Survivability of the Electric Grid

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***Abstract*—Power Industry is facing revolutionary changes. The drive toward a lower carbon footprint leads to the high penetration of renewable energy resources. As more variable and demand response resources are integrated into the power grid, grid operation is experiencing an increasing level of uncertainty. The decision making process under such environment becomes very challenging. Also, the grid architecture and control have become more decentralized as distributed resources grow, entailing new control paradigms and reliability metrics in order to achieve a higher level of flexibility and resilience. All these changes are disruptive enough to even cause transformations in utility businesses that need to deal with completely unknown situations. This paper analyzes the DOE OE-417 data to expose the deficiency of the existing reliability concept. The concept of survivability is then introduced and illustrated with the frequency disturbance event.**

***Index Terms*—Complex Systems, Grid Architecture, OE-417, Reliability, Survivability**

I. INTRODUCTION

Reliability has been the central issue for power system planning and operation in the past several decades. According to North American Electric Reliability Corporation (NERC), reliability is defined by resource adequacy and operational reliability. The former ensures an adequate level of resources to meet the projected load. Such level is often measured by the Loss of Load Expectation (LOLE) with the typical criterion of 1 day in 10 years. The latter secures the operability of the system taking into account contingencies. The security is often measured by the N-1 criterion, i.e., the system can maintain balance and stability with the loss of any single element. Reliability is maintained by the system operator at the same level for the entire system, and is treated as a public good. Such reliability concept was developed for a centralized system with a manageable level of uncertainty.

Under the conventional reliability framework, resource adequacy encompasses the probability of having enough generation resources to meet demand while taking into account the likelihood of each resource experiencing a forced outage and the stochasticity of the load. Operating reliability encapsulates the system's response to unexpected contingencies that are deemed credible by expert judgment. Credible contingencies include single events such as transmission line, substation, transformer, and switchgear failures, as well as multiple common-mode contingencies.

There are two primary problems with this conventional framework: *First*, the scenarios that have catastrophic impact such as the 2003 blackout in U.S. but with a low probability are not explicitly analyzed. As cascading failure events have demonstrated, it is rarely the isolated single or multiple common-mode contingencies that are to blame but a handful of independent contingencies coupled with the stressed system operating state. Additionally, the most frequently occurring disturbances to power systems are weather-related events, and these are capable of initiating multiple non-common cause contingencies. *Second*, the conventional reliability framework is not suited for incorporating significant demand-side or distributed energy resources and other smart grid components. Distributed energy resources are being built deeply in the distribution networks and the boundary between transmission, sub-transmission and distribution is blurring. Significant part of these distributed generation resources is unobservable for the system operators. This has introduced an unprecedented level of **uncertainty** to the system operators not only in the locations of distributed resources, but their intermittent nature as well, e.g., the output of wind and PV generation can swing significantly in time. The tribal knowledge of system operators is failing in dealing with completely unfamiliar patterns of the system behavior. Even the concept of a contingency is changing from being binary (the element of the grid is "on" or "off") to a continuous value in time change. The large swing in system load or generation by several thousand MWs within a comparatively short period of time, used to be considered as abnormality or emergency, is becoming part of a "new" normal operation pattern.

Consequently, conventional power system reliability modeling may prove insufficient to effectively evaluate and plan for the well-being of complex power systems as the structures of these systems evolve over subsequent years. Expanding the reliability framework to analyze the propensity of the system to experience cascading failure given unexpected contingencies, and the overall "stress" on the system would be a useful addition to the conventional reliability theory. To address that deficiency between the conventional reliability theory and the increasingly complex and decentralized power grid with significant amount of uncertainty, new system attributes such as **resilience**, **robustness** and **survivability**, which are a small subset of the terminology that has been used in other fields such as ecology and network systems to describe the well-being of complex systems, may prove valuable in extending the traditional reliability theory for power systems.

