intended to provide toward grid operations are reviewed. These products and services involve electric energy as well as a variety of derivative products, generally referred to as grid services.

A grid operator must minimize costs and balance supply and demand while maintaining the grid power flows and voltages within acceptable operating limits. The grid operator relies on products and services such as frequency regulation and energy balancing. As explained above, these services that have traditionally been secured from conventional generation resources might now be cost-effectively secured through transactive exchanges.

The grid operator also must be vigilant against credible contingencies to avoid interruption of service. The main products a grid operator relies on for this purpose are contingency reserves. These come in the forms of spinning and non-spinning, also known as supplemental reserves. These services have been traditionally secured from conventional generation resources but might now be cost-effectively secured via transactive exchanges. The market prices for these products may become much higher under stressed grid conditions compared to their prices under normal grid conditions. Traditional market-based transactive exchanges for grid services were the domain of the bulk power system in a time when there were no abilities for self-supply in distribution systems. With growing deployment of DERs in distribution systems, there are new sources for provision of grid services from DER assets. TESs are the means by which those DER can effectively be engaged, especially if the numbers of DER are varied geographically.

A grid operator must also make sure that the grid can contain the spread of an outage and afterward have resources in place to restore services. For this purpose, grid operators rely on black start service. Grid restoration services have traditionally relied on conventional generation. These services could now be procured in forward-looking transactive exchanges with transactive market participants.

Table 2 summarizes the conventional grid services (“products”), along with a short description and the associated “value” from the grid operator’s perspective.

Table 2. Conventional Products for Economic and Resilient Grid Operation

Product	Description	Value
Energy Procurement	Most basic economic management of electrical energy commodity	Commits and dispatches an economic portfolio of energy resources
Balancing Energy	Refers specifically to the energy imbalance service of FERC Orders 888 and 2000 [4]	Of increasing importance for following dynamic, intermittent renewable resources
Reserve	Online (“spinning”) or offline (“supplemental”) generation capacity that can be deployed within minutes [4]	Fast replacement of energy resources after the loss of scheduled generation or transmission
Frequency Regulation	Capacity that can respond to the 2-10 second automatic generation control (AGC) commands issued from the system operations control center [4]	Resources share responsibility for short-term balance corrections within schedule periods and correct scheduled power exchanges
Volt/Var Support	Reactive power provided by generators and synchronous condensers in transmission; by capacitors and tap changing transformers in distribution [4]	Corrects voltage quality. Decreases electricity transport losses
Black Start	Strategic, secure restoration of service after a service outage	Best strategies rapidly restore customer service

In the next section we present representative use cases pertaining to the matrix cells in Table 1, and where relevant the corresponding revenue streams associated with transactions involving the products and services in Table 2.

In addition to the value streams that can explicitly be monetized based on the products and services listed in Table 2, indirect value streams result from the underlying transactive actions including reduced customer outages, reduced economic harm, reduced loss of service life, increased public safety, reduced greenhouse gases, and other beneficial social and environmental impacts that may not be easily quantifiable, but must be recognized as beneficial byproducts in the discussion of various use cases.

4.0 Example Use Cases

In this section, we offer some representative use cases to illustrate how TESs might be used to augment grid reliability and resilience. The use cases represent each feasible combination of grid condition (normal, stressed, and emergency) and grid response (avoid, resist, and recover) in Table 1. For each use case, we first describe in greater detail the matrix cell of Table 1 to which the use case pertains. We then explain the current practice in dealing with the use case's specific combination of grid condition and event response. We then suggest how TES might provide a similar event mitigation and the value stream it addresses for the use case's stakeholders.

Some of these use cases are adapted from scenarios that were presented originally in [5] and [6].

4.1 Normal × Avoid

In this situation, no event is currently foreseen threatening system reliability; however, preparations are made to avoid or defer a credible system event. Under normal grid conditions, the primary objective of the grid operator is to operate the power system economically (at the lowest cost) and reliably (avoid degradation or interruption of service to consumers). The avoidance measures taken under normal grid conditions include, among others, balancing supply and demand while maintaining the grid power flows and voltages within acceptable operating limits.

