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CIGRE US National Committee
2023 Grid of the Future Symposium

A Discussion of Resilience in Power Grids

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SUMMARY

Reliability and resilience in power systems are being re-evaluated by the Federal Energy Regulatory Commission and the North American Electric Reliability Corporation. The goal is to ensure that power grids in the US are robust against High-Impact Low-Frequency (HILF) events and the risk of cascade failures and blackouts, and the negative impacts on the economy and society of such events are kept to a minimum. Contributing prominently to this focus is interdependency in critical infrastructure networks. Power systems, natural gas, telecommunications, and transportation for example form a complex web of institutions and physical systems that must also be engineered and secured for reliability. No single transmission company, independent system operator, regulatory agency, or other government entity is capable of understanding, monitoring, or managing the complex network of dependencies on critical infrastructures. Yet, when failures in one system cascade into adjacent systems of the network the result may be high-consequence cascading "catastrophes" or Black Swan events, including blackouts and water shortages. HILF events, which are increasing, may relate to a range of hazards, including natural and weather-related, cyber incidents, accidents, and intentional attacks. In one recent and tragic HILF event, the February 13–17, 2021 Winter Storm Uri in Texas initiated a failure in the natural gas production system that cascaded first to the natural gas power generation system and then to the wider ERCOT power system, the water distribution system, and the petrochemical industry of Texas. No single system operator was responsible, and yet the consequences – including fatalities, recovery challenges, and extreme costs – were everyone's problem. This paper discusses the drivers of HILF events, the distinct roles of resilience and reliability in power systems, and definitions and frameworks for those objectives, and presents a new method and set of metrics available to assess and improve resilience in power grids and other critical infrastructure systems in the face of HILF events. In resilient networks, inevitable failures stay small and don't become catastrophes.

KEYWORDS

Power Systems Resilience, Power Systems Reliability, Cascading Failures, Network Science, High Impact Low Frequency.

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INTRODUCTION

The Federal Energy Regulatory Commission (FERC) and the North American Electric Reliability Corporation (NERC), play crucial roles in overseeing and regulating the electric power industry in North America. FERC, an independent regulatory agency within the United States Department of Energy (DOE), has multiple responsibilities including regulation of energy markets, infrastructure oversight, hydropower licensing, and regulation compliance [1]. NERC, a non-profit organization, is responsible for promoting and enforcing the reliability, security, and stability of the bulk power system in North America, including reliability standards development, grid monitoring and assessment, compliance and regulation enforcement, and emergency preparedness and response planning [2]. NERC's reliability standards aim to prevent large-scale blackouts; it also works with industry stakeholders, government agencies, and other entities to develop and test emergency response plans for major grid disturbances and natural disasters. FERC and NERC are essential in maintaining a reliable and secure electric power system in North America. While FERC focuses on regulating energy markets and interstate transmission, and NERC concentrates on the reliability and resilience of the bulk power system, cooperation between these two entities is essential to ensuring a balanced and well-functioning energy sector.

Recognizing heightened risk, including for security and resilience in bulk power systems, FERC and NERC are evaluating new methodologies and standards, and seeking new assessments, to enhance the reliability of power grids. NERC's recent Technical Conference on Physical Security raised a question about the process of determining the applicability of particular assets for special attention [3]. This includes the consideration of how critical assets should be identified in relation to extreme events that may affect resiliency, including uncontrolled separation and cascading, in the bulk power system. An effort is also ongoing at FERC to better anticipate, prepare for and respond to blackouts.

The urgent need for this reexamination of how to identify critical assets, address the risk of High-Impact Low-Frequency (HILF) events, and improve resiliency can be seen in the ongoing rise in the number of outages and high-consequence events [4]. DOE data can be used to determine the relative involvement of transmission and distribution assets in major outages. According to [5], the median distribution substation in the US serves 2,439 customers; outages affecting more than 100k customers will impact an average of 41 distribution substations, and so likely will involve transmission assets. Analysis of 22 years of data on power outages from DOE [6], considering events with over 100k customers affected that presumptively involved transmission assets, shows that transmission and distribution related power failures are each growing at around 1%, as shown in Figure 1Figure 1.

To address the need to improve grid stability in the face of heightened risk, this paper first examines why questions about extreme events are arising now, discusses current frameworks for resilience, then analyses the distinct meanings and roles of reliability and resilience in relation to HILF events involving uncontrolled separation and cascading, and finally proposes how such events can be addressed, including consideration of the interdependence of electricity systems with other critical infrastructures.

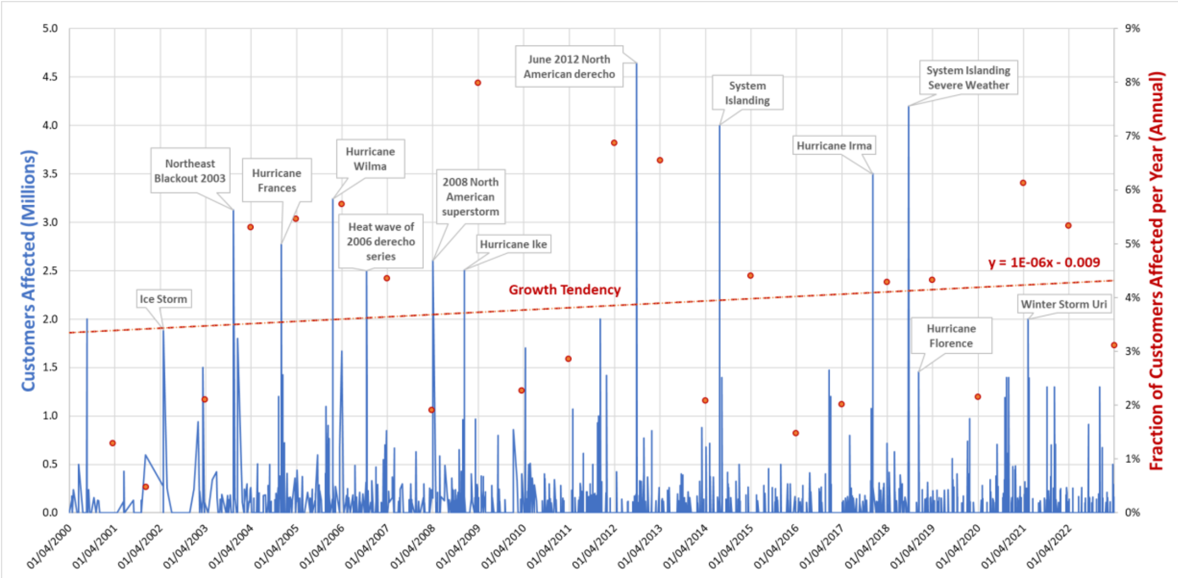

Figure 1 - US Blackouts and Major Power Outages Impacting Transmission Assets (+100k Customers)

THE RISE OF HIGH-IMPACT LOW-FREQUENCY EVENTS

As was noted in the Physical Security Technical Conference [7], an open question is how assets should be identified as critical in relation to potential sources of cascading failures such as weather events, as well as physical attacks, cyber incidents, or major accidents – all hazards that can contribute to HILF events. One question is why assets that have been considered part of standard operations might become significant factors in cascading failures. A number of changes are especially relevant in this new era of extreme events implicating engineering systems that have until now been considered safe and manageable from a reliability perspective.

The strong emphasis in recent decades on increasing efficiency in individual systems, including the power grid [8, 9], has highlighted resilience as an issue. New methodologies were developed to operate the system close to its capacity, and investments in system asset expansion were postponed in exchange for additional monitoring and more flexible procedures. These new procedures allowed for flexibility in real-time operation limits but also meant less margin for error. As a result, the system is less robust and more prone to cascade failures caused by unexpected events, whether traceable to humans or models, a combination of both, or other factors. As all other critical infrastructures depend on continuous electrical energy availability, power grid efficiency decisions heavily impact the resilience of critical infrastructures in general.

Also important is the significant increase in complexity of the North American power grid over the past few decades. This complexity arises from a variety of factors, including the integration of renewable energy sources, the proliferation of distributed energy resources (DERs), and the expansion of smart grid technologies. For instance, the integration of large-scale wind and solar farms introduces intermittent generation patterns that require advanced forecasting and real-time balancing to maintain grid stability. Additionally, the growing adoption of DERs, such as rooftop solar panels and energy storage systems, decentralizes power generation and challenges the traditional centralized grid model. To manage this complexity effectively, grid operators must invest in sophisticated control systems, grid management tools, and enhanced communication networks to ensure seamless coordination and optimize energy flow across the interconnected grid. As the grid becomes more interconnected and reliant on digital technologies, it becomes more vulnerable to cyber incidents, and a range of accidents and physical attacks, leading to potentially widespread disruptions.

Interdependencies among critical infrastructure systems are another defining element of HILF events. Critical infrastructures are not independent and cannot operate alone for an extended period [9]. Cascade failures can spread between interdependent critical infrastructures. The risk of catastrophic failures caused by HILF events in one system on adjacent critical infrastructures is usually opaque to systems operators and their regulatory agencies. This makes critical infrastructure vulnerable to unforeseen events in their own system and in third-party liable systems. Extraordinary consequences of cascading breakdowns in interdependent critical infrastructure systems are shown by the ramifications of winter storm Uri in Texas in 2021. According to [10] and [11], in that incident malfunctions that spread amongst the power, gas, and water networks resulted in at least 151 fatalities and serious economic implications of the order of US$ 155 billion.

Many hazards are intensifying the risk of HILF events. Severe weather events, such as hurricanes, wildfires, and winter storms, have become more frequent and intense, further straining the grid's resilience. Infrastructure aging and deferred maintenance in some regions increase the likelihood of equipment failures and cascading failures. Intentional cyber and electronic attack by adversaries has become a more significant threat due to the role of asymmetric and gray zone tactics in international conflict; criminal attacks are more dangerous due to the range of destructive methods available to individuals. HILF events can also be initiated by electromagnetic pulses or failures in multiple internal computing and control networks.

HILF events on the power grid are rare and unpredictable occurrences that have gained in importance as they have become more frequent, and their devastating consequences more fully recognized. Such events are referred to as "black swans" in power systems as in other systems because of their low frequency of occurrence, ranging from years to decades, combined with their extreme costs and burdens to utilities and society. HILF occurrences result in cascading failures and long-term service interruptions, making them a critical risk factor for loss of life, legal liability, and extended asset damage that may lead to bankruptcy [12, 13].

Black swan events are considered impossible to predict due to “unknown unknowns” in their inception. A result of this fundamental uncertainty is that the large-scale damage of HILF events is not accounted for in capital planning, or in insurance and other financial investment. In terms of money, the effects are direct (lost revenue from services not provided), indirect (reputational damage, legal responsibility, fines, and other regulatory response) and flowing from community costs to human lives, health and well-being and the economy. Notwithstanding the prevailing focus on maintaining ongoing operations, HILF events typically comprise the majority of overall system risk. Notorious black swan events include the Three Mile Island nuclear disaster, the Northeast Blackout, the Fukushima nuclear accident, as well as the Winter Storm Uri gas-electricity-water cascade failures.

For all these reasons, it has become paramount to adopt a methodology to increase critical infrastructure systems resilience, identify critical assets associated with such failures, and mitigate those risks so that failures due to unforeseen disruptions are kept small, and there is capability to restore service quickly after such events.

FRAMEWORKS FOR RESILIENCE

The problems of cascading failures, blackouts, and HILF events in critical infrastructure have been linked with the ideas of both resilience and reliability. Resilience has many technical measures and definitions; prominent among them are measures of the system's reliability, ability to resist damage from a hazard, and ability to quickly recover from damage. Resilience can be defined as the ability of a system to absorb, cope, and restore from a disturbance, as well as adapt itself, learning from past disturbances [8].

For the power systems, resilience has been defined as the "ability of an electrical system to prepare for, absorb, recover from, and adapt to a disturbance, while maintaining its essential functions, structure, and identity" by CIGRE Working Group C4.47 [8]. This definition emphasizes the power system's capability to endure and recover from disruptions, adapt, and evolve in response to the environment over time. CIGRE Working Group C4.47 also emphasizes the significance of a comprehensive and systemic approach to resilience. This approach involves incorporating advanced technologies and tools, efficient risk management and planning, and stakeholder collaboration. Figure 2Figure 2 illustrates CIGRE's definition of resilience for power system disturbances in a graphical format.

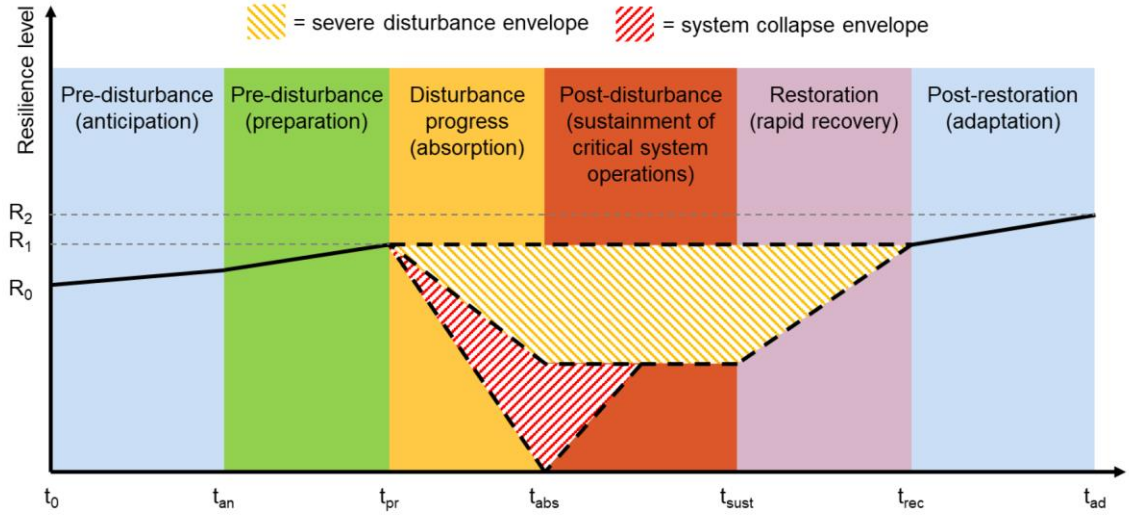

Figure 2 - CIGRE WG C4.47 Resilience Trapezoid from [8]

Resilience is a multidimensional concept that is applied differently across various fields and applications by the Institute of Electrical and Electronics Engineers (IEEE). IEEE has defined resilience for electric power systems 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" [14]. The IEEE's definition of resilience includes several key components, such as the importance of maintaining essential functions and services during disruptions, the need for effective response and recovery, and collaboration among stakeholders. Figure 3 Figure 3 presents a graphical description of IEEE´s resilience definition for power systems disturbances.

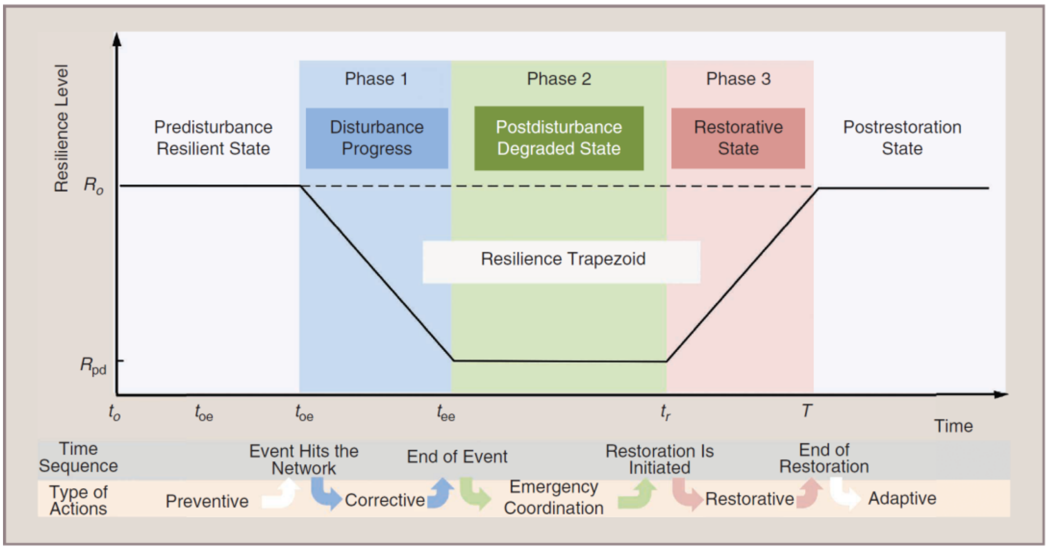

Figure 3 - IEEE Time Varying Resilience Multi-Phase Trapezoid from [14]

The National Academies is a non-profit organization that provides expert advice publicly. It includes the National Academy of Sciences, the National Academy of Engineering (NAE), and the National Academy of Medicine. In 2014 the National Academies established a program on Risk, Resilience, and Extreme Events, known as Resilient America in a response to a National Research Council 2012 report called "Disaster Resilience: A National Imperative." Taking the next step toward the development of resilience metrics, tools, and standards for the bulk power system, the NAE hosted a workshop in October 2022: “Creating A Sustainable National Electric Infrastructure While Maintaining Reliability and Resiliency of the Grid”. Several ISOs, transmission companies and power utilities and engineering firms participated and the NAE released a report in 2023 [15]. Some of the workshop findings were that:

- New tools are necessary for integrated resource and T&D planning and investment prioritization.
- The creation of grid resilience standards is necessary.
- Probabilistic assessments are necessary to account for HILF event impacts on power grids.

As the NAE report indicates, existing definitions of resilience stop short of providing a methodology that translates those definitions into practical metrics, standards, and tools that can support planning and investment. Engineers, financial managers, and risk managers such as insurers, have not yet adopted quantified measures for resilience. NERC’s recent Technical Conference on Physical Security in relation to applicability, cascading and resiliency, among other topics, represents another powerful call for practical solutions [7].

RELIABILITY AND RESILIENCE

The FERC and NERC examination of the reliability standard in relation to physical risks associated with cascade failures that manifest weakened resiliency of the power grid presents an opportunity to review the intertwined meanings of reliability and resilience in the face of increasing HILF events characterized by radical uncertainty, complexity, and interdependency.

Reliability is well defined and supported in terms of metrics, standards, tools, and financing. Put simply, reliability centers on keeping systems going. Referring to the ability to be trusted or perform consistently well, reliability is generally measured by the probability of an asset performing a required function under certain conditions for a specific time [16]. Because the main objective of critical infrastructure systems and their operators is to provide reliable service, system performance is measured and regulated in supplier service contracts and by the government in most jurisdictions. Reliability alone, however, cannot guarantee resilience in the face of unexpected and severe events. Standard methods to determine reliability cannot predict cascade risks and how unexpected events may lead to catastrophic cascade failures and blackouts. As is increasingly well recognized, reliability investments applying usual procedures are insufficient to ensure resilience and prevent cascading failures associated with HILF events.

Resilience is the correct framework through which to view the problem of all hazard, cascade risk within and across the bulk power system and other critical infrastructure. Resilience can be linked to a system's ability to withstand and recover from the outcomes of all kinds of failure events. Building resilience to HILF events enhances overall reliability with respect to routine failures and reduces total risk in critical infrastructure systems.

In contrast to reliability, resilience is a blank slate with respect to metrics, standards, tools, and financing. While reliability is focused on continuous performance, resilience is based on the assumption that failures are both uncertain and inevitable. Resilience centers on keeping inevitable but uncertain failures small while also ensuring rapid recovery after an incident. Uptime is commonly used to measure reliability, which focuses on minimizing service failures under routine circumstances. A better metric for resilience is a service failure's consequence (or risk). Resilience focuses on minimizing consequences (or risks) created by service failures under extraordinary circumstances. Consequences are determined both by the scale of the failure itself and the time and cost of recovery.

At the most fundamental level, achieving resilience depends on effective adaptive learning from things going wrong on a large scale. This may draw on customs and traditions, government law and regulation, monitoring and data collection, transparent performance data and engineering design standards. Because the context for resilience is extraordinary events, strong risk perception is a second fundamental principle of successful resilience, whether shaped by organizational culture, leadership, or external factors. Organizations with proactive risk assessment mechanisms and robust accounting systems that integrate risk measures are better equipped to effectively identify and respond to risks and to enhance resilience in the face of uncertainties and challenges [17]. Technical definitions and metrics of resilience and system risk, serve as tools within the adaptive learning cycle to measure and improve resilience based on proactive risk assessment.

If a utility operator must choose between the two goals of reliability and resilience, it is becoming increasingly clear that resilience is paramount. Risk is a more fundamental measurement, and the catastrophic consequences of major failures in critical infrastructures far outweigh the inconvenience of routine outages. Fortunately, we can pursue both reliability and resilience because the two goals are complementary: resilience is necessary to support and improve reliability under extraordinary circumstances. Figure 4Figure 4 provides a table comparing reliability and resilience.

	RELIABILITY	RESILIENCE
Timeframe	• Daily (statistical predictability)	• Decades (unpredictable "Black Swans")
Costs	• Lost revenue • Contractual costs • Repair • Recovery • Prevention	• Loss of life • Extreme costs • Uninsured liability • Bankruptcy • Reputational injury • Prosecution • Political and regulatory response
Focus	• Asset failure • Hardening against anticipated hazards • Preventative maintenance and replacement • Limited customer differentiation • Annual budgeting	• Critical function failure • Mitigation for unanticipated events • Containing and recovering cascading failures • Critical customer protection and recovery • Variable budgeting
Metrics	• Well established quantitative standards • Each sector measures its own performance • Service reliability metrics • Asset service life & optimal replacement schedule • Reliability ROI for Capital and Rate Planning	• **Emerging quantitative standards** • **System interdependency analysis** • **Cascade risk and resilience scoring** • **Interdependent system resilience mitigation & optimization** • **Critical customer & recovery order planning** • **Resilience ROI for Capital Improvement and Rate Planning**

Figure 4- Reliability and Resilience

PROPOSED METRICS FOR RESILIENCE

The power industry is innovating in response to the resilience challenge, building on current reliability practices. In power systems, ensuring reliability is crucial in preventing system failures. To achieve this, engineers use models that simulate the loss of individual components in the system, representing known failures in terms of intensity, duration, and frequency. This methodology, commonly known as the "N-1" criteria, is well established in power systems planning and operation. N-1 is sometimes extended to N-k when considering combinations of failures. These disturbances, generally associated with single-component failures, occur frequently and have a relatively high degree of statistical predictability. In response to the problem of potentially high-consequence cascade failures, the N-k criteria have been expanded to identify cascade path vulnerabilities in real-time operation [18]. These remain bound by single initial asset failures or by a pre-defined failure combination chosen. Fixed engineering criteria, such as transmission line overloading, are used to identify cascade paths one asset at a time using power flow analysis.

Important as this innovation can be to operational reliability, it does not address black swans, which emerge from unknown unknowns and low-frequency events. Nor do expanded N-1 practices address the problem of cascading failures among interdependent systems. Interdependency failures represent a notable challenge in adapting current reliability methods to resilience purposes for HILF events. Modern reliability engineering depends on physical models, and physical models of interdependent infrastructure systems are still in their infancy. Those models are fundamentally challenging and costly to construct and validate. The time frame for their mature development is not responsive to the urgent need for answers to the questions posed by NERC and FERC concerning HILF events.

The time is right for resilience frameworks to evolve into dedicated metrics, standards, and tools that power system operators, transmission companies, and utilities can use to ensure grid resiliency, and financial institutions can apply cost-benefit measures to resilience investments. At the 2022 Grid of the Future Symposium, Criticality Sciences, Inc. presented a methodology to measure risk and resilience for critical infrastructures. As described in more detail in [4], several fundamental tools were presented, such as Maximum Probable Loss (MPL Risk^{SM}), Lewis Score^{SM} (0-10) for resilience, Recovery time and cost (from MPL Risk^{SM} events), and Ranked Criticality Assets^{SM} for cascade resiliency. Note that those metrics consider all hazards and focus on HILP events to evaluate the resilience of power systems. They are probabilistic methods, as recommended by NAE [15], based on network science and engineering analysis, and therefore, they can also be applied to a range of critical infrastructures and consider the interdependency of critical infrastructures.

A resilience assessment of the Brazilian power grid was performed using an output of the state estimator, providing a snapshot of the whole Brazilian power grid with all transmission assets. This snapshot provided the topology of the power grid and was used to identify the direct consequence impact of losing transmission assets in terms of megawatts. For asset vulnerability analysis, six years of historical fault data were used. The analysis, performed around September 2022, presented an MPL Risk^{SM} of approximately 23% of the total static risk and a Lewis Score^{SM} of 6.2 alongside a list of critical assets to HILF cascade failures. Note that MPL Risk^{SM} is a correlation of the amount of power shed, for the statistically most likely HILF event identified on the Monte-Carlo analysis, and the total load of the system at that snapshot. If the energy cost is considered, MPL Risk^{SM} provides a risk in dollar value per hour.

On August 15^{th}, 2023, a blackout event occurred in the Brazilian power grid, as presented in Figure 5 [19]. It impacted the entire Brazilian grid with the exception of one state (an isolated system). According to initial information from the Brazilian ISO, the blackout was initiated by incorrect protection actuation on a transmission line. The entire country's power consumption was approximately 73484 MW right before the event and, right after the event, the load dropped to approximately 54383 MW. The load shed during this Blackout amounts to around 26% of the entire load of the system for that event [19]. Additionally, of the 10 top critical assets identified in the September 2022 analysis, the 1st and the 5th assets were involved in the 8/15 event cascade failure.

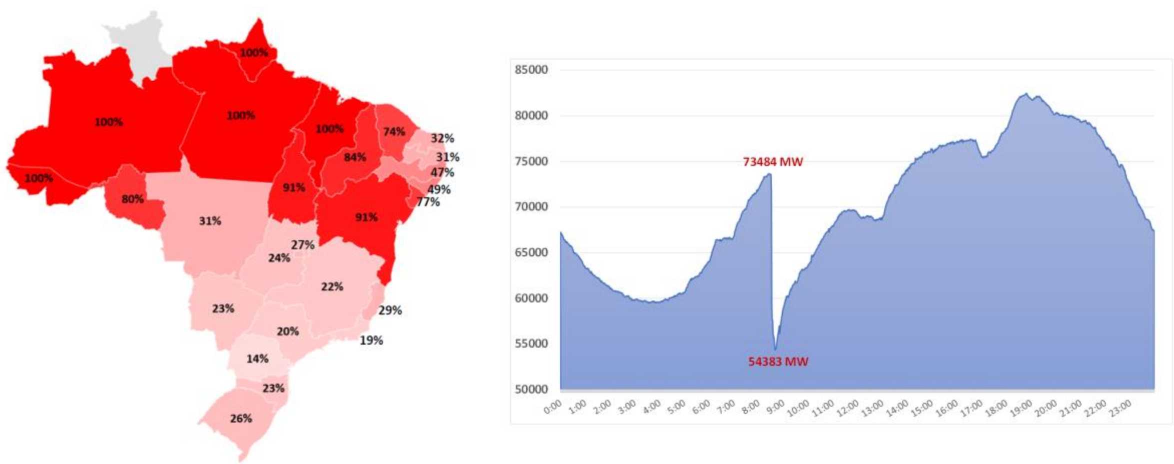

Figure 5 - Brazilian Blackout 8/15/23. Percentage Load Shed by State (left) and Power Grid Load (right) [19]

These resilience metrics -- the MPL Risk^{SM}, Lewis Score^{SM}, and Ranked Criticality Assets^{SM} -- have shown promising results for transmission systems to anticipate the risk of all-hazard HILF events.

CONCLUSIONS

This paper discusses resilience in power systems, examining drivers of regulators' and the power industry's focus on HILF events and on resilience, presenting key definitions and frameworks for resilience established and embraced by power systems-related institutions, such as CIGRE, IEEE and NAE, analyzing the relationship between reliability and resilience, and spotlighting available metrics to measure resilience in power grids.

It highlights the need for a probabilistic-based resilience standard that can be used as a benchmark for regulation and standardization across the industry. The ideal solution should be able to provide clear guidance on whether a power grid is adequately resilient or excessively fragile with respect to mitigating unpredictable and all-hazard failures that are "Black Swan" events, with a theoretical basis that is orthogonal and complementary to the prevailing power systems engineering and modeling approach that is primarily focused on reliability. This resilience standard should also consider the interdependence of systems and the likelihood of a cascade failure spreading from other critical infrastructure systems. Such a probabilistic methodology is available through the Lewis Score and MPL. Comparing the results from the 2022 analysis on the Brazilian power grid and the Brazilian blackout that occurred on 8/15/23, it is possible to observe that the proposed method to measure resilience in power grids produced compelling results and should be further tested and validated as a solution to assess resilience in power grids for risk mitigation and capital investment purposes, to be included in resilience metrics and regulatory frameworks.

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