In this paper, we will first discuss the evolution of electric grid in Section I. Then we demonstrate the deficiency of the existing reliability indices by analyzing the Department of Energy (DOE) OE-417 data in Section II. The concepts of resilience, survivability and sustainability are introduced in Section III. Conclusions are discussed in Section IV.

II. ELECTRIC GRID EVOLUTION

Modern power systems are going through different stages of evolution driven by technical, economic, and regulatory events. They went from decentralized, very loosely coupled grid to highly interconnected centrally controlled systems. The increased complexity and lack of ability to manage it led to major blackouts forcing significant changes in system planning and operation. The Great Northeast Blackout of 1965 led to the creation of the power pools with control centers running Energy Management Systems (EMS), centralized regional planning and control. Each pool linked together multiple neighboring transmission companies with much stronger ties among them (Fig. 1). Besides local control centers, power pools created pool control centers. Not only did this help increasing the reliability and resilience by the ability to provide balancing assistance, but also resulted in savings for the member companies by using less expensive generation to meet the regional load. The interties between the pools were still weak and only used for emergency help. With the inception of the markets in late 90s and creation of ISOs/RTOs, market players started placing economic transactions across the pool boundaries increasing the complexity of the grid operation. This led to reinforcement of the transmission and tighter integration of the interconnected systems. The complexity of such an architecture required new ways of the system control. The Economic Dispatch (ED) being done in each market area independently created so-called seams issues – inefficient utilization of the interties. This, in turn, required additional information technology and communication infrastructure to coordinate market operation across large geographic areas. Electric grid had become a very large complex cyber-physical system. All these changes and attempts to increase grid reliability have not lowered the risk of large blackouts. On the contrary, the number and frequency of blackouts is increasing, which is the property of very large complex system that exhibits self-organized criticality [1].

Another property of large cyber-physical systems is a high interdependence of different infrastructures. Not only do we have to monitor the system for electric grid contingencies, but for the failures in communication and information technology systems. The system resilience is getting much weaker, which requires new solutions for system planning and operation. Today, power systems are operated almost exclusively on the preventive paradigm. Every contingency is considered to be of probability 1, and the system is dispatched in such a way that no one failure causes violation of reliability criteria (i.e., N-1 standard). This approach, being quite expensive on the first place, becomes economically prohibitive in the new environment. More corrective actions must be introduced to make power system operation less expensive.

All the above requires significantly different control paradigm, new grid architecture, new algorithms, new models and new reliability criteria.

Fig.1. Creation of Power Pools

III. DOE OE-417 DATA

The Loss of Load Expectation (LOLE) is widely used in the power industry as a reliability index. Most regions in the US, e.g., PJM, MISO, NYISO, ISO-NE, Maritimes, Quebec, IESO, adopts the "*one day in ten years*" as the LOLE criterion in the regional power system planning. It is natural to examine the reliability level of the system that was planned under the LOLE criterion.

The US Department of Energy (DOE) mandates the reporting of electrical disturbances by control area operators, reliability authorities and other electric utilities through the online Electric Emergency Incident and Disturbance Report form OE-417 form[1]. In this section, we analyze the OE-417 data of the years from 2003 to 2011. Based on the analysis, we reveal the deficiency of the existing reliability indices and the need for new indices.

There are total of 889 OE-417 records during 2003-2011. Each record includes the duration of the reported event. The histogram of the event durations is depicted in Fig. 2. It can be seen that most of the events lasted between several hours to several days.

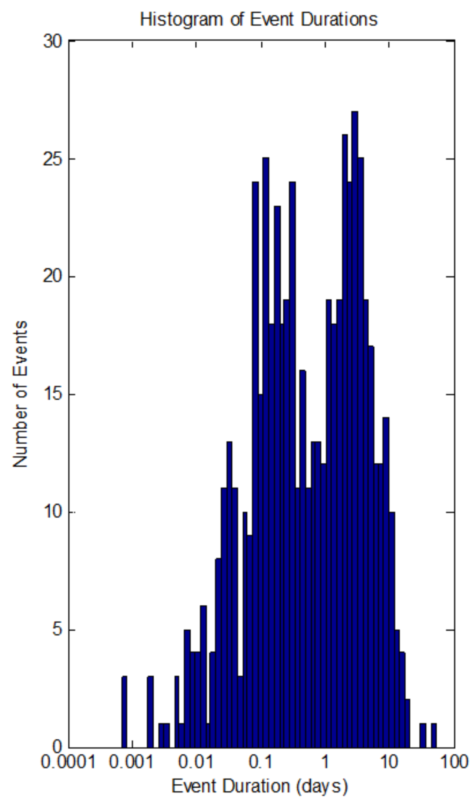

Fig.2. Histogram of event durations

Since we intend to examine the LOLE criterion adopted by NERC, we categorize the events into different regions as depicted in Fig. 3.

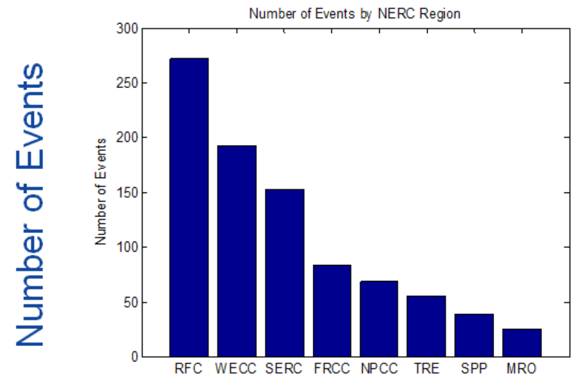

Fig.3. Number of events by NERC regions.

We also categorize the cause of the reported disturbances into 11 types in Fig. 4 based on the reported event details. Among the above categorized event types, it can be seen that weather or natural disaster accounts for the majority of the disturbances.

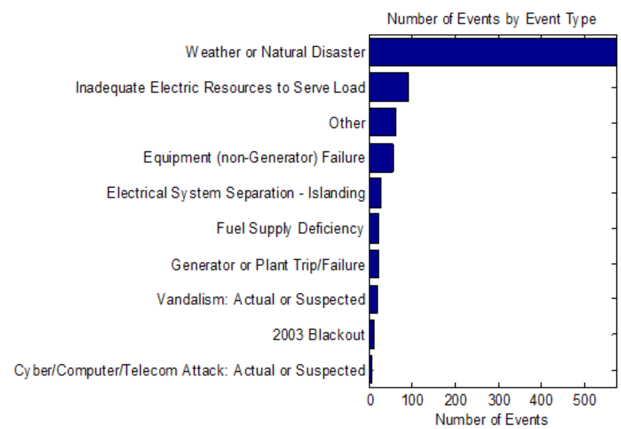

Fig.4. Number of events by event types.

The existing LOLE criterion covers the loss of load events due to insufficient generation. In practice, power system planners calculate the LOLE based on generator outage model and load probabilistic model. To examine the LOLE with the OE-417 data, we find the following three event types are closely related to the LOLE model: Inadequate Electric Resources to Serve Load, Generator or Plant Trip/Failure, and Equipment (non-generator) Failure. Therefore, we calculate the empirical LOLE based on the OE-417 data with these three disturbance types. The calculated LOLEs for different regions are depicted in Fig. 5. It can be seen that regions exhibit a wide range of performance across different years.

[1] See https://www.oe.netl.doe.gov/OE417/

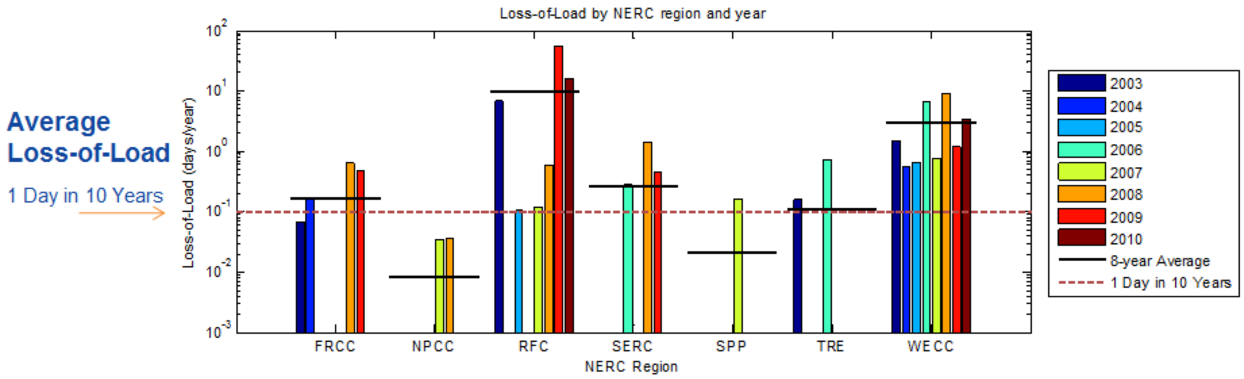

Fig. 5. LOLE by regions.

Also, the empirical LOLEs do not seem to converge to the planning criterion of 0.1 days/year LOLE. The reasons may be caused by the categorization of the reported disturbances or the ambiguity in the reported event details. However, one reason should not be ignored, i.e., the planning process is an open loop control since the regional planners are never required to check the planned the systems after the fact for reliability levels.

In addition, the weather or natural disaster category, which has the most coverage of the reported events, is not modeled in the traditional reliability evaluation. The comparison of the events covered under the current reliability models and those that are not covered is depicted in Fig. 6. The light colored dots in the figure represent the events covered by the existing reliability models, while the dark dots in the figure represent the events not covered by the reliability models. Apparently, the majority of the reported disturbance events are missed out in the power system reliability models during the planning process. As a result, the insufficient coverage of power system reliability models raises the natural question of how useful the existing LOLE criterion is for maintaining the power system reliability.

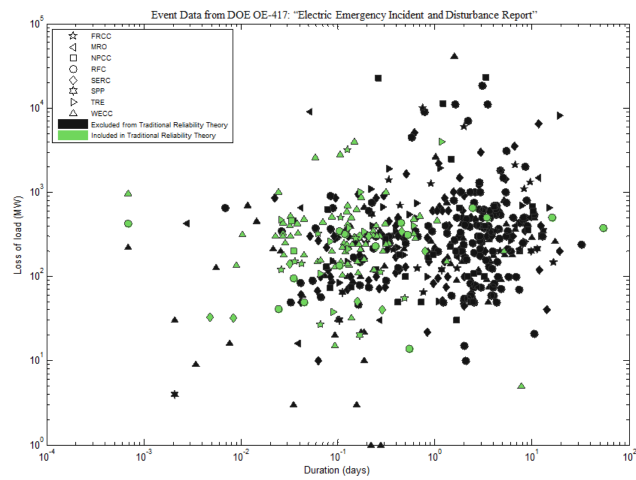

Fig. 6. Events covered in the current reliability models

Furthermore, the existing reliability models used for LOLE evaluation do not characterize the cascading failures of the power system. However, based on the OE-417 data, we can calculate the probability of the loss of load events versus the loss of load size. As depicted in Fig. 7, it appears that the tail follows the power law distribution. This result is consistent with recent findings in the literature [1]-[2]. Therefore there is non-negligible probability for the events with large loss of load such as cascading events.

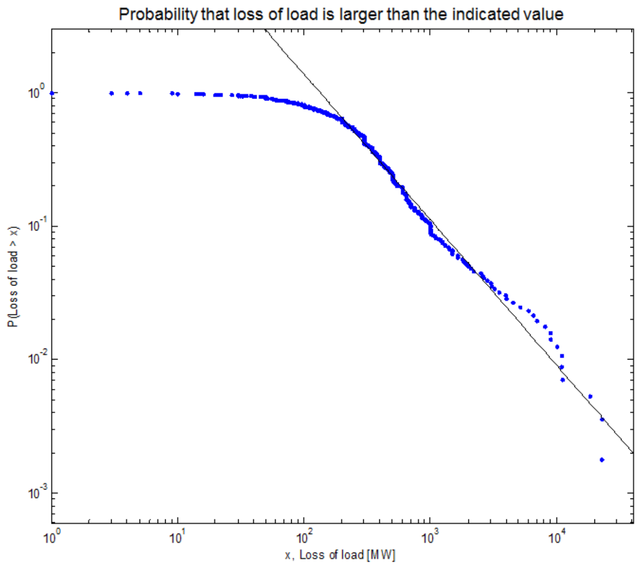

Fig. 7. Disturbance probability vs. disturbance size.

The above analysis points to the deficiency of the existing reliability criteria and models. With the increasing uncertainty and complexity of the power system, such deficiency will only magnify. As a result, a new set of criteria that better characterize the well-being of the power system is needed urgently. In the following section, we propose a set of such new criteria.

IV. SURVIVABILITY OF POWER SYSTEM

While the existing reliability concept appears to be deficient in measuring the well-being of the more uncertain and complex power systems, several other concepts, e.g., resilience, robustness, survivability, etc., have been discussed and used in other industries [3]-[9]. However, one problem with these terms is that their meaning has become confused, interchangeable, and often varies between and within disciplines. Below we summarize several key system features to distinguish different concepts. Then we develop a comprehensive survivability concept based on these features.

- *Reducing the number and the severity of disturbances, and operating the system in a safe distance from critical points to protect the system against* ***endogenous*** *disturbances*. This feature relates to actions taken to remove or reduce the sources of disturbances that can be controlled or protected against, e.g., improving the lighting protection on transmission lines and operating the system with a safe margin. This feature may be conditionally described by the **stability** concept.
- *Reducing the number and severity of disturbances, and operating the system in a safe distance from critical points to better position the system against* ***exogenous*** *disturbances*. This feature means that the system is built and operated through the controllable system components so that it is immune from certain range of exogenous disturbances such as weather and physical attacks. This feature is captured by the **robustness** concept.
- *Acceptable quality of service, minimal loss of value, and maximal speed of recovery during and after the system is subject to* ***endogenous*** *disturbances* or the absence of disturbances (i.e., normal operation). This is the field analyzed in conventional reliability theory: given that system components may fail, how often do such failures occur and what is the impact on the system, its customers, and on power-delivery This also encompasses normal operation in the sense that the system should provide an acceptable quality of service when there are no contingencies, so there are no inherent flaws in the system design. This feature may be defined by the **reliability** concept.
- *Acceptable quality of service, minimized value-loss, and maximized speed of recovery during and after the system is subject to* ***exogenous*** *disturbances*. The response of the system to external challenges is considered in this characteristic. For example, how will the system respond to a directed attack on the most critical infrastructure, or perhaps from a high-impact natural disaster? Also, the time to recovery of the system should be as short as possible. This feature may be captured by the **resilience** concept.

The above four features respectively define the stability, robustness, reliability, and resilience concepts of a power system. Note that these concepts focus on different aspects of the well-beings of a power system and are complimentary to each other. With the increasing level of uncertainty and complexity in the evolving power grid, any of the concepts alone is not sufficient to represent the system well-being. Therefore, below we define a comprehensive concept of **survivability** that encapsulates the aforementioned four features within the medium-term time frame after the disturbance.

Survivability: *Reactive adaptation in the medium-term to better handle disturbances and improve the quality of service*. In response to disturbances, the system is able to react on the medium time scale of days to months to position itself against the effects of new unexpected disturbances. Namely, it captures the system's ability to restore its stability, reliability, robustness and resilience within the medium time.

Other definitions of survivability can be found in the literature, e.g., [10]. The above survivability concept specifically introduces the time dimension, which helps managing the cascading events that could spread in days. A further extension of the survivability concept to a longer time frame leads to the concept of **sustainability**, which deals with the ability of the system to make long-term changes (on the order of years to decades) that will anticipate future challenges and add enhanced functionality. This includes the ability to integrate smart grid concepts, while controlling or at least understanding the complexity, so as to only elicit beneficial autonomous behavior and self-organization.

All the above concepts are illustrated in Fig. 8 below.

One important application of these concepts is to develop comprehensive system well-being metrics in addition to the conventional reliability metrics. Consider a hypothetical system disturbance depicted in Fig.9 where $f(t)$ could be an indicator of system health such as frequency or voltage.

Satisfactory response of a system in the face of exogenous disturbances is a critical component of system well-being. In a hypothetical disturbance event shown in Fig.9, a system which is least affected by the disturbance will be preferable. To measure how **resilient** the system is to the disturbance, several potential metrics are introduced. First, the change in f during the disturbance averaged over all N events is

$$\overline{\Delta f} = \frac{1}{N}\sum_{i=1}^{N}\Delta f_i \ .$$

This metric can provide a measure of how significant the average effect of the disturbance is on the system.

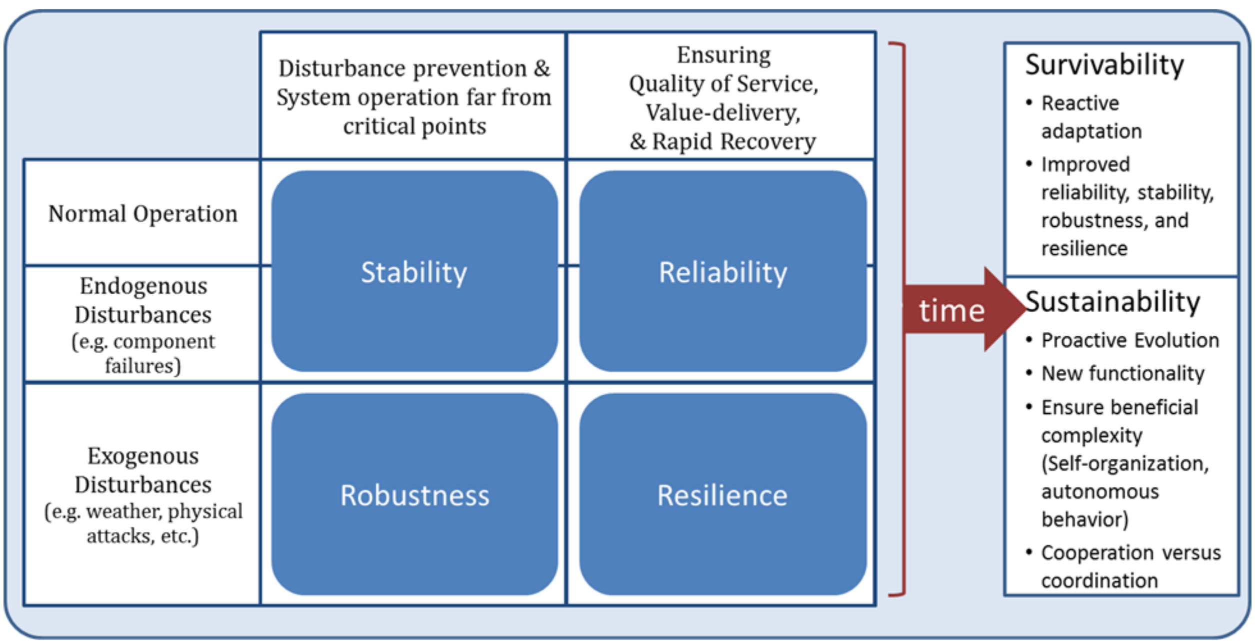

Fig.8. System well-being characteristics and their relations

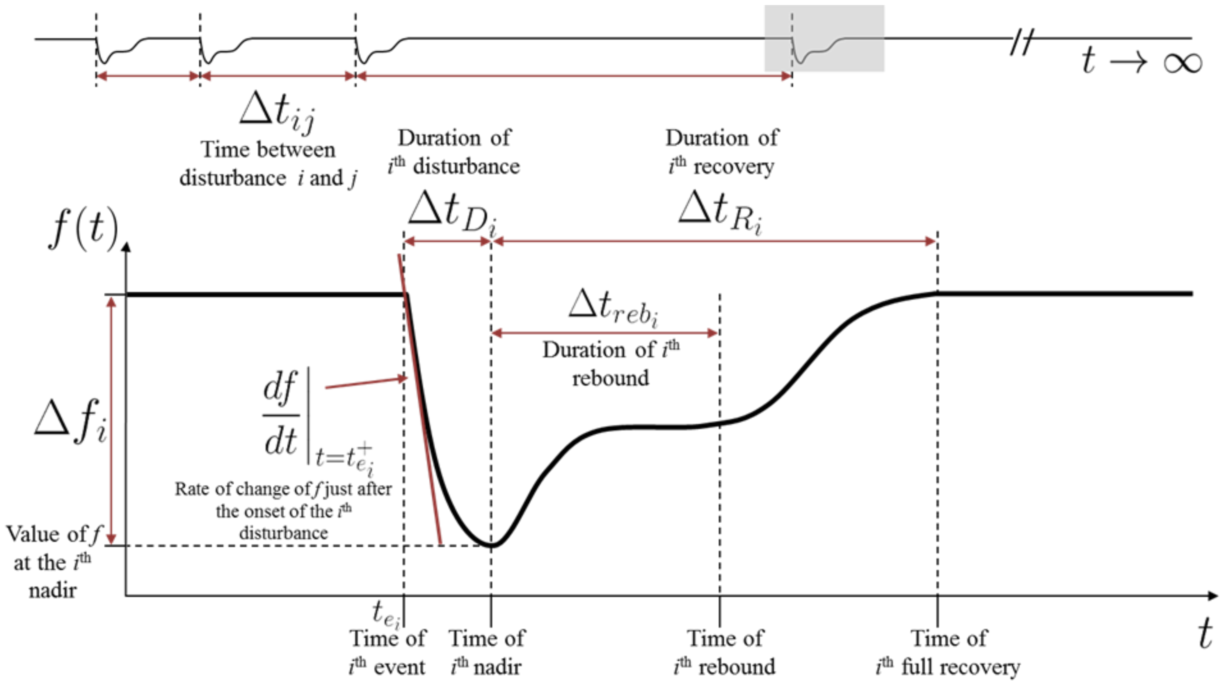

Fig. 9. An illustrative disturbance event and system metrics.

A second metric for resilience is the rate of change of f right after the onset of the disturbance event i, i.e.,

$$\left.\frac{df}{dt}\right|_{t=t_{e_i}^+} .$$

This metric is related to the system inertia. Systems with greater inertia will not change as rapidly as those with less inertia, thus allowing more time for system operators to take actions to prevent greater damages.

Similarly, the longer the system stays in the reduced operational state, the greater the potential for further disturbances and damage, and the greater the loss of value-delivery. Therefore, a natural resilience metric is the average duration of the recovery, averaged over all events, i.e.,

$$\overline{\Delta t_R} = \frac{1}{N}\sum_{i=1}^{N} \Delta t_{R_i} .$$

The ability of a system to operate as far as economically possible from critical points is essential for the well-being of the system. In this context critical points are the threshold between low and high probability of system disturbances, either during normal operation, or in the presence of exogenous disturbances. As the system increases its load level, it may reach a value at which the probability of large cascading failures rapidly increases. This is illustrated in Fig.10, where the system stress is measured by the system load level x and the cascading probability is represented by p.

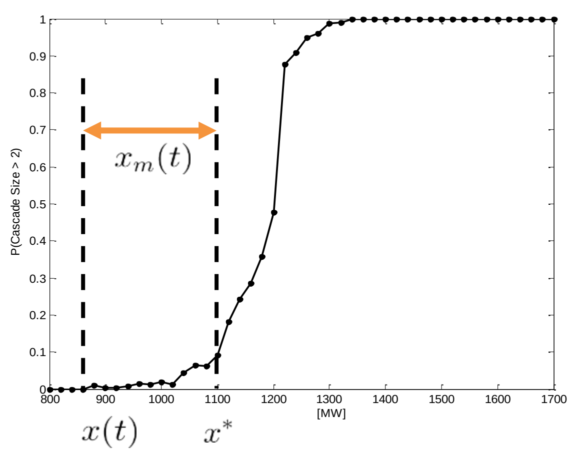

Fig.10. Measuring system stress and the system's operational distance from criticality

Assume that the system is operating at a stress level $x(t)$ at time t and that the predefined critical stress level is x^*, then the operating margin between the two is a measure of how **stable** the system is, i.e.,

$$x_m(t) = x^* - x(t) .$$

The measure of how **robust** the system is how rapidly that phase transits from a low probability of cascading failure, to an almost certain cascading failure. This metric can be defined as:

$$\xi = \frac{\Delta p_c}{\Delta x}$$

Finally, the system **survivability** concept can be measured by certain cascading risk index. Since the cascading events can spread over days, it's difficult to mathematically model the entire process. Often the cascading risk can be evaluated through simulations. Some online tools have been developed [11], and the users can specify the threshold for cascading indices defined in the tool, e.g., islanding load, generation loss, load loss, etc.

The introduction of new concepts and metrics such as the above ones is necessary for the future power systems which will exhibit very different characteristics from the current reliability-based systems. These concepts and metrics, in turn, will also shape the future grid architecture and consequently how we plan and operate the system.

Furthermore, under today's centralized control scheme, the risk associated with the power system uncertainty is almost exclusively managed through "***preventive***" actions by the system operator, i.e., the system is designed to sustain a set of predefined contingencies. However, with the power grid evolving into an increasingly complex system and becoming more interdependent on other systems, making the system violation-proof would be nearly impossible and expensive. Meanwhile, in reality, the system can survive certain violations as long as the system can correct the violations within certain timeframe. Such "**corrective**" actions under the new concept of survivability take advantage of the system's flexibility feature, and therefore are less expensive than the preventive actions. The cost savings with the modeling of corrective actions come at the expense of computational complexity since the post contingency states need to be modeled or simulated (Typical ways of modeling corrective actions include two-stage stochastic programming or robust optimization, both are computationally challenging for real-time operations in particular). A comprehensive comparison of the preventive and corrective controls is difficult due to the complexity of the study and the lack of appropriate metrics, and very few publications can be found on the topic [12]-[13]. Further research is needed to provide the important cost benefit analysis for trade-offs between the corrective and preventive control paradigms.

V. CONCLUSION

Reliability criteria such as LOLE have been widely adopted by the power industry in the past decades. While the goal of these criteria is to ensure a reliable power system, few studies have examined whether the planned systems have achieved the goal. We studied the DOE OE-417 data to reveal the disconnection between the reliability criteria and the empirical reliability levels of the planned systems. Our analysis indicates the deficiency in the existing set of power system reliability concepts and the need to expand the existing set to new concepts such as survivability of the system. Such need becomes more prominent due to the profound evolution of the power grid into a more decentralized, uncertain and complex system. New concepts including resilience, sustainability and survivability are introduced, and their possible measures are discussed. Such discussion will induce more debates on the critical issues of how to operate, plan, and control the future power systems.

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