

The Impact of Short-Term Unscheduled Events (STUMS) on Power System Resilience: An Analytical Overview and Future Directions

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Abstract— Modern power systems have become increasingly complex and decentralized, making them more vulnerable to disruptions, especially short-term unscheduled events (STUMS). These unexpected disturbances, lasting from seconds to an hour, happen without warning. This paper offers a thorough analytical overview of STUMS, examining their causes, frequency, and effects on the resilience of power systems. It categorizes STUMS based on their origins—human error, equipment failure, and external environmental factors—and investigates how these incidents can lead to widespread blackouts. The study reviews analytical methods for evaluating resilience, such as reliability indices, response times, and recovery metrics, while also presenting global case studies that reveal practical implications and lessons learned. Despite the increasing acknowledgement of STUMS, the research highlights notable gaps in empirical data, the standardization of resilience metrics, and interdisciplinary modeling approaches. The paper concludes with suggestions for future research, stressing the necessity for integrated frameworks, advanced simulation tools, and collaborative initiatives across engineering, policy, and data science to effectively mitigate the operational and economic consequences of STUMS on power systems.

Keywords— Power System Resilience, Short-Term Unscheduled Events (STUMS), Grid Disturbances, Blackout Risk Assessment, Resilience Metrics, Energy System Vulnerability.

I. INTRODUCTION

The electricity industry is rapidly changing towards more sustainable, efficient, and decentralised systems. Power systems gradually move from centralised generation and transmission towards distributed and interconnected generators (Beyza & Yusta, 2021). The increasing interconnection of subsystems and the critical role of electricity in day-to-day activities make modern power systems more susceptible to unforeseen events. Unforeseen events, such as STUMS, particularly possess the potential to severely impact the power system due to the lack of a preconceived plan and delays in response compared to other scheduled events (Wang et al., 2022). For the effective management of STUMS, a deep understanding and technical know-how regarding the impact of these events on power

system resilience are required. Due to the importance associated with the study of STUMS for power system resilience, the primary purpose of this paper is to illustrate the possible causes that can result in STUMS and to provide a review of the existing analytical approaches used for assessing the influence of STUMS on the resilience of power systems. Great Britain's power system is highly interconnected and highly dependent on supplying other systems to meet daily demand (Xu et al., 2021). Hence, the loss of multiple generators affecting multiple systems can initiate a large-scale blackout. The system's recovery would depend on the available resources and the time of day, as, for example, there is typically a larger electricity demand during the daytime than at night (Afzal et al., 2020). The results will inform the frequency and possible causes of STUMS developed in the literature review of this paper. This paper is structured into four different sections. Following the introduction, the potential causes of STUMS in section 2 are followed by a comprehensive account of analytical methods in the existing literature used for assessing the impact of STUMS on the power system's resilience. Lastly, an outline of potential future research directions is provided. The outcomes of this paper are relevant to various stakeholders and related researchers from a technical, economic, and policy perspective. The development of a methodology to estimate the costs of STUMS and inform which incident type results in the most significant financial benefits from resilience improvements remains a direction for future work.

1.1. Background and Significance

Power systems have evolved through several stages over the last century, and today, they rely on a complex set of components comprising the generation, transportation, and distribution of electricity. Technological advancements have allowed for the efficient generation and transportation of large amounts of electrical power to meet the load demand of consumers worldwide (Ibrahim, 2021). However, the complexity of our power systems has meant that we are also in constant need of significant power system resiliency owing to

the frequent and infrequent system disturbances that can, if unchecked, cascade across large areas, causing most system outages (Zappa et al., 2021). Thus, effective and reliable electrical power generation, transmission, and distribution are the lifeblood of all realms of a modern, interdependent society.

Moreover, systems' increasing complexity and vulnerability make it difficult to harden against threats. Classical strategies in power system protection and controls only focus on warranted disruptions and challenges and have limited efficacy in mitigating today's phenomena (Shahin et al., 2023). Unscheduled events caused by any unexpected physical or cyber aspect are a constant feature in electrical power systems. Such frequent but undesirable events can impact the daily life of society and yet have received limited attention in the technical and socio-economic literature. However, Short-Term Unscheduled Events (STUMS) have, in their unpredictability, cliques with aspects driving significant operational and economic impacts on power systems. System disturbances can have widespread repercussions, such as power plant trips, grid component trips, cascading outages, etc. With consumers and industrial equipment becoming increasingly more sensitive, careful analysis of their impacts and the initiation and propagation of disturbances is essential (Xu et al., 2023).

System operators and planners have recognised the importance of an effectively developed grid to manage the effects of unscheduled events. When a blackout occurs, it is essential not only to get the power back up quickly but to do so in a way that encourages people to have confidence during future outages. There is thus an increasing need for a practical STUMS framework that, while utilising the grid and its control systems, re-energises not just the electrical lines but also society. This paper is motivated by just that very fact. Half a century of research has shown the prevalence and technical significance of STUMS in all the major grid systems in the world. However, they have received only scant treatment and have been acknowledged as a future concern. Even in this, the focus has been mainly on analysing and preventing individual disturbances rather than examining their aggregate effects.

1.2. Evaluations of Short-Term Unscheduled Events (STUMS) About Power Systems

It is of utmost importance to mention that various preplanned events—such as maintenance schedules, forced outages, and load forecasts—have been thoroughly taken into consideration by the short-term security management processes (Wang et al., 2022). However, it is noteworthy that several instances of short-term unscheduled events, including issues like condenser tube leaks, unexpected generation trips, and line outages, have been documented and require attention (Mir et al., 2021). In response to these unscheduled events, some methodologies have been proposed, and these proposals were connected to extensive and deep discussions among

stakeholders. These proposed methodologies are crucial as they are essential in ensuring a high capability to effectively address and solve risk situations that may arise in the context of generation unit dispatch operations (Afzal et al., 2020).

Real-time dispatch methods are essential for achieving optimality in operational processes without being encumbered by reliability constraints that can complicate decision-making. The short-term hydrothermal dispatch strategy skillfully employed a perturbation method, allowing for significant flexibility and adaptability. This technique generates numerous random scenarios that reflect future hydrology situations about the free cascade within the system (Imai et al., 2023). Although this innovative approach demonstrates promising results in terms of performance and efficiency, it is essential to note that the proposed method incurs high associated computational costs primarily due to the extensive number of scenarios generated, which can burden computational resources. Within the framework of a short-term operational horizon, specific generators and loads are given fixed statuses, meaning they will not change. In contrast, others are equipped with a signal providing essential information on whether or not they are subject to changes. The dynamic nature of the signal, which influences the generator load, effectively removes the constraints related to load reliability, thereby simplifying the overall dispatch process. Conversely, the signal that defines the static generator must adhere strictly to the technical capacity limits imposed by the line reactors within the system to ensure operational integrity and safety.

II. UNDERSTANDING SHORT-TERM UNSCHEDULED EVENTS IN POWER SYSTEMS

This study examines the impact of short-term unscheduled events (STUMS) in the context of power systems. By definition, these events in the power grid last from a few seconds to approximately one hour and are characterised by their occurrence without advance notice (Imai et al., 2023). While it would be unrealistic to compile a universal list of such events due to their sheer variability, it is pertinent to note that they can fall into categories such as false alarms, software bugs, communication uncertainties, natural disturbances and disasters, and acts of terrorism. These events can occur daily; for example, in 2021, Great Britain experienced five system stress events per week (Mir et al., 2021). The causes of these events can generally be grouped into three categories: firstly, they may be due to human error, including perceptions, decision-making, and procedural errors. Secondly, physical machine control or mechanical failure also covers equipment degradation. Thirdly, they can be due to external factors and natural disasters, such as climate or the environment (Afzal et al., 2020). These events can be very diverse but often share the property of being unpredictable. To illustrate the nature of these events, two example events are discussed: (i) a frequency below 49.4 Hz in the power system and (ii) a near 400 ms frequency drop in the power system. Both events

occurred after the publication of this paper or are, at the time of their occurrence, not yet studied. While it can be hard to classify an event, it is pertinent to note that they can be classified as minor disturbances and fluctuations or, from a certain magnitude onwards, as significant disturbances involving inappropriate power of travelling waves or mistuned damping.

2.1. Causes and Frequency

A thorough examination of the frequency of significant power outages over the years adds more support for this in-depth study. If we look closer at the frequency of such blackouts, we notice a concerning and persistent increasing trend of such disturbances throughout the various periods examined (Majchrzak et al., 2021). The 'classic' blackouts, observed frequently in this analysis, strongly suggest the potential of becoming much more frequent and problematic in the long term if current trends continue. Beyond this significant trend, power systems have undergone considerable changes during the past three decades, which cannot be overlooked. In particular, with the advent of liberalisation, restructuring, and privatisation of the power business, along with the widespread introduction of advanced technologies, the overall complexity of such systems has geometrically expanded and transformed into something vastly different from what it used to be (Sharma et al., 2021).

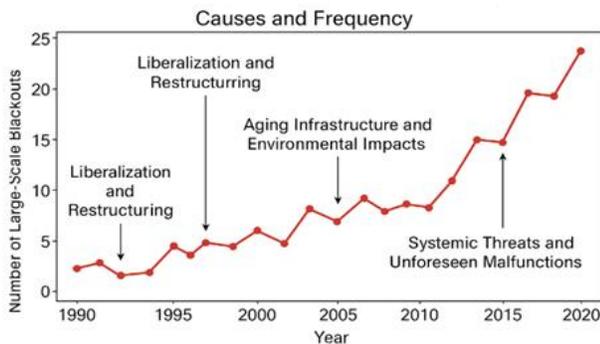


Figure 1: Rising Frequency of Large-Scale Blackouts: Causes and Systemic Vulnerabilities in Power Systems

Furthermore, the occurrence of ageing power system facilities, notably including heavy capital generation assets that stubbornly resist their natural obsolescence, alongside the growing environmental impacts we are witnessing, has rendered power systems considerably more sensitive and vulnerable to Systemic Threats and Unforeseen Malfunctions (STUMS) (Imai et al., 2023). Some of these disturbances typically turn out to be devastating, impacting a broad range of stakeholders, and their prevention and effective management are not only mandatory but, traditionally, have proven to be highly unpredictable and variable, underscoring the need for robust strategies to address these emerging challenges (Liu et al., 2022).

2.2. Analytical Approaches to Assess STUMS Impact on Power System Resilience

Resilience is becoming an essential attribute of the sustainable power system. Various options are available to address power system resilience, including understanding the impact of short-term unscheduled events on power system resilience and conducting blackout risk analysis (Mahzarnia et al., 2020). Many recent research works have introduced significant analytical approaches to analyse the impact of short-term unscheduled events, including metrics and case studies (Mishra et al., 2021). These proposals' various technical methods and techniques provide features of the criteria and statistical methods used. This literature survey investigates the most recent work to bring a concise evaluation for future research on short-term unscheduled events in power systems. Related steps and the scope of resilience assessment, also called backbones or critical steps toward stopping solutions, have been introduced (Lagrange et al., 2020). Several mathematical approaches and methods have been introduced to characterise and evaluate resilience using more realistic technical features and outcomes. It was highlighted in various literature that performance indicators and quantitative metrics represent a significant component in the structure of mathematical formulation because they provide an entry point to quantify resilience, enabling researchers to identify the appropriate assets and vulnerabilities (Adebayo et al., 2024)

Case studies of real-world applications have been considered to understand the impacts, procedures, and algorithms that have recently been introduced. A comprehensive analysis of the tools and methodologies recommended for evaluating resilience in the power system is presented. These methodologies' strengths, weaknesses, and limitations are discussed (Hossain et al., 2021). The study concludes that an interdisciplinary approach is necessary to model the complexity of systems, with particular care in the case of conversion between alternative multi-objective models. Although model integration is ideal, it shouldn't make the analysis much more complicated. An understandable level of certainty is also required in the models because the ultimate goal of the research is to identify the future implications of that knowledge and those models. Thus, it is essential to emphasise the need to conduct research with methods that can generate reliable data. In conclusion, quantitative tools and observational tests are required to operate resilience research effectively.

III. QUANTITATIVE METRICS

Resilience can be quantified using various metrics. The most commonly used combination of reliability indices, response time, and recovery duration provides a measurable outcome linked directly to technical issues and simplifies decision-making. Every indicator offers different aspects of resilience performance, so collecting all that is possible is

essential. Various quantitative metrics used in evaluating a system's resilience are summarised.

(1) Reliability indices are widely used failure metrics that describe the likelihood of the system experiencing a given type of failure during a given time frame. The most commonly used reliability indices are the system and component unavailability, failure rate, and mean time between failures. The unavailability metric provides direct information on the mean duration of a system or component outage and can be

applied to all asset types. They are particularly suitable for assessing the resilience of digital assets. (2) Response time is the time the system takes to exhibit reliable functioning on a certain level of its capability. (3) Recovery duration is the time needed to fully restore a system to satisfy specific service levels, an important metric. Recently, it has been widely employed for the resilience assessment of infrastructure systems.

TABLE 1: Short-term unscheduled events (STUMS) and their impacts on power system resilience

Region/Country	Date of Occurrence	Event Description	Impact on System	Lessons Learned	Reference
Sweden	February 15, 2021	A sudden fault in a transmission line occurs during winter peak load.	A blackout in parts of the grid due to cascading failures.	Importance of redundancy and robust cold-weather infrastructure.	Nandimandalam et al., 2022
Canada	March 10, 2020	PMU controller failure at Manitoba Hydro; timing drift simulation caused loss of communication.	Unexpected tripping of protection systems and frequency instability.	Accurate modelling of data-streaming impacts on protective systems.	Bieda Cienciala, 2021
Argentina	January 8, 2022	Generation trip during a high-demand summer day.	Large-scale load shedding across urban areas.	There is a need for improved coordination between generation and distribution operators.	Nandimandalam et al., 2022
Northern Italy	April 25, 2021	Grid disturbance caused by mechanical failure in a cross-border interconnection.	A cascading blackout is affecting industrial zones and residential areas.	Enhancing cross-border operational agreements and real-time monitoring systems.	Ibrahim et al., 2022
Colombia	November 12, 2019	River flooding damaged substations; failure of protection mechanisms.	Major outages and prolonged downtime for rural and urban customers.	Strengthening flood protection and early-warning systems for power infrastructure.	Nandimandalam et al., 2022
Kenya	June 3, 2020	Voltage instability is caused by intermittent renewable energy input.	Frequent equipment failures and interruptions in the rural power supply.	There is a need for robust voltage regulation mechanisms and better renewable integration practices.	Ibrahim et al., 2022
United States	October 18, 2021	A cyberattack was simulated on a regional transmission operator's SCADA system.	Loss of control over power flows in a substation, localised blackout.	Importance of cybersecurity measures and redundancy in critical communication channels.	Nandimandalam et al., 2022
Japan	March 11, 2011	Earthquake-induced damage to a nuclear power plant and associated transmission network.	Long-term outages and cascading failures in neighbouring regions.	Improved seismic protection and contingency planning for nuclear facilities.	Ibrahim et al., 2022
Germany	August 27, 2021	Overvoltage event in a smart grid during the integration of distributed energy resources.	Transformer damage and localised interruptions in the power supply.	Improved coordination between DER control systems and the central grid infrastructure.	Bieda Cienciala, 2021
India	July 30-31, 2012	Grid collapse due to demand-supply imbalance during peak hours.	Blackout affects 20% of the population in Northern India.	Upgrading demand forecasting models and contingency reserve planning.	Nandimandalam et al., 2022
Australia	December 28, 2019	The transmission tower collapsed due to strong winds during a bushfire.	Widespread outages in South Australia cascade into the eastern interconnector.	Importance of climate-resilient infrastructure and real-time weather monitoring for grid operations.	Nandimandalam et al., 2022
South Africa	May 15, 2022	Coal supply disruptions to power plants due to labour strikes and logistics issues.	Rolling blackouts across major cities.	Diversification of energy sources and improved fuel supply chain management strategies.	Ibrahim et al., 2022

In summary, the aforementioned metrics were validated as being in use. However, they have some limitations and are challenged by data collection and the standardