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CIGRE US National Committee
2022 Grid of the Future Symposium

Resilience of Power Grids to Catastrophic Cascading Failures

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SUMMARY

Despite advances in protection technologies, the availability of better power systems modeling and virtually unlimited computational power for engineering analysis, the frequency and impact of failures and especially of high-consequence cascading events are not diminishing proportionately. Renewable energy generation, especially converter based such as solar photovoltaic and wind, and the expansion of high voltage direct current transmission are creating new challenges for power grid operation. Hazards from extreme weather and "intelligent adversaries" may be increasing, thwarting efforts to harden power systems and prevent primary failures. Meanwhile, experience continues to demonstrate that "Black Swan" hazards are unavoidable.

All other critical infrastructure systems are dependent on the power grid to provide stable, around-the-clock services for normal societal functions. The power grid itself is also dependent on many infrastructure systems to properly function, such as telecommunications to provide observability and controllability, and gas distribution to provide fuel to thermal power plants. Unfortunately, the policy, science, engineering, and operations of interdependent critical infrastructures is still in its infancy. Many dedicated institutions are involved in the operation of a region's interdependent infrastructures, vastly complicating both failure mitigation and recovery operations.

Given these challenges, we argue that operators and researchers should adopt alternative engineering paradigms to complement the standard engineering approach. This paper presents such an approach, one that is naturally suited to interdependent network analysis and to mitigation of all kinds of hazards, including high-consequence cascading failures. A method to measure resilience to high-consequence cascading failure on power transmission grids is proposed. Results for the Brazilian transmission system are produced using NetResilience®, a network science and engineering software package, and presented herein.

KEYWORDS

Power Systems Resilience, Interconnected Systems, Power Systems Reliability, Network Science

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INTRODUCTION

The size and complexity of the power grid have been increasing in the last decades, creating challenges for real-time operation reliability and power system infrastructure resilience. Advances in transmission and generation technology, associated with the decarbonization campaign to address climate change, are drastically transforming the grid dynamics and characteristics. According to [1], the total renewable energy generation in the United States has increased by 131.83 % from 2000 to 2021, with solar photovoltaic (PV) generation increasing by 23304.08% and wind generation increasing by 6693.73% in the same period.

The growth of renewable, non-dispatchable, generation (e.g., solar, wind, etc.) in the energy matrix increases the risk to the power grid. As shown in [2], converter-based renewable generation decreases the system's inertia, affecting its ability to respond and recover from significant power imbalance events. Therefore, systems with higher renewable penetration are less capable of responding to frequency variations (e.g., loss of generation units and load loss) and, therefore, more susceptible to cascade events. Another side effect of the increasing renewable generation observed on the distribution system, the so-called distributed energy resources (DERs), is the inversion of the expected power flow from the transmission to distribution networks. Moreover, the high density of independent converters might lead to oscillation issues due to control interactions. Therefore, DERs present challenges to power systems reliability and increase the risk of cascade events [3].

High voltage direct current (HVDC) transmission is expanding in the US, heavily propelled by the increasing renewable generation deployment [4]. HVDC allows control over power transmission, an advantage over standard alternated current transmission, that allows distant bulks of location-dependent power generation, such as wind, to be directly diverted to load centers. HVDC technology is a viable solution to deliver energy to major load centers in the US from long-distance large renewable power sources. As presented in [5], HVDC transmission could provide around US$ 65 billion of economic benefit over standard alternated current transmission in the US from co-optimization of generation and transmission for a 15-year planning horizon. However, HVDC also brings more complexity to real-time operation and reliability of power systems, and therefore more risk of cascading failure events of far greater geographical extent and societal consequence [6].

Moreover, the incidence of extreme weather events is increasing in the last decades [7], escalating the chances of sudden weather-related outages with extensive asset damage to generation, transmission, and distribution systems. Besides direct impacts on power grid utilities, there are many indirect impacts on communities, businesses, and public health associated with the lack of energy and delay in restoring power to affected areas. “Intelligent adversaries” are increasingly targeting the power grid with physical and cyber threats. Prevention of primary failures of power grid components is becoming more difficult every day as the intensity and number of threats increases.

Power systems reliability analysis associated with real-time operation and expansion planning of the power grid, as done by Independent System Operators (ISOs), Regional Transmission Operators (RTOs), and Distribution utilities usually only consider power systems as an isolated and independent entity. As shown in [8], other systems networks could directly affect the power grid and, thus, increases the risk of cascading failures, consequence impacts and critical asset identification. Therefore, a methodology to identify the consequences and vulnerabilities of interdependent and interconnected critical infrastructure systems (e.g. gas pipelines, telecommunication, transportation, etc.) should be considered when evaluating power grid resilience and risk analysis.

A good estimation of the power grid resilience to cascading failures, with estimated consequence impacts in US$ and a proper identification of critical assets, can help assess the actual risk exposure for the utility and evaluate mitigation options.

RISK ANALYSIS ON POWER SYSTEMS

The power system is an essential infrastructure for the operation of fundamental societal functions. All other critical infrastructures are dependent on continuous electrical energy availability [8, 9], making the power grid among the “most critical” of infrastructures.

ISOs, RTOs, and Distribution Companies have mature and standard methodologies to define risk and reliability. Risk in power systems is calculated as a function of consequence and the probability of a failure event happening [10], and reliability is estimated based on simulation analysis and historical observations. Those reliability simulations analysis require accurate and detailed physics-based models of the network, including dynamic and control models. Power engineering models focus on simulating the loss of any single asset on the system at a time representing failures of known intensity, duration, and frequency. This reliability methodology is well established for power systems planning and real-time operation, commonly cited as the “*N-1”* criteria. *N-1* is sometimes extended to *N-k* when extended to combinations of failures.

For reliability analysis, many methodologies are proposed in the literature to calculate the probability of a fault occurring in the system and leading to load loss, as seen in [10-13]. Those methodologies are usually associated with the *N-1* criteria and the consequences of losing a piece of equipment spread the fault to neighborhood assets and, ultimately, impact energy delivery. However, this approach is based on chosen premises such as only one or very few selected equipment will fail at a time. Also, all protection schemes are assumed to operate correctly and all power grid outage dynamics will behave like the simulated models. Another important assumption is that no other critical system infrastructure can affect the power system, meaning no system interdependency is considered in the simulations.

Critical infrastructure systems, such as power, gas, telecommunications, and water, have interdependencies that must be considered when analyzing infrastructure resilience [9]. For instance, a power outage can spread to the water system or a failure in the gas distribution can affect the power grid as shown in [14]. Those system interdependencies have different impacts and consequences. This correlation must be appropriately addressed when evaluating any single system resilience. However, physically-based models of interdependent infrastructure systems remain in their infancy. They are fundamentally costly and challenging to construct and validate due to the variety of physics, institutions, data sources, and scales involved, along with the severe computational complexity.

The frequency of power outages in the US has been increasing in the last decades, despite all developments in technology, protection systems, availability of accurate models, and processing power for reliability and resilience simulation analysis. As shown in Figure 1, created from data provided in [15], the overall frequency of outages with energy interruption in the last decades is still increasing, as well as the number of people affected by those interruptions (over 2% growth on average).

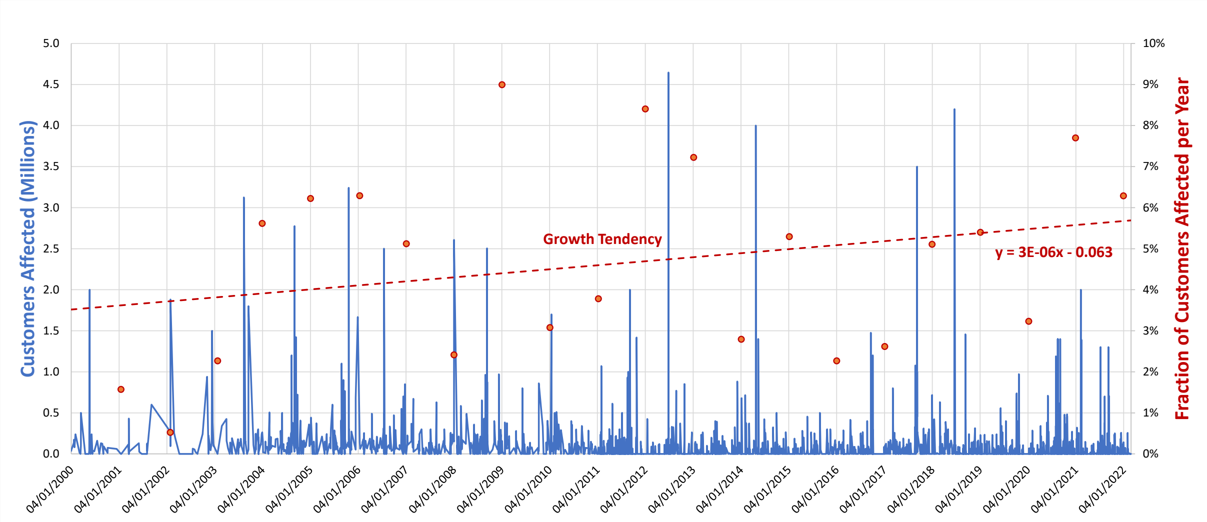

Figure 1 - Customers affected by power outages in the US, 2000-2022, (left/blue axis) millions of customers, (right/red axis and trendline) fraction of customers. The fraction of customers affected is increasing over time.

