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Summary

One of the major goals of new grid operation regimes, such as transactive energy systems (TESs), is to make the power grid more resilient to withstand natural or man-made disasters and potential reliability events, and to continue to serve the maximum number of its customers. But it is a well-known fact to system operators that not all customers are the same. This implies that any discussion of TESs' impacts on the resilience of the power system should consider the needs of its critical customers (such as the power system operation centers, fire and police stations, and hospitals) over those of other customers. When evaluating the resilience of the system, bonus points must be awarded to any system that could maintain its power supply to critical customers during a disturbance that may cause an outage.

This report discusses critical infrastructure (CI) as found in the literature and then categorizes it based on the field to which the operations belong (such as human life/safety-related, operations management, necessary city operation, industrial customers, etc.). Each of these CI categories is further divided into types of critical customers (e.g., the human life/safety-related category has different types of customers like hospitals, fire and police stations, etc.). The entire demand of each of the critical customer types is not categorized as critical load (CL); instead, only a portion of the total load of these critical customers is characterized as critical load. This is done based on the categories of equipment, the function of which is crucial in the operation of the overall facility. CL categorization is performed to provide the ratio of the critical load portion to the overall load, so that it can serve as a parameter in the resilience evaluation of the grid through a metrics-based approach. Such categorization is important as it helps to augment the existing quantifiable resilience metrics with CL categorization. The metrics for a power system need to not only consider how well a system performed during a disturbance event, but also how it reduced strain and supplied power to its CLs. The first step in this process is characterize CLs in the system.

After CL characterization, the next step is the inclusion of these loads in the resilience metrics. To that end, in this report weight-based augmentation of resilience metrics is proposed, where certain customers (the ones that are categorized as critical) are assigned higher weights than others. Though an overview of assigning weights to customers is discussed, there is no one-size-fits-all approach for every power system. The decisions made about assigning such weights to customers vary greatly from one operator to another, based on their unique systems and the current and predicted states of critical customers. This decision-making can include the type of disturbance event, which might only affect certain parts of the system. In general, analyzing critical customers before an event helps understand system vulnerabilities. It also helps in planning and conducting operations during the event, evaluating system performance after the event, and supporting better planning for future events.

An alternative to the current practices of managing the grid for outages is an innovative TES, which has the potential to provide a platform for including distributed energy resources for managing CLs. This report also describes how TES qualities can help (1) to maintain power supply to critical customers for uninterrupted operations and (2) to restore lost power supply to the critical customers rapidly.

Acronyms and Abbreviations

BS	Black start
CAIDI	Customer Average Interruption Duration Index
CAIFI	Customer Average Interruption Frequency Index
CHP	Combined heat and power
CI	Critical infrastructure
CL	Critical portion of the entire load of critical customers
DER	Distributed energy resource
DG	Distributed generator
EV	Electric vehicle
FEMA	Federal Emergency Management Agency
HVAC	Heating, ventilation, and air-conditioning
IEEE	Institute of Electrical and Electronics Engineer
PPD	U.S. Presidential Policy Directive
PV	Photovoltaic
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
TE	Transactive energy
TES	Transactive energy system

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1.0 Introduction

Virtually every aspect of modern society (healthcare, transport, heat, water supply, and so on) relies on electricity, which makes the electric power grid one of the nation's most critical infrastructures (CIs). The staggering cost of a power grid outage and its impacts on human well-being, the country's economy, and national security necessitates ensuring the provision of continuous availability of a high-quality power supply to end-users, with very few interruptions over an extended period. During a grid disturbance, however small or large, power system equipment experiences degradation from its usual operational performance levels and consequently impacts customers' power supply. For example, when hurricanes Harvey, Irma, and Maria hit the United States in August and September 2017, causing a combined $265 billion in damage, more than 28 million customers in Texas, Florida, and Puerto Rico were left without electricity for several days (Federal Emergency Management Agency (FEMA) 2017). In such situations, it is almost impossible to maintain the supply of electricity to all connected loads in the system. On the contrary, shedding some loads helps avoid cascading failures and enables continuing service of other loads. But it is essential to keep the lights on for critical services despite the disturbance on the grid or to bring them back as soon as possible if they are taken down.

1.1 Critical Infrastructures

(Presidential Policy Directive (PPD) -- Critical Infrastructure Security 2013) advocates importance of security and resilience of CIs as: "Critical Infrastructure Security and Resilience advances a national policy to strengthen and maintain secure, functioning, and resilient critical infrastructure." In efforts to maintain such high level of security and resilience of CIs, various federal and state authorities are staging efforts to identify and provide roadmaps for higher security of CIs. For example, Cybersecurity and Infrastructure Security Agency (CISA) identified 16 types of CI sectors and laid down various guidelines for their security (CyberSecurity & Infrastructure Security 2020). However, based on experience with disastrous conditions causing major grid outages, the infrastructure security community in the United States has recognized that it is simply not possible to prevent threats to all assets. Consequently, the idea of assuring a continuous supply of services to critical assets has started to emerge among the utilities across the nation (Eto and Kintner-Meyer 2020).

Within a utility, critical customers such as hospitals, fire stations, emergency shelters, and research institutes are recognized and given priority for maintenance of uninterrupted power supply and restoration of power as soon as safely possible. This indicates the need for having resilient CI by improving the availability of critical customers and the critical portion of their loads (critical loads (CLs)), where the aim is to

- enable a faster response to grid disturbances when they occur,
- mitigate the extent of damage and suffering that communities endure, and
- expedite the recovery of critical functions.

Thus, the discussion of grid reliability and resilience metrics, e.g., customer outages per time, loss of load per event, etc., would be incomplete without a representation of the operational requirements of CIs. Because the number of critical customers and the critical portion of their load within any CI can vary, including them in generic metrics advocates a procedure for categorizing CLs based on their service to the overall CI. Suppose an indicator of the performance of a system is the number of customers who lose service during an event and the period of time they are offline. If a utility tries to restore a CL first, chances are that a handful of loads will be consequentially given priority over vast residential areas that have a higher number of customers. If the performance indicator is purely the number of customers, the utility may not fare very well under this scenario, because it should be prioritizing the important measure of restoring CLs, which is potentially more valuable to society.

This report discusses CLs that are directly powered by electricity, but the supporting infrastructure, which helps bring the power back online and provides support to the CLs to perform required services, is equally as important as the final power supply consumed by the CLs. However, as a metrics-based approach, which measures grid performance due to grid disturbance, the interruption of power supply to CLs can already include the contribution of supporting CI.

1.2 Introduction to Power System Reliability and Resilience

The design and operation of the existing electric power grid allow the infrastructure to deal with known and credible threats thus making the system reliable. Reliability metrics such as System Average Interruption Duration Index (SAIDI), System Average Interruption Frequency Index (SAIFI), Customer Average Interruption Duration Index (CAIDI), and Customer Average Interruption Frequency Index (CAIFI) are widely accepted by the utilities for measuring system performance and ensuring that the grid is sufficiently prepared for any contingencies that occur under relatively normal conditions. Although several efforts have been made to improve system reliability by assessing routine interruptions, it is becoming apparent that further considerations beyond classical reliability-oriented views are necessary because of the changing hazard landscape and complex grid operations creating high-stress grid conditions—the so-called new normal condition. While clear definitions and metrics for the reliability of the power grid exist, none is widely accepted for grid resilience. In the context of the power system, the Institute of Electrical and Electronics Engineer's (IEEE's) task force on the definition and quantification of resilience (Industry Technical Support Task Force April, 2018) defines resilience as "the ability to withstand and reduce the magnitude and/or duration of disruptive events, which includes the capability to anticipate, absorb, adapt to, and/or rapidly recover from such an event." The U.S. Presidential Policy Directive (PPD) 21 defines resilience as "the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions." In its definition of resilience, PPD 21 further clarifies that resilience includes a system's "ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents" (Presidential Policy Directive (PPD) -- Critical Infrastructure Security 2013). These definitions vary widely, but to some extent agree that the resilience of the system is not only in how it reacts to and recovers from a disastrous imposition, but also in how it prepares for it.

Numerous ongoing and interesting resilience-oriented studies seek to understand and quantify the resilience of the various systems (Kwasinski 2016, V. Chalishazar 2019, Johnson, et al. 2020, Hanif, Chalishazar and Hammerstrom 2020). These help foremost in understanding which systemic investments can have more impact and how to plan for future investments (Chalishazar, et al. 2020). The quantification of system resilience also provides a platform for comparing preparedness and response to various high-impact natural disasters nationally and globally and for learning valuable lessons about which actions to replicate or avoid. Quantifying system resilience requires the establishment and application of resiliency metrics. While the metrics for resiliency can be used in the context of various systems and infrastructure, this paper discusses the metrics in the context of power systems. Existing literature about resilience metrics uses different aspects of power systems in formulating the metrics because of the lack of a universally adopted definition of resilience. The metrics are mostly developed for low-probability high-consequence hazards and are based on the performance of the power systems (Poudel, Dubey and Bose 2020, Panteli, et al. 2017). Some resilience metrics are based on the topology of the system (Poudel and Dubey 2019, Chanda and Srivastava 2016). Other metrics use the time and cost of recovery, load recovery factor, and lost revenue as the performance measures for quantification (V. Chalishazar 2019, Chalishazar, et al. 2020). A few metrics based on outage magnitude and community impact are suggested by Vugrin et al. (Vugrin, Castillo and Silva-Monroy 2017) during the resilience analysis process.

Another line of thought in addressing grid resilience is to include reliability considerations in the resilience metrics and definition (Kwasinski 2016, GridWise Architecture Council 2020, Hanif, Chalishazar and Hammerstrom 2020). The notion of introducing reliability consideration is that measuring system resilience through “resilience events,” which are infrequent hazard conditions, usually leads to difficulties in truly testing system resilience. In an attempt to tackle these difficulties, Johansson et al. (Jonas, Hassel and Zio 2013) use two different approaches for vulnerability and reliability analysis of power transmission systems to understand choke points in power system operations. Reliability, in fact, can be a great metric for actual and historical device and system failures and can be used as a metric or baseline into the future, but only in a statistical sense (i.e., likelihood of failure). For these reasons, following the approach proposed in the report by Sarmad et al. (Hanif, Chalishazar and Hammerstrom 2020), this report includes the consideration of both reliability and resilience and refers to them interchangeably using the term “grid disturbance.” Grid disturbance is defined as a potential threat to the grid that may or may not cause an outage.

While the developed metrics help utilities carry out baseline assessments, response and recovery activities, and drive the planning and investment efforts, it is important that during any grid disturbance event, the CLs that directly affect human life and security remain connected. However, the authors did not find in the literature any consideration of including such information, especially related to CL, such as quantification of human/societal consequences during reduced system performance. This omission makes the role of CLs in developing resilience metrics more important than before. For resilience metrics to consider realistic operational challenges, the priorities in loads need to be considered. The priorities can be based on load categorization, as discussed in detail later in this report.

1.3 Transactive Energy Systems

One of the main purposes of quantifying resilience metrics for a system is to understand how to improve the overall system performance during grid disturbances. With increasing automation, sensor, and generation availability from the distribution grid through distributed energy resources (DERs), there are opportunities to enhance resilience at various levels. One such mechanism, transactive energy (TE), uses the bandwidth from consumer loads to modulate power consumption (Widergren, et al. 2017, Hammerstrom, Widergren and Irwin 2016). Here, bandwidth refers to the range of power consumption that a customer is willing to operate at, with minimal disturbance to their normal activities. TE systems (TESs) are a collection of economic and control techniques that use market-based constructs to manage the supply and demand of electricity within a power system. Because of the ability to coordinate DERs with system operations, TESs have been widely discussed as a means of managing the increasing need for flexibility in grid operations (Kok and Widergren. 2016). Such flexibility can be exploited to maintain the power supply to the maximum possible number of customers, as safely as possible, before, during, and after an event. The ability to flexibly manage customer loads can also provide enough buffer to operate CLs in a system with a safety margin. With these TES qualities, TESs are envisioned to facilitate the avoidance of, resistance to, and recovery from the grid disturbance, thereby affecting the priority-based resilience metrics.

1.4 Report Objective and Organization

The objective of this report is to introduce a metrics-based approach for evaluating power grid performance in terms of its CL supply when experiencing a grid disturbance. To this end, we propose a structure for classifying the critical portions of the infrastructure that have been identified as being critical based on historical disasters. We then propose a weighting-based approach to quantifying the positive impacts of prioritizing CLs. Further, we show how the proposed weighting-based formulation can be implemented to augment and enhance the current and already in-use metrics from the literature to provide a more granular and in-depth view of the system, which clearly shows the impacts of the load prioritization carried out by utilities. By using the “grid disturbance” term in explaining the system behavior, we attempt to harmonize the resilience and reliability definitions/metrics, while including the impact of CLs. Through grid disturbance analogies, we also identify system characteristics with and without TES qualities. Hence, the impact of CL and its influence due to TES to improve system performance are also analyzed. We next describe a working example to clarify the implementation of the proposed formulation.

The rest of the report is organized as follows:

- Chapter 2: Critical Load Quantification and Categorization
- Chapter 3: Metric-Based Evaluation Model
- Chapter 4: Critical Load Prioritization Using TES Qualities
- Chapter 5: Working Example
- Chapter 6: Conclusions and Future Work.

2.0 Critical Load Quantification and Categorization

To include CLs in resiliency metrics, the first step is to categorically identify and define CLs. In the context of this work, CLs are broadly identified as those operations that are required for the health, safety, security, and economic well-being of any community. Multiple other infrastructures, in addition to the power systems, can have an impact on the operation of CLs. For example, damaged roadways of the transportation infrastructure can inhibit the supply of goods and personnel for smooth operation of CLs. Because this work is focused on specifically understanding the power supply to CLs, only the effect of power system unavailability on the operation of CLs is considered here.

In general, much of the discussion in literature surrounds CI, and not just CLs or specific facilities. So, it is important to distinguish between CL and CI. According to Blokus (Blokus 2018), "critical infrastructures are those physical and information technology facilities, networks, services and assets which, if disrupted or destroyed, would have a serious impact on the health, safety, security or economic well-being of citizens or the effective functioning of governments". Keeping this in mind, CLs are characterized further in this chapter.

The effect of any hazard on the operation of the CLs is also based heavily on the system under consideration. The loss of electric power to some CLs can be more devastating than that to others. Because of this, we provide a generic classification of the CI in the broadest sense. The different types of CI can be

- human life/safety related, for example, police/fire station, hospitals
- operations management, for example, government offices, emergency relief centers
- necessary city operation, for example, water pumping station
- industrial customers.

However, the entire load demanded by the each of the CI customer types cannot be tagged and quantified as CL. Only a partial amount of load would be critical and would be needed for the critical services to be operational. Within every CI type there are different types of customers, and within each of these customer types there can be further distinctions for what composes CLs. For example, in the case of industrial customers, CL refers to a component, or set of components, the operations of which are identified as being critical, and which if failed, give rise to significant adverse consequences (Li, Barker and Sansavini 2018). Such distinction of CLs within a CI allows the operator to shut off noncritical loads so that backup resources can stay within their generation capability while mitigating the impacts of an emergency by keeping critical facilities running longer. For example, when super-storm Sandy made landfall on the eastern coast of the United States, Princeton University used its gas-turbine combined heat and power (CHP) plant that was vital to maintaining important facilities such as research labs, experiments, and data that could have been compromised by a loss of power (Hampson 2013). In doing so, noncritical loads around the campus, such as those related to administrative buildings and some classrooms, were shut off. Figure 1 describes the structure of the proposed categorization, which starts at the top with CI types followed by different types of customers that would fall under that particular CI category. Under each of the customer types there would be a smaller subset of operations that would be considered critical and would be classified as such; they are described as Categories A, B, … , E, etc. in Figure 1. For example, for a customer type of hospital, its critical loads may be categorized as A) In use Operation Rooms (ORS), B) emergency lightings etc., as they represent the most essential services to operate a hospital.

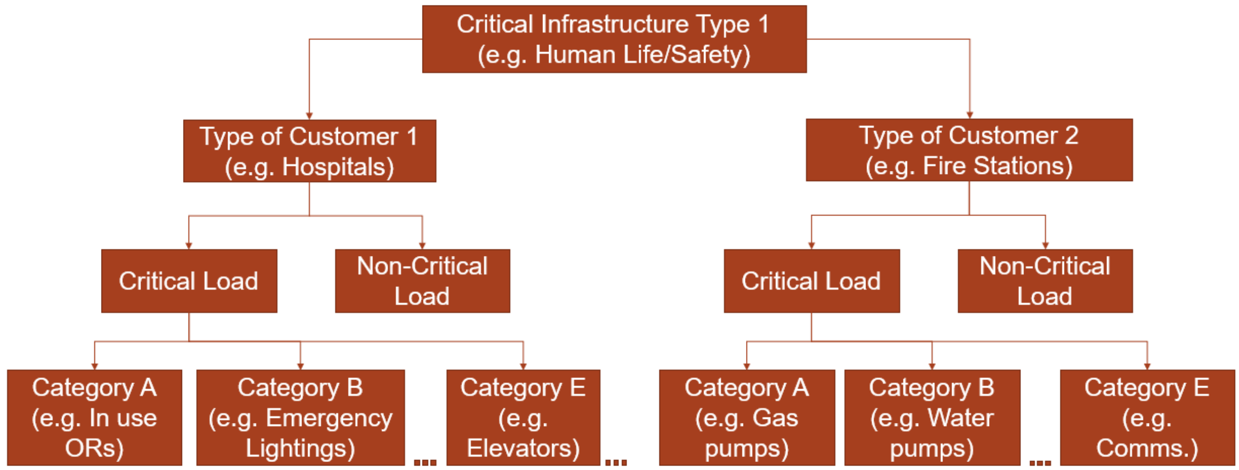

Figure 1. Proposed critical load classification and categorization structure

While every customer can have a distinct set of CLs, categorizing and understanding their individual energy consumption can help power system operators dispatch the minimum required power for safe operations. The following subsection further discusses such categorization of critical operations for loads that are considered critical.

2.1 Tasks Performed by Critical Loads

For any individual type of customer, the part of their entire load that is categorized to be critical also depends on the tasks performed by the related services, as shown in Figure 1. So, it is important to consider the functionality of each equipment before classifying it as CL. For example, in an emergency shelter, the minimum requirement would be to have functional lighting, so that much load should be classified as critical for the emergency shelters. Depending on the weather conditions, which are often not pleasant in most resilience level natural hazard events, the HVAC system might be required to operate as well. Hence, each load within a particular customer type (that is a part of any CI type) should be further divided into categories that would help them not only prioritize CL from noncritical load but also prioritize between multiple critical load categories during and after a grid disturbance event. An example of human life/safety CI with two different types of customers, hospitals and fire stations, is illustrated in Figure 1.

Similar task categorization is performed in industrial systems as a part of risk analysis (Zio and Sansavini 2011). Such evaluations inform the electric service requirements for commercial and industrial customers based on IEEE standard 3001.2-2017. Because of the customers' inherent understanding of their own facilities, it is vital that they, and not the utilities or the system operators, categorize which equipment operation/function is classified under the CL category.

2.2 Load Criticality Based on the Resilience Event

Another consideration while categorizing critical customers the need to map out which customers are critical for what kind of events. For example, a hospital that is at a higher elevation might be less critical during a flood than another hospital located in the flooding zone. That said, although the hospital on higher grounds is saved from structural damage, the electricity supply to both hospitals can be interrupted because of damage to the power system assets. Hence, based on the location of the substations, underground or over-ground line types, and other equipment, the criticality of loads can vary from event to event.

While trying to define performance evaluation metrics that are usable by the power systems for several different types of events, assigning varying levels of criticality based on events can prove to be challenging when trying to derive uniform metrics. However, the actions taken by a system operator during an event may need to consider the current state of the system. Using engineering judgment, critical customers will need to be further categorized based on their current state of criticality. A utility operator can perform such studies as a part of vulnerability assessments for different types of events. To that end the ensuing chapters of this report also talk about the inclusion of weights for different customers and their impacts on the quantification of performance evaluation metrics.

3.0 Metric-Based Evaluation Model

The proposed evaluation model is presented in Figure 2, which shows power grid disturbance as a potential threat to the grid that may or may not cause an outage in the grid. The impact of grid disturbance on the system is quantified using a performance measure and is captured through its characteristics. The performance measure serves as the identification of the metric to be monitored/measured/analyzed, whereas the system characteristics capture the trajectory of the system state due to the grid disturbance. The three components of grid disturbance theory (explained later in this chapter) are (1) grid disturbance, (2) system characteristics, and (3) performance measures. Because the focus of this report on analyzing CL inclusion in the system evaluation, we augment grid disturbance theory components using CL classification/categorization. The CL classification/categorization procedure identifies weights to be assigned for measuring the percentage of CL available to be included in the generic performance measure.