The use case of interest involves incorporating TESs to provide for prosumer incentives and grid operator reliability/avoidance objectives under normal grid conditions. Increasingly, distribution grid operators are facing challenges due to a lack of visibility to the operation of prosumer assets. At the bulk level, the cumulative impact of distributed generation is compounded by the large, unpredictable swings in renewable generators like wind farms.

At present, distribution utilities resort to administratively setting rates and programs such as time-of-use pricing and/or other connection agreement control mechanisms (e.g., curtailing photovoltaic (PV) solar generation to avoid reverse flows or voltage impacts) to address distribution grid operational issues. Bulk power operators need higher quantities of grid services (such as frequency regulation) as well as new grid services (such as flexible ramping) to address the transmission grid operational challenges.

A TES could address these operational challenges to the mutual benefit of the prosumers, renewable generation operators, and grid operators. As an example, consider large swings in renewable generation. These swings can cause line overloads resulting in tripping of transmission or distribution lines. In a transactive market setting, these swings translate into market-clearing prices that increase when demand exceeds supply and decrease and may even be negative during over-generation conditions. Prosumers with flexible loads such as distributed storage can reduce these imbalances by charging during periods with low or negative prices and discharging during high prices.

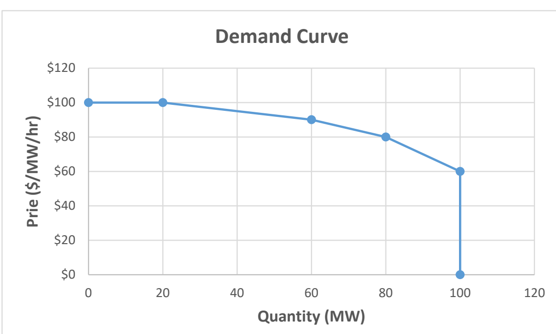
The value streams from the prosumers' perspective include revenues through participation in a variety of exchange mechanisms within the same electric grid control area/balance area and peer-to-market transactions. Distribution system operators can gain improved situational awareness of prosumer interchanges that could impact the grid and can engage in market-based exchanges to address conditions that may stress the grid. Lower costs for system balancing and maintaining grid operational reliability are achieved due to larger volume of balancing energy offered from both conventional and distributed energy resources; the savings in operation costs are passed along to passive customers due to reduced grid operation costs. Environmental and societal benefits occur because of reduced curtailments of solar or wind generation during high solar or wind periods (oversupply) and reduced deployment of fossil generation during supply-deficient periods.

4.2 Normal × Resist

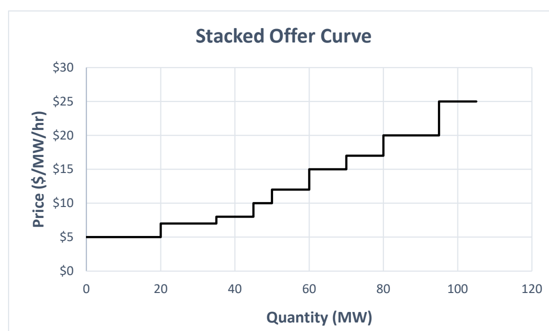
This combination represents normal operating conditions where no event is currently foreseen threatening system reliability; however, preparations are made to resist grid stresses and thereby diminish the severity of an event. The use case of interest involves actions by the grid operators to enable the grid to withstand stresses resulting from stress-causing incidents like tripping of a line or sudden loss of a generation facility, and the incentive-based participation of prosumers to help accomplish this objective.

Grid operators employ spinning and supplemental contingency reserves to help the grid withstand stresses resulting from equipment outages. Today, these grid services are procured primarily from conventional generation resources. Prosumers, although having relatively low impact individually, can collectively provide these services. However, utilities or aggregators often leverage the prosumer capabilities through administrative arrangements and directly control the prosumer-side assets instead.