RESILIENCE AND RELIABILITY IN POWER GRIDS

Reliability is, by definition, the ability to be trustworthy or perform consistently well. For power systems applications, the reliability definition is generally accepted as the characteristic of an asset expressed by the probability that it will perform a required function under stated conditions for a stated period of time [10]. Power systems reliability can also be divided into two terms, adequacy and security. Adequacy is the balance between generation and load, and security is the ability of the system to respond to disturbances and transients. Those disturbances are usually frequent, associated with single asset failure, and have relatively good statistical predictability. The standard measures to increase reliability mainly focus on preventing component failure by hardening assets against known hazards and preventive maintenance. From the financial point of view, reliability is a cost/benefit analysis for the kind of event that can lead to revenue losses, recovery and new prevention requirements. It is self-evident that resilience is a prerequisite for reliability. We argue that resilience to rare and severe events is the weak point in the predominant power reliability engineering paradigm.

Resilience is associated with the capacity of a system to resist and recover from the impacts of all kinds of failure events, including low probability, high consequence (LPHC) events that often dominate total system risk. LPHC events on the power grid are usually associated with extreme weather (e.g., hurricanes, ice storms and floods). Still, they can also be initiated by cascading failures from other infrastructure systems, physical attacks, cyber-attacks, electromagnetic pulses, failures in multiple internal computing and control networks, and increasingly forest fires, for example. Those so-called Black Swans have low-frequency occurrence (e.g., years to decades), extremely low predictability, and present extreme costs and burdens to utilities and society [16, 17]. LPHC events present elevated risks of loss of life, legal liability (insured and non-insured), and extended asset damage for the utilities that may lead to bankruptcy. A critical aspect of power grid resilience is the capacity to restore service quickly after LPHC events. There is reason to believe that LPHC events drive total risk and cost in critical infrastructure systems, and that building resilience to LPHC events simultaneously enhances resilience to routine failures. Therefore, blackstart capability and flexible restoration plans, considering surplus assets, critical loads, and crew availability, are paramount- as are the measures taken to keep failures small and limit total consequences to a scale and scope that can be managed by available recovery assets.

Table 1 presents a few worldwide LPHC events that heavily affected the power grid and energy delivery to the population [18-21]. LPHC events are rare enough that empirical data characterizing them is not typically available for an individual power network, but by surveying the totality of LPHC events worldwide we can begin to estimate their prevalence and severity. Resilience calculations for power grids can take advantage of this LPHC failure event data.

Table 1 – LPHC Events Affecting the Power Grid Worldwide

Year	Country	Population Affected (Millions)	Date
2021	Pakistan	200	January 9, 2021
2020	Sri Lanka	21	August 17, 2020
2019	Venezuela	30	March 7, 2019
2019	Argentina Paraguay Uruguay	48	June 16, 2019
2019	Indonesia	120	August 4, 2019
2016	Sri Lanka	21	March 13, 2016
2015	Turkey	70	March 31, 2015
2015	Pakistan	140	January 26, 2015
2014	Bangladesh	150	November 1, 2014
2012	India	620	July 30, 2012
2009	Brazil Paraguay	60	November 10, 2009
2005	Indonesia	100	August 18, 2005
2003	Canada United States	55	August 14, 2003
2003	Italy Switzerland	56	September 28, 2003
2002	Philippines	40	May 21, 2002
2001	Philippines	35	April 7, 2001
2001	India	230	January 2, 2001
1999	Brazil	97	March 11, 1999
1965	Canada United States	30	November 9, 1965

As presented in [22-24], historical failure data from utilities can be used to identify the critical assets in each system that contributed to the propagation of a small and localized failure into a LPHC cascading failure event. Once those critical assets are identified, mitigation options can be evaluated. This type of mitigation focuses on preventing primary failures, but on restructuring networks so that they resist LPHC cascading failure events by keeping primary failures small and localized.

NETWORK SCIENCE

The use of network science to evaluate power systems' resilience to cascading failure has been discussed in the literature [25, 26], but has received far less attention than the standard power engineering paradigm. The network-based approach would typically employ the (interdependent) network topology, a method to weigh consequences associated with asset service failure and recovery cost, characterization of recovery processes, probabilistic estimation of the chances of cascading failure along the network topology, and a mathematical approach to identify the critical assets on the system which tend to contribute to cascading system failures. Cascading failure probabilities are empirically determined, as are the direct (to the operator) and total (societal) consequences of critical infrastructure failure.

Figure 2 presents an example of critical infrastructure impact correlation. In this example, gas pipeline systems and telecommunication systems can fail due to cascades from the power system, and vice versa- but failures in water systems do not often cascade back to power or telecommunication networks.

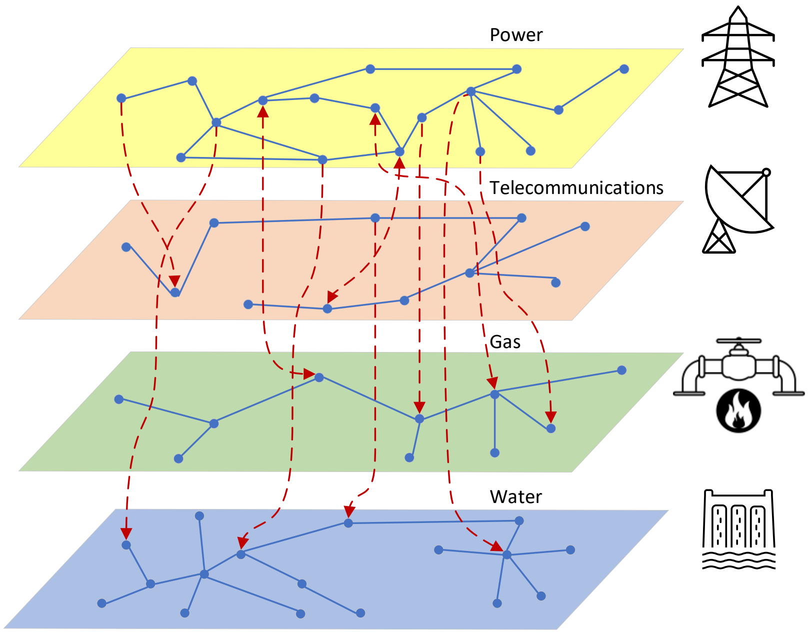

Figure 2 - System Interdependencies

Therefore, interdependent systems can be modelled together using network science, and this may be done far more feasibly and simply with the probabilistic and topological approach than with the physics-based engineering modeling approach for larger and more complicated networked systems [27, 28]. Naturally, the network approach has both advantages and disadvantages compared to the physics-based modelling approach, but interdependency is an argument in favor of the simpler and more flexible network approach. The network approach provides a largely complementary and orthogonal view into interdependent network resilience and can be used to critique and corroborate the standard engineering approach, adding robustness and confidence when used in tandem. The system is greater than the sum of its parts, so analysis of the interdependent networks yields fundamentally different and superior resilience findings [29].

SIMULATIONS

The objective of this paper's simulation is to demonstrate the network resilience method for a major national power transmission system- in this case, the Brazilian interconnected system. The Brazilian transmission system supplies the entire nation of Brazil and has approximately 170000 km of high voltage transmission lines, as seen in Figure 3. It has 176 GW of installed generation capacity and attends to a population of approximately 213 million. This system is heavily dependent on renewable generation, with 86 % of its energy matrix based on hydro, wind, solar, and biomass generation. It has four long-distance HVDC transmission lines to bring renewable energy to load centers [30].

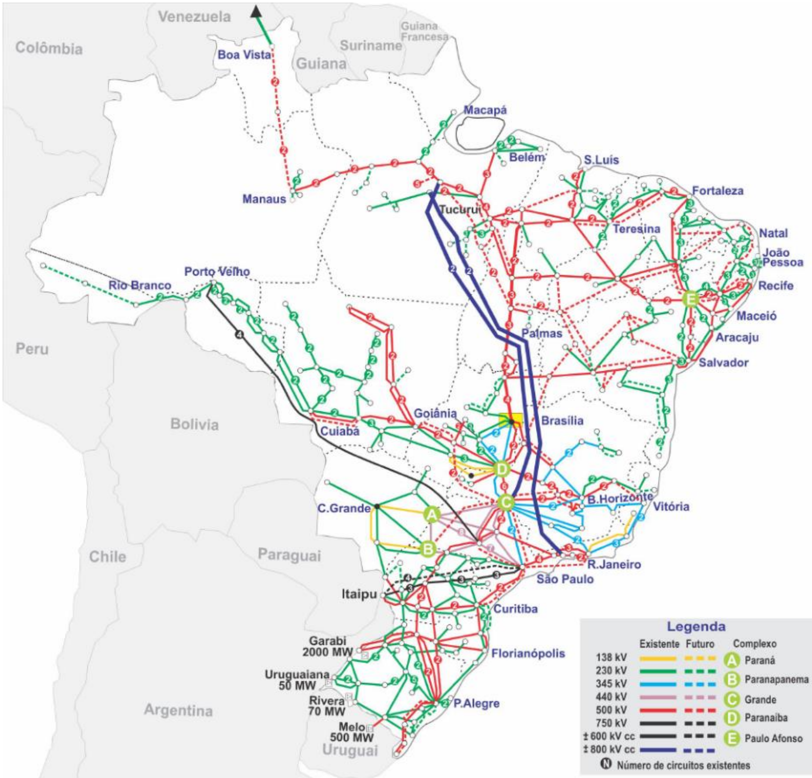

Figure 3 - Brazilian Interconnected Power Transmission System

A measurement of the risk (or consequences) and the resilience of the Brazilian network is calculated using the NetResilience® software (patent pending) and open-source transmission system data. This software was created by Ted Lewis and based on the literature presented in [26]. The software employs a monte-carlo approach to estimate cascading failure extent and severity for all possible primary failure initiation events, resulting in a distribution of consequences (US$/h) for many thousands of simulated failures, along with statistical results for the tendency of each network component to participate LPHC cascading failures. The probability of cascading failures between components- a key input to the system- is directly estimated from approximately 6 years of historical failure data of the same Brazilian system. The consequences of failure are estimated based on the load and generation connected to all substations on a typical day, and the cost per hour of service failure is based on the highest energy cost observed in 2021 for the Brazilian system energy market [31]. The transmission network was aggregated into 5086 equivalent buses and 9700 transmission links (transmission lines and transformers) for the simulation.

Maximum probable loss (MPL) is a statistic of the consequence distribution estimated for all possible cascading failure events in the system and is a function of the exceedance probability for cascade failure and marginal consequence, as can be seen in Figure 4. NetResilience® provides a MPL value (in cost per hour) for the likely cascade failure with the highest direct consequence (lost of revenue), as well as a static risk representing the direct loss per hour to the system operator for a complete service failure in Brazil, neglecting the broader societal consequences. The simulation found a maximum probable loss from cascading failure events of US $12.5 million per hour, which is roughly one-quarter of the static risk of US $55.8 million per hour.

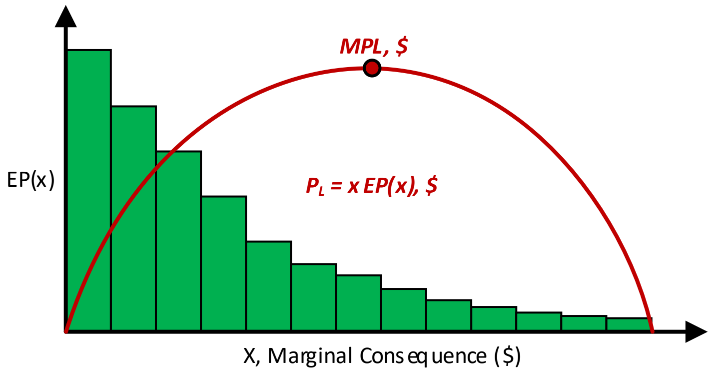

Figure 4 - Maximum Probable Loss (MPL), a statistic of the consequence distribution.

NetResilience® also measures the system's resilience to cascading failure events using a normalized scale, the Lewis Score™. The Lewis Score™ ranges from zero to ten and has a "tipping point" of five. Below this tipping point any random failure on the network has the tendency to "blow up" into a LPHC event and the network is "fragile". Above the tipping point the network tends to naturally suppress the spread of failures, so consequences stay small and the network is "resilient". Simulations on the Brazilian system estimate its Lewis Score™ as 6.2, so the Brazilian Interconnection is resilient to cascading failure events (Figure 5). However, that score could still be significantly improved by restructuring the network topology and hardening critical assets that tend to disproportionately participate in LPHC cascading failure events (Figure 6, "hot" colored assets have a higher cascade frequency).

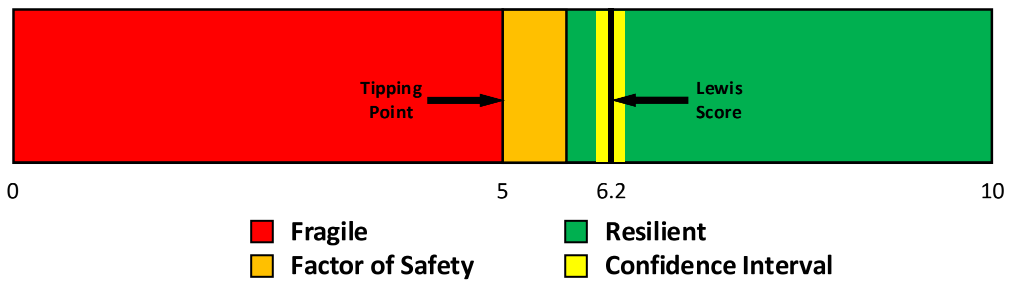

Figure 5 - Lewis Score™

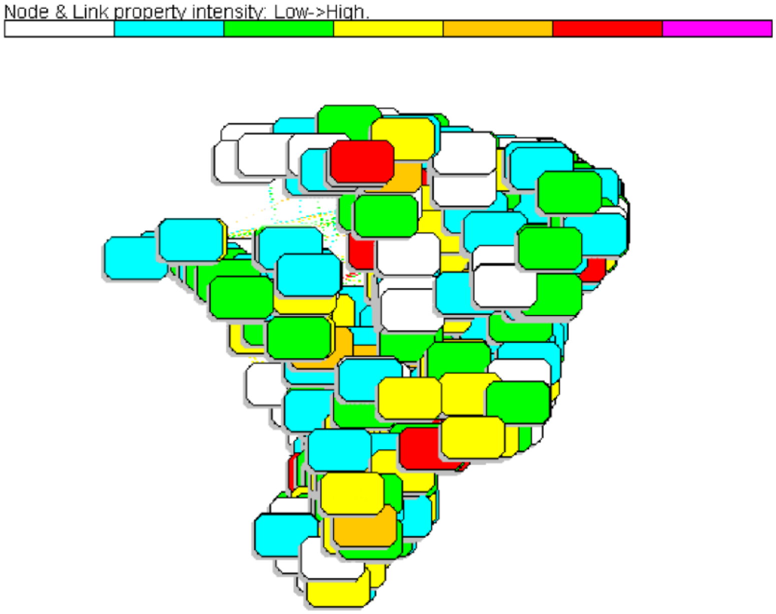

Figure 6 - Cascade Frequency Heat Map Illustration for the Brazilian Interconnection; results are anonymized for security considerations ('property intensity' = Cascade Frequency)

CONCLUSIONS

This paper presents a discussion on the importance of adopting a wider perspective on the engineering of power systems resilience to low probability high consequence cascading failure events. New methodologies to measure the power grid's resilience are called for as a basis for regulation, standardization, and reliability engineering. The ideal method(s) would effectively handle interdependent network failures, mitigate unpredictable "Black Swan" events (i.e. all-hazard failures), establish clear guidance on whether or not a network is adequately resilient, and would have a theoretical basis that is orthogonal and complementary to the dominant power systems engineering and modelling approach. The proposed method and the Lewis Score™ satisfy these criteria by providing robust measurement for resilience to LPHC events, including maximum probable loss and critical asset identification. This network engineering method can therefore provide valuable information for ISOs, RTOs and distribution utilities to evaluate system hardening, mitigation solutions and expansion planning in the light of the risk posed by unpredictable "Black Swan" events and LPHC cascading failures. A cascading failure event that brings down roughly a quarter of the entire nation's power supply is not at all a rare "outlier" event in the Brazilian Interconnection, based on the NetResilience® simulation. This is a cascading failure that needs to be planned for, and for which some mitigation is likely to be cost effective. A limitation of this study is the lack of inclusion of interdependent networked systems such as natural gas, telecommunications, and water. This limitation could be addressed by future work using an expanded dataset.

ACKNOWLEDGEMENTS

The authors acknowledge funding from Criticality Sciences, Inc. The findings are those of the authors, and not necessarily of Criticality Sciences, Inc. or of other employers of the authors.

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