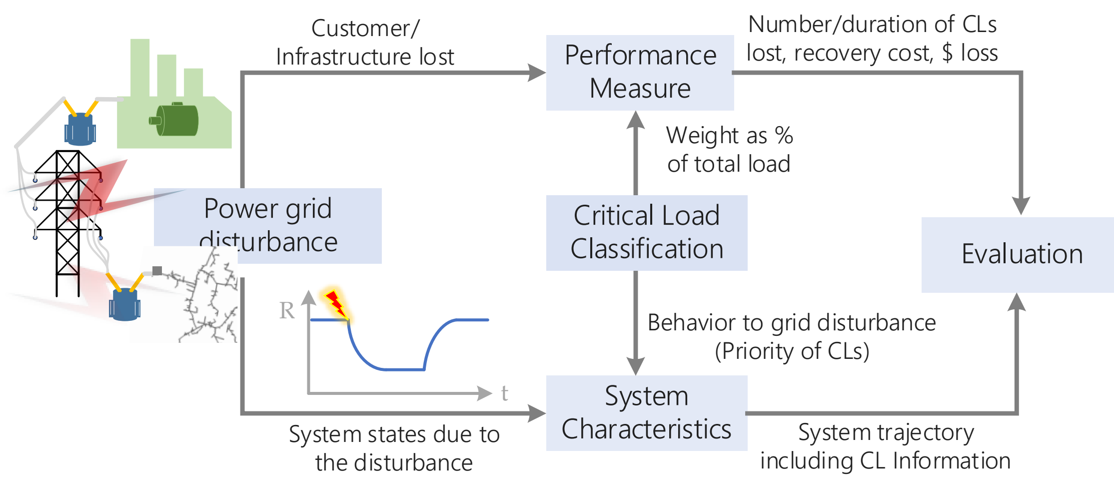

Figure 2. Proposed methodology for evaluating grid disturbance with the inclusion of critical loads in performance measure and system characteristics.

3.1 Brief Introduction to Grid Disturbance Theory

In this chapter we briefly discuss the concept of power system performance evaluation related to a grid disturbance (Hanif, Chalishazar and Hammerstrom 2020). Later in the report, we augment this evaluation with the inclusion of CL categorization. The reason for adopting such a generic evaluation method is twofold. First, it allows us to represent system characteristics to a grid disturbance in a more holistic manner. That is, the system characteristics pave way for the inclusion of CLs categorization and new operation and control opportunities (such as those provided by TESs). Hence, the influence of TESs to improve CL availability for a grid disturbance can be qualitatively described. Second, the grid disturbance view of resilience is generic enough to be tested side-by-side using a readily available metric from the literature, given that it coincides with the philosophy of harmonizing the consideration of reliability and resilience.

The grid disturbance theory presented in detail by Hanif et al. (Hanif, Chalishazar and Hammerstrom 2020) is briefly explained here. The theory provides system impacts related to a potential outage—a grid disturbance—through three system features:

- Avoid: Avoiding a/any grid disturbance,
- React: Reacting to a disturbance to reduce the system degradation, and
- Recover: Recover rapidly in the aftermath of the disturbance.

Figure 3 shows these three features of the system along with an example of the system characteristics (time-evolving trajectory) and performance measure (number of customers online). In Figure 3, the three system features of avoid, react, and recover are intended to be operable independently. In this way, each feature can capture its pre-defined role in the grid disturbance phase and help analysts/designers plan for the respective phase independently. Next, we explain the performance measure and system characteristics of the grid disturbance theory, focusing on including CL information in them.

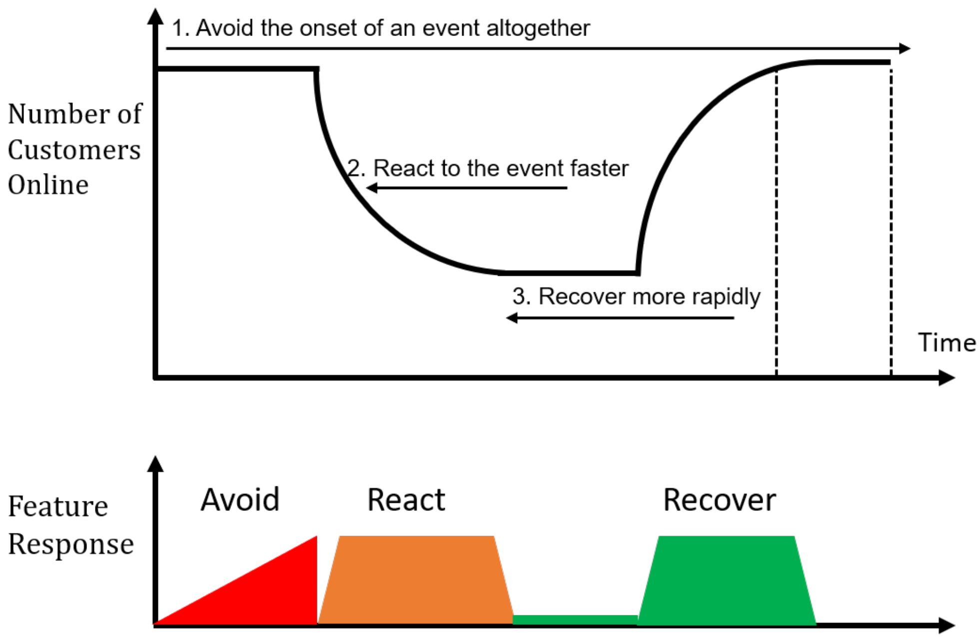

Figure 3. Example of a system performance trajectory for a grid disturbance.

3.1.1 Performance Measure

When grid normal operating conditions are compromised by a disturbance, it is a common practice to measure the performance of the system using a suitable consequence category (Vugrin, Castillo and Silva-Monroy 2017). Some common examples of consequence categories are critical electrical service, restoration, monetary, community function, and other critical assets. Among such categories, this report focuses on the critical electrical services and selects cumulative critical customer-hours of outages for measuring the performance of the system. We selected this performance measure for the following reasons:

- It provides a concrete comparison basis for system performance evaluation with and without inclusion of CLs. Chapter 3.3 explains a procedure for including CL information in a pre-defined generic performance measure that does not differentiate between all customers.
- It incorporates the time factor, which allows it to be represented in the system characteristics and eventually accounted for within each stage of grid disturbance.

3.1.2 System Characteristics

System characteristics translate performance measures to the avoid, react, and recover phases in response to a grid disturbance. This is because each phase is modeled by a functional form, consisting of parameters reflecting their respective system characteristics in that phase. For example, a hardened system may be able to avoid the grid disturbance more than a vulnerable system. Similarly, an innovative design and control methodology affects these characteristics and eventually changes the system trajectory to a grid disturbance. Considering that performance measure I is defined for the system, the system characteristics dictate parameters to help find periods during which the grid stays in the avoid, react, or recover stages. Table 1 briefly introduces these time durations and how they identify key system states, for a grid disturbance.

Table 1. Overview of the time duration obtained from system characteristics and a pre-defined performance measure.

Duration	Description
t_s	Duration of avoiding the disturbance
t_{react}	Duration of reacting to degradation caused by the disturbance
$t_{recover}$	Duration of recovery from a degraded state of the system

In Table 1, each duration is obtained using a parameterized functional form that reflects system characteristics. These functional forms then show the system performance and its evolution trajectory through each phase. For more information about these functional forms, the reader is directed to Hanif et al. (Hanif, Chalishazar and Hammerstrom 2020).

In principle, information about load criticality can be embedded in functional forms, such that the trajectory itself gets modified for accurate estimation of performance measures. However, this would have shifted the focus of the report toward a more involved CL modeling procedure where intrinsic details regarding load models and system characteristics need to be appropriately represented. We believe this is beyond the scope of this report, because the goal here is to demonstrate a metric-based evaluation that is influenced by the inclusion of CL. However, the grid disturbance theory does categorize important phases of the system trajectory, which can be used as a qualitative measure to include methods to improve system response through TESs.

With the above clarification, this report is going to adopt a quantifiable metric that has acceptance in the literature and can also be obtained through grid disturbance theory.

3.2 Base Evaluation Model

The base evaluation model in this report was developed based on a quantifiable metric. To this end, we adopt a metric from the literature by Kwasinski (Kwasinski 2016), which represents system availability as a measure of grid resilience. Note that this concept is in line with the philosophy of harmonizing the reliability and resilience considerations for assessing system performance in response to the grid disturbance. Moreover, this metric also supports the inclusion of CL information in the performance measure, as outlined in Chapter 2, as a crucial criterion of the proposed evaluation methodology. Kwasinski (Kwasinski 2016) nominates the cumulative resilience of every customer in the grid as a performance measure. That is, the time for which a customer is served during a resilience event (or more generally grid disturbance) accounts for the resilience of the individual customer:

$$R_I = \frac{T_{U_i}}{(T_{U_i} + T_{D_i})} \quad (1)$$

Equation (1) shows the individual availability where $T_{U,i}$ and $T_{D,i}$ are the up time and the down time of i^{th} customer during the time of consideration. The base resilience, R_B, of the portion of the grid under evaluation during a resilience event, can be calculated as the summation of the individual resilience of all customers. Mathematically, for N customers, base resilience is defined in Equation (2):

$$R_B = \frac{\sum_{i=1}^{N} T_{U,i}}{\sum_{i=1}^{N} T_{U,i} + T_{D,i}} \quad (2)$$

$R_B \in (0, 1]$, where 1 means there was no customer experiencing a down time whereas for a very small value of R_B, almost all customers went offline very rapidly. Another quantification of system performance can be obtained by expressing the fraction of customers experiencing an outage in an area at a given time. It is referred as the outage index, θ_t, which can be calculated as follows:

$$\theta_t = \frac{n_{0,t}}{N} \quad (3)$$

with $n_{0,t} = \sum_{i=1}^{N} (1 - s_{i,t})$ being the number of customers experiencing an outage and $\theta_t \in [0, 1]$, with 1 being all customers experiencing outage and 0 being no customers experiencing outage. Note that the evaluation of outage index requires information about the status of each individual customer ($s_{i,t} = \{0, 1\}$) at a given time.

From above, quantifications for the resilience of the grid require customer outage data during the entire onset of the grid disturbance, i.e., for all three phases of avoid, react, and recover. These data about customers affected during an outage are often easily available from utilities, making this metric usable and calculable.

Note that the cumulative up $\sum_{i=1}^{N} T_{U,i}$, down time $\sum_{i=1}^{N} T_{D,i}$ and outage index θ_t are in fact a function of system characteristics. Hence, in principle, for the same performance measure of customers connected to the grid, grid disturbance theory can also be used to obtain them as follows: $\sum_{i=1}^{N} T_{U,i} = f(t_s, t_{react}, t_{recover})$, $\sum_{i=1}^{N} T_{D,i} = f(t_s, t_{react}, t_{recover})$ and $\theta = f(t_s, t_{react}, t_{recover})$. However, investigations to obtain such functional forms are not pursued in this report. The main reason for this is that such a procedure is much more involved and may deviate from the main objective of this report, i.e., to demonstrate the impact of CL categorization on quantifiable grid resilience metrics.

3.3 Critical Load Modeling for Evaluation Model

During a grid disturbance, the main objective is to account for the CLs online so that they can be reflected during the avoid, react, and recover phases. As mentioned in Chapter 2.1, only a few customer types are identified as being critical for a given feeder or a substation during the time of scarcity. This is because not all customers have the same expectations of needing the same level of reliable firm service for their appliances and loads. The formulation in the chapter below is intended to include the CL information in a systematic fashion so that they are reflected appropriately in the evaluation metrics.

3.3.1 Critical Loads Weight Formulation for the Evaluation Model

Suppose C is the set of customer types within a feeder that represents all customers within a community such as residential buildings, apartments, malls, hospitals, fire stations, research institutes, emergency shelters, and so on (i.e., C = *{'Hospitals', 'Fire Stations', 'Malls', 'Residential Buildings, etc.}*). It is important for a utility to represent different services in the community as different sets. During a grid disturbance, it is common to lose service to any type of customers and it is imperative to include the concept of weights for each customer type so that the system tries to be biased more toward a CL during an emergency condition. With this consideration in mind, we modify the previously defined base resilience metric in Equation (2) by including weights for different customer types such that the proposed metric defines the base resilience for N loads with a weighted concept. Let w_c be the weight of a customer type $c \in C$. The augmented base resilience metric is then given by Equation (4). This metric first evaluates the base resilience of each customer type and combines them with the assigned weights. Note that the total sum of weights is kept at one $(i.e., \sum_{c \in C} w_c = 1)$ to keep the resilience metric value in the range of 0 and 1.

$$R_B^{aug} = \sum_{c \in C} w_c \frac{\sum_{i=1}^{N_c} T_{U,i}}{\sum_{i=1}^{N_c} T_{U,i} + T_{D,i}} \tag{4}$$

In Equation (4), $\sum_{c \in C} N_c = N$ is the total number of customers in the grid under consideration. Because the availability of critical customers is defined by using up and down times of the critical portion of their loads, the metric defined above will be enhanced only if the CLs receive power on a continuous basis. Thus, it is deemed important to include the priority of loads, and hence the base resilience metric defined in (2) is modified with the inclusion of the weights for the customers to better represent the performance of the grid.

The fraction of customers experiencing the outage in an area, with respect to all the customers in the area at a given time, is defined as outage incidence (see the mathematical representation in Equation (3)). Because the loads are populated with weights, the metrics not only reflect the number of customers while quantifying the outage, but also include weight factors giving an indication of loss of CLs during an outage. Mathematically, this is expressed in Equation (5):

$$\theta_t = \frac{1}{N} \sum_{c \in C} w_c \sum_{i=1}^{N_C} (1 - s_{i,t}) \tag{5}$$

where $s_{i,t}$ is the status of i^{th} load at time t. The maximum outage incidence is observed when $\sum_{i=1}^{N} (1 - s_{i,t})$ equals the peak number of outages N_o observed before the recovery is started.

4.0 Critical Load Prioritization Using Transactive Energy System Qualities

The system performance trajectory for an outage is given in Figure 4, which shows potential system objectives and mitigation strategies. The area under the system performance trajectory curve signifies the system performance loss, which, in this case, is customer-outage-hrs. Note that for a full understanding and assessment of resilience, which is a multidimensional concept, both the resilience level of a given system and transition times between the system states associated with an event are needed.

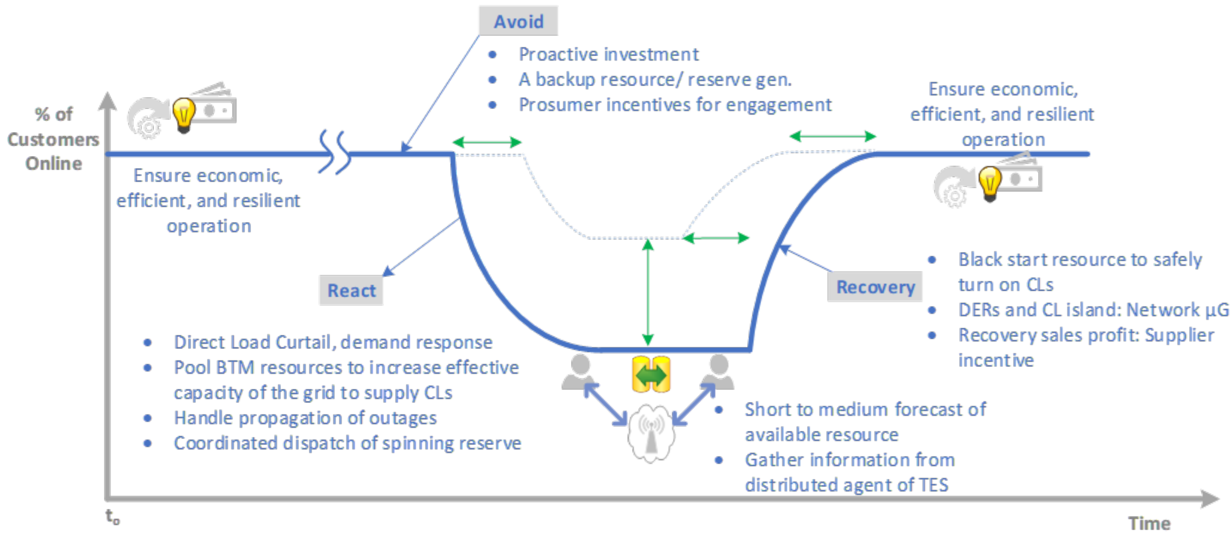

Figure 4. System performance trajectory before, during, and after an outage with potential system operation objective and mitigation strategies.

In the following chapters, we describe how the availability of the CLs, incorporated using appropriate weights, can be improved, thereby improving the system performance in response to an outage. We rely on the progression of performance measures in anticipation of the onset of an event, like the grid disturbance theory (as briefly presented in Chapter 3).

4.1 Improving Evaluation Metrics

With the inclusion of weights in the formulation, the objective here is to minimize the outage duration of loads by considering their priorities. To increase the weighted availability of the CLs, the area under the resilience curve needs to be decreased. This is done by prioritizing the critical customers and the CLs and bringing them into service quicker or while reacting to an event having continuous supply to the CLs thus decreasing their overall downtime. The system resilience metric is influenced by the three resilience components corresponding to avoiding, reacting, and recovering from such an event (see **Error! Reference source not found.**). If the event is altogether avoided or if the likelihood of the event is diminished, then the average time between events increases and they may eventually get deferred. If the system can respond faster to the onset of an event or system improvements resist and react to the event more rapidly, then the depth of the event may be diminished, thereby making the area shallower. Similarly, if the improvements in the system mean the system can recover from the events more rapidly, the tail of the event trajectory moves forward in time, i.e., shortening the event duration and increasing the rate of recovery, then the area can again be reduced. To summarize, the availability of CLs may be increased if a system can (1) avoid or defer the event, (2) respond or react to the event, or (3) recover from the event rapidly. In what follows, we detail the qualities of TESs that help a power system effectively avoid, resist, and recover from events while increasing the service availability to critical assets in the feeder.

4.2 TES Qualities and Mapping to Critical Loads Availability Improvement

It is well understood that TESs have been developed for efficient economic operation, but it is worthwhile to explore the application of TESs to meeting reliability and resilience objectives. Embedding load criticality into the performance measure and system characteristics will allow the TESs to respond in a way that preserves CLs, and the effectiveness of the TESs ability to preserve CLs will be captured within the metrics along with the impact on overall system resilience. TESs may either directly or indirectly harvest the monetized values of the existing grid products and services when the event progresses. Table 2 provides a non-exhaustive list of TES qualities that help the power system effectively avoid, react, and recover from the events (Hanif, Chalishazar and Hammerstrom 2020). These TES qualities are then summarized in the following chapters under the avoid, react, and recover phases of a resilience curve with a focus on improving CL availability. Note that the examples given here are representative of potentially many more applications that can originate from TES mechanisms.

Table 2. TES qualities for avoid, react, and recover.

	Avoid	React	Recover
Actor Motivation	Own self-interest to avoid events.	Own self-interest to lessen event severity.	Own self-interest to recover from event.
Contracted Response	Economic scheduling and reserve generation during the emergency.	Contracted autonomous. Can reduce the propagation of event	Prioritizing response with respect to criticality of load
Forecast time Horizon	Forecast supply conditions and system availability	Forecast update with the new information disclosed during the event	Short to medium forecast of the available resource
Locational Granularity	Fine, on order of possible event causation	Fine, on order of possible event causation	Medium, on order of event impact
Nature of DER Control	Economically steerable, continuously variable preferred.	Shift in operating modes for supporting the critical loads. Pooling up the resources for additional supply injection.	Black-start capability to safely turn on the critical loads in an isolated microgrids. TESs can show rapid restoration compared to current black-start practice. Concept of network microgrids increases the availability of critical load.

	Avoid	React	Recover
Prosumer Incentive	Favorable incentives keep prosumer devices constantly engaged.	Standby payments keep prosumer devices ready to respond. Direct load curtails or demand response to increase effective capacity of the grid.	Prosumer reward for supplying in islanded state. Injecting power from the local resources to grid instead of using locally.
Supplier Incentive	Prevent incurring startup costs.	Avoid damages to generators. Prevent damaging off-nominal conditions.	Recover sales profits. A supplier is incentivized if production is profitable.
Transacted Commodity	Commitment of spinning and non-spinning reserves, both up- and down-regulating	Coordinated dispatch of spinning reserve	Coordinated dispatch of non-spinning reserves. Sensing and facilitation of information flow.
Resource Procurement	Proactive investment and redundancy	Trucks and crew rollover for damage assessment and improved situational awareness	Purchase service assets for repair and speedy recovery

4.2.1 Avoid

The TES motivates the actors (consumers/prosumers or suppliers) to participate in avoiding the event by valuing the cost of service loss from CLs. For example, a service provider is motivated to manage vegetation, if made aware of the consequences of an outage resulting from a fault (Hollenbaugh and Champagne 2006). The valuation of the critical service loss also motivates utilities to plan their system with some level of redundancy. With the proper incentives, constant engagement of several entities can be ensured while working collectively to ensure resilience during any probabilistic event. The TES can leverage a model with a proper quantification of the loss of critical services versus the cost of dispatch/prepositioning and the operational cost of such generators owned by a non-utility entity. This helps to make an optimal decision about the proactive investment and increasing system redundancy. For example, mobile emergency generators can be prepositioned to ensure the continuity of supply to critical services despite the extreme event (Lei, et al. 2018). Similarly, a suitable forecast model within a TES will always provide an idea of supply conditions and an update on the system availability.

4.2.2 React

Once the event starts to progress, the grid becomes less available because several sources go down. The stress in the grid causes equipment to fail and customers to lose service. One of the most important features of a resilient system is that it should resist the event as much as it can to prevent damage and propagation of the outage. The TES can help the grid resist/react to an event in many ways, thereby reducing the impact and preventing the propagation of outages.

A TES may incentivize prosumers to control the behind-the-meter DERs such as rooftop photovoltaics (PVs), household storage, light-duty electric vehicles (EVs), and controllable loads that are located at commercial and residential buildings in response to an extreme event. For example, some households and buildings could be incentivized to defer the non-essential loads to off-peak times, curtail the loads, or tap their local storage resources—all of which increase the effective capacity of the grid to meet the supply requirements for the critical services (Chen and Liu 2017). Similarly, the nature of DER control could be changed as an input signal from a TES such that customers have their DERs supply the grid instead of using them locally for supporting the critical services with a provision of prosumer incentives. A TES can update the forecast with new information that is disclosed during the event to update the supply condition and system availability. It helps the system prepare for the recovery or give a better idea of the required resources for the continuous supply of CL for the next time horizon based on the loads' bid magnitudes corresponding to their prioritization (Gao, et al. 2016).

4.2.3 Recover

If the system can respond faster to the onset of the event, the area engulfed by the curve should be shallower, recovery might initiate sooner, and the metric area would likely be smaller. While the infrastructure recovery may take longer for the repair processes after an extreme event, the critical services must be made online as soon as possible with some other smart actions. From a generator contract perspective in a TES environment, it is worth prioritizing the contracted response with respect to the criticality of the load it is supplying. The forecast time horizon is also important while bringing the CLs online with limited resources so that the resources are not depleted, and they remain online until the grid comes back online. In such a case, 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. In addition, large footprints of renewable energy resources limit their application for the islanding operation during recovery. A TES can help in managing diverse power sources to improve service availability. Note that to increase the service availability of CLs, it is necessary to increase the availability of sources supplying the CL (Song, et al. 2012). A concept of networked microgrids and power-sharing is an example where the TES features help for managing the efficiency, reliability, resilience, and sustainability of electric power services (Eskandari, Li and Moradi 2018). Another TES feature to support recovery during an extreme event is to use the black-start capability to safely turn on the CLs in isolated microgrids. A TES can show rapid restoration compared to the current black-start practice.

5.0 Value of the Metric Augmentation: A Working Example

Chapter 3 suggests that there is a need to improve the existing metrics and proposes the augmentation that needs to be carried out to include a weighting concept for CL prioritization. This chapter further clarifies the implementation of the proposed concept using a working example. The first step is to know and understand the system that is going through a disturbance event. For this purpose, we are going to use the illustrative grid topology given in Figure 5.

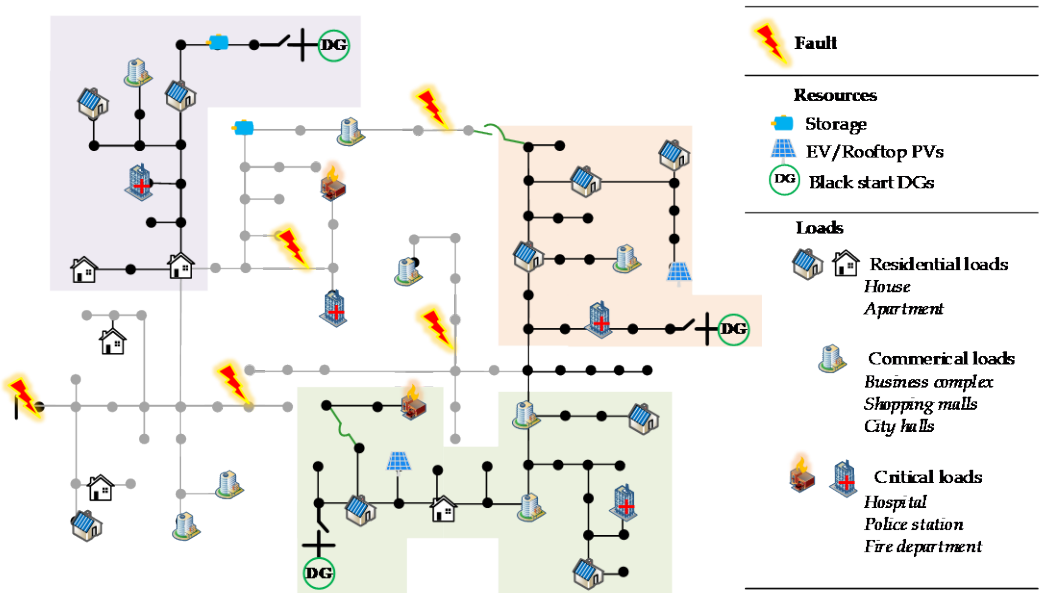

Figure 5. Grid topology for the working example.

In this representative system, there are three types of customers: (1) Critical (4 hospitals and 2 fire stations), (2) residential (100 homes), and (3) commercial (10 commercial buildings); and three different types of resources: (1) Storage, (2) EV/rooftop PVs, and (3) black-start capable distributed generators (DGs) that participate in transactive markets and can be used by system operators whenever needed. For this working example, a grid disturbance event which brings major outage to the grid and is recovered within a day is considered. Table 3 summarizes the different customer types and their assigned weights. These values are selected randomly for demonstration purpose and might not reflect the actual values used in practice.

Table 3. Customers type and their assigned weights.

Customers	Counts (N_c)	Weight (w_c)
Hospitals	4	0.4
Fire stations	2	0.4
Residential	100	0.1
Commercial	10	0.1
Total	116	1

In what follows, we perform a few case studies to see the value of CL in the proposed resilience metric. For the case studies, we show how the new resilience metric in Equation (4) captures the CL concept, while the original base resilience metric defined in Equation (2) fails to do so. To make things easier Equations (2) and (4) are stated again in this chapter.

$$R_B = \frac{\sum_{i=1}^{N} T_{U,i}}{\sum_{i=1}^{N} T_{U,i} + T_{D,i}} \tag{2}$$

$$R_B^{aug} = \sum_{c \in C} w_c \frac{\sum_{i=1}^{N_c} T_{U,i}}{\sum_{i=1}^{N_c} T_{U,i} + T_{D,i}} \tag{4}$$

A time frame of one day is considered. Three different case studies show different individual availabilities of the customers, and it can be observed that the value of the resilience metric increases with increased availability of customer. The uptime and downtime of each customer are taken and plugged into the equations to evaluate the metric. For example, in Case I, out of 4 hospitals, 3 hospitals were always connected and never lost service for the entire day while one hospital was out of supply for 70% of the time (i.e., was on service for only 30% of the time in a day), thus making their total uptime $3.3\ (i.e., 1+1+1+0.3)$. Doing similar calculations, the metric for Case I is evaluated using Equation (8). Similar calculations are performed for the metric calculation when a customer's uptime and downtime changes for different case studies.

$$R_B = \frac{3.3 + 1.5 + 91 + 8.2}{116 * 1} = \frac{104}{116} = 0.896 \tag{6}$$

Table 4 shows the value of resilience metrics using Equation (2) for three different case studies with Case I being a base one. In Case II, we can see that the resilience metric increases from 0.896 to 0.931 when the availability of residential customer is increased from 91 to 95. While in Case III, the resilience metric increases to a value of 0.90 with a slight increase in the availability of hospitals and fire stations (see Table 4Table 3). Considering the numerical values, one can conclude that the resilience is higher for Case II because this method evaluates the base resilience without a proper distinction between the customers.

Table 4. Resilience metrics value for different cases using Equation (2).

Customers	Case I	Case II	Case III
Hospitals	3.3	3.3	**3.4**
Fire stations	1.5	1.5	**1.8**
Residential	91	**95**	91
Commercial	8.2	8.2	8.2
$\boldsymbol{R_B}$	**0.896**	**0.931**	**0.90**

Table 5 shows the value of resilience metrics using Equation (4)(2) for the similar case studies as before. In this evaluation, the resilience metric is observed to be higher in Case III than in Case II. This is because, the proposed metric also accounts for CL weights and significant improvement in resilience can be observed only when the CLs receive power on a nearly continuous basis (i.e., higher uptime).

Table 5. Resilience metrics value for different cases using Equation (4).

Customers	Case I	Case II	Case III
Hospitals	0.4 * (3.3/4) = 0.33	0.4 * (3.3/4) = 0.33	0.4 * (**3.4**/4) = 0.34
Fire stations	0.4 * (1.5/2) = 0.3	0.4 * (1.5/2) = 0.3	0.4 * (**1.8**/2) = 0.36
Residential	0.1 * (91/100) = 0.091	0.1 * (**95**/100) = 0.095	0.1 * (91/100) = 0.091
Commercial	0.1 * (8.2/10) = 0.082	0.1 * (8.2/10) = 0.082	0.1 * (8.2/10) = 0.082
R_B^{aug}	**0.803**	**0.807**	**0.873**

From the example presented above, we have shown that once an augmented metric is on hand, it can be used to evaluate the resilience metric for any grid disturbance event and guide the grid's response to it. Consider that the grid area of the above presented example contains three different types of distributed resources such as: (1) storage, (2) electric vehicles/rooftop solar photovoltaic systems, and (3) black-start capable distributed generators. To utilize these resources, a transactive platform can be proposed which allows the system operator to coordinate them to improve its underlying grid resilience. Such a framework is shown in Figure 6 and its working explained as follows. When a grid experiences a disturbance event, several control actions can be carried out to minimize the effect of an event in all avoid, react, and recover phases. As pointed out in Chapter 4.2, several TES qualities can help to improve the system performance as the grid progress through different stages. The CL concept is useful in bringing the critical services back sooner based on their priority. After the recovery is done and the system is back to the normal condition, one can use the augmented resilience metric presented in this report to evaluate the overall performance of the grid.

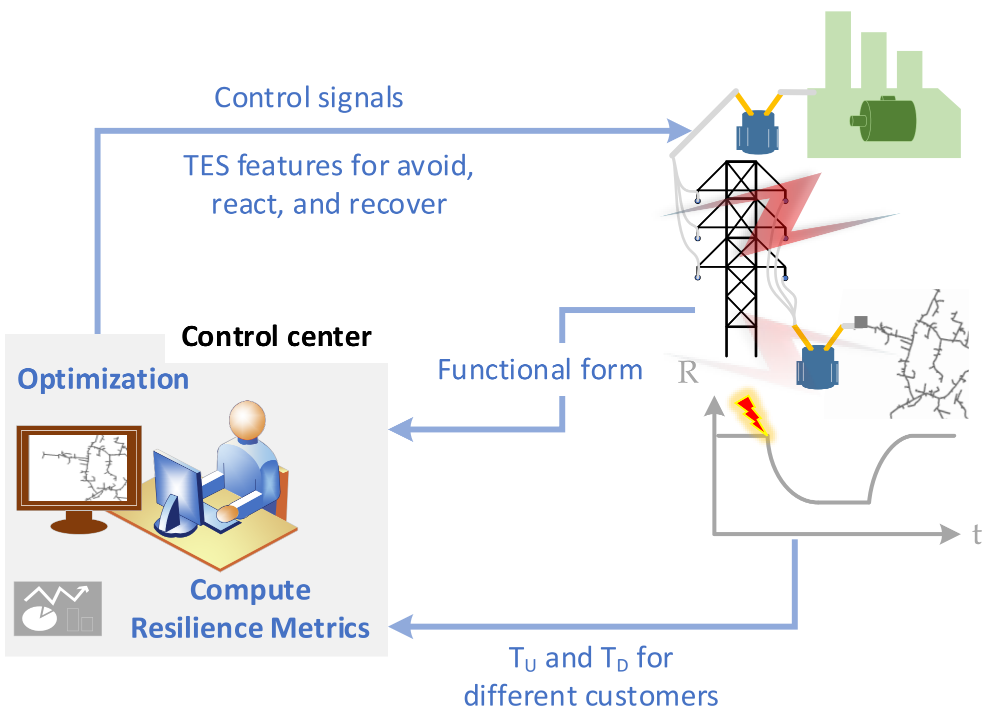

Figure 6. A framework for evaluating the resilience metric.

6.0 Conclusion and Future Work

In most literature, CI, critical customers, and CLs, are used alternatively and are not clearly defined. Although most literature in the field of power system resilience and reliability does agree that there should be some level of prioritization for critical customers, almost none of it provides any metrics that can facilitate the evaluation of critical customer prioritization. This report provides a detailed characterization of CIs, critical customers, and CLs that clearly defines boundaries for each of them. It also proposes a weight-based augmentation to some previously existing resilience metrics to show the impact of critical customer prioritization on those metrics.

In addition, this report discusses different TES features that can improve the proposed resilience metrics, thereby increasing the weighted availability of the critical customers. A thought experiment on the proposed approach shows that the weight-based augmented resilience metric provides a proof-of-concept for the adoption of customer priority to support critical services during an outage. The future work in this research may include:

1) The concept of dynamically changing weights in evaluating grid performance to disturbance. This is because as a disturbance event progresses the relative criticality of different critical customers may change and to be able to capture this accurately and represent it in the existing metrics may turn out to be an essential part of resilience evaluation,

2) Further research on combination of various performance measures and metrics combination to accommodate and/or evaluate critical load prioritization and hence improving the assessment of system performance for any disturbance event, and

3) Developing a comprehensive framework to simulate and analyze the role of TE qualities in critical load prioritization.

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