A TES platform could engage prosumers to offer market-based provision of such services. Typically, the grid operator's price curve for procuring contingency reserves looks like Figure 2a. The grid operator must secure a quantity of contingency reserves to withstand the most severe single contingency (or combination of contingencies) as stipulated in minimum operating reliability criteria. This is illustrated by the target quantity 100 MW in Figure 2a. However, in a bid-based spot market for contingency reserves there may be insufficient supply to meet the target quantity. To encourage entry of additional supply, scarcity pricing segments are incorporated in the contingency reserve demand curve as shown in Figure 2a raising the price to attract additional supply of reserves to minimize the potential shortfall. Normally, because of the small size, each prosumer is expected to offer a single price for the quantity offered. The platform would stack the prosumer offers, as shown in Figure 2b.



(a)



(b)

Figure 2. Transactive (a) Demand and (b) Prosumer Supply Curves

Depending on the alternatives offered into the market, two situations may occur: the supply/demand curves intersect so that supply sets the price (Figure 3a), or the price is set by scarcity segments of the grid operator's demand curve (Figure 3b). In Figure 3b, the prosumer quantity segments above 80 units are assumed not to have been offered.

Figure 3. Market Intersections in which (a) Supply or (b) Demand Scarcity Sets the Price

In the case of supply scarcity, the lucrative price signal set by the demand curve encourages prosumers to offer more supply into this reserve product market, thus increasing the capability of the grid to prevent the occurrence of outages in case of contingencies.

The beneficiaries in this use case include prosumers, the grid operator, and passive consumers. The prosumers receive payments based on market prices, which will not be less than their offer prices; the grid operator enjoys operating a more reliable and contingency-resistant grid; consumers get the benefit of more reliable electricity service.

4.3 Stressed × Resist

Here we examine a scenario where the grid is experiencing high demand, all reserved resources have been exhausted, and steps need to be taken to lessen the eventual severity of the event.

The case of an emergency load curtailment is considered. The scenario is achieved when a region that has been experiencing high temperatures has now entered the afternoon peak (Scenario 1: Peak Heat Day and Energy supply in [5]). The grid is experiencing a stressed condition since it has already tapped all bulk utility resources and first tier DERs. Any additional loads would impact the reliability of delivery to existing services. Today the corrective action is to bring on reserve DERs, curtail services, or a combination of both to large customers with interruptible contracts.

A TES would incentivize participants to increase the effective capacity of the grid to help it transition back to a normal condition. Such methods include both reducing the price-responsive and flexible load and bringing on additional supply injection from distributed generation and storage resources. For example, some households could be incentivized to defer the use of non-essential services to off-peak times or to tap into local storage resources. Other customers might be incentivized to have all behind-the-meter DER resources supply the grid instead of using their power locally.

The value provided by this TES is that the operator may not need to call on reserve resources or curtail customers' service. The TES might delay or even prevent adverse consequences from a stressed condition by using predictive analytics. Advances in information technology/operational technology (IT/OT) integration along with new tools such as machine learning provide a powerful mechanism to predict trends, provided they are used with privacy as an overarching guideline.

4.4 Normal × Recover

Consider a grid that experiences frequent instances of poor voltage regulation. It is not currently stressed; however, based on history, the grid will at some time encounter and must recover from a voltage sag. Voltage sags are usually caused by system faults but may also be the result of heavy startup currents caused by energizing large loads. A motor can draw six times its normal running current, or more while starting. Imagine a situation where, due to recent commercial developments, there is an uneven distribution of single-phase loads drawing unbalanced currents from the system. When two or more motors start up in close succession, the subsequent voltage sags cause sensitive electronic equipment in a nearby facility to trip offline. A static synchronous condenser (STATCOM) could be used to inject or absorb the desired amount of reactive power in each of the phases to restore the voltage of different phases to permissible limits and mitigate the problems of voltage unbalance. Voltage imbalance due to uncoordinated load startup can be reduced or eliminated by improved coordination of generation and loads at a local level.

Coordination methods are mechanisms to ensure that decentralized elements stay focused on common problems as the decentralized elements explicitly cooperate to solve a common problem. TESs could coordinate these large distributed loads with nearby voltage sources, even on a phase-by-phase basis. Through appropriate use of incentive signals, a TES could coordinate voltage injection with load startup or even synchronize load startup with generation availability, thus reducing or potentially eliminating the impacts of sags.

Coordination of transactive and traditional controls can provide value by assuring stability through multilevel constraint fusion so that the TES is optimized but does not cause adverse impacts to the grid within which it operates. This coordination allows for control federation and disaggregation at the feeder level so that the TES and the entire feeder are both optimized within the goals and constraints that need to be observed.

4.5 Stressed × Recover

In this section, a grid that has encountered stresses and takes steps to hasten recovery should the grid stress cause equipment to break or customers to lose service is examined.

A good example of this scenario today would be the staging (prepositioning) of emergency equipment and crews during stormy weather. There exists a strong correlation between storms and customer outages. Therefore, the resource may be placed nearer to where the damage and outages are predicted to occur. If an outage does occur, then the staged equipment and crews can more rapidly begin repairs and more rapidly restore customers to service. Research is also underway toward the fractionation of grids into smaller functional grids, or microgrids. The primary objective of this capability is avoidance and resistance to the propagation of outages. Still, it can be argued that microgrids, once isolated, should possess their own black-start resources, restore their own power service, and then more easily reconnect to the larger grid system.

In a scenario that includes a TES, the distributed communications of the TES might first gather granular information and automate alerts concerning storms and other system stresses and thereby improve the recovery efforts of the existing system. If a TES values the cost of equipment and service loss, then the likelihood of incurring an outage and its corresponding costs can be weighed in a microgrid's decision to either isolate or remain grid-connected. The microgrid's black-start resources might be armed, ready to recover power to the isolated microgrid, as well.

Value in the recovery column of Table 1 derives from the rapidity with which equipment can be repaired, and customer service recovered. If a TES's participation in the scenario can be shown to provide such value at a cost that makes it competitive, it should be considered and adopted.

4.6 Emergency × Recover

In this section, a case where customers have lost their service and grid infrastructure may have been damaged, and actions are taken to repair the damages and return service to customers is examined.

Today, the corrective actions taken in this scenario are quite manual. Repair personnel is dispatched to locate and fix damaged equipment. Once fixed, black-start system restoration is conducted. This approach is a standard grid service for recovery that is traditionally provided by conventional generation facilities, which must be systematically energized to both supply needed startup power and support voltage. If the outage is vast, the grid may need to be sectionalized to match discrete resources and loads, and the energized region is expanded until all service has been restored.

This scenario is a new horizon for TESs. Researchers have broached the topic of applying TESs to black-start restoration [7] and thus achieving some degree of automation. Conceptually, a TES would have resources offer their capacities toward this scenario at prices at which each would be willing to supply black-start service. These resources would be matched to corresponding load bids, where the loads' bid magnitudes correspond to their prioritization. Arguably, the planning for these transactions could be planned during normal grid conditions and revised as the grid becomes stressed. An inherent challenge will be the reliance on system communications, on which transactive coordination might rely, having electricity.

Therefore, the value provided by a TES as it performs the equivalent of black-start service competes with business as usual. If a TES can be shown to more rapidly restore service at a competitive system cost when compared with current black-start practices, then the transactive approach should be considered and adopted.

5.0 Conclusion

This paper offered a model of reliability or resilience responses that TESs could make or prepare for under varying grid conditions. A matrix was developed that presents the interplay between grid conditions, identified as normal, stressed, and emergency, and systems' capabilities to avoid, resist, and recover from events. The matrix provides a mechanism to guide the design and application of TESs such that the incentives and associated controls work together to prioritize grid reliability and align prosumer incentives with grid operational objectives to the mutual benefit of prosumers, grid operators, and passive consumers. This paper supplies needed context concerning how TESs may be applied to resilience and reliability objectives.

A set of use cases validated the various six feasible combinations of grid conditions and event responses and demonstrated that TESs might be designed and implemented to mitigate events while aligning participant values.

In closing, it may be pointed out that TES can provide different value streams for various grid and event combinations depending on how they are used. Under Normal × Resist setting, they can provide balancing energy. Under Normal × Avoid setting they can provide contingency reserves. For Normal × Recover, they offer configurability. They can be effective under the Stressed × Resist by providing configuration arming to limit the scope of outages if they do occur. Under Stressed × Recover combination TES can perform actual switching to recover from outages. Finally, under Emergency × Recover TES may even help in providing black-start capability when the outage has occurred by creating small, islanded systems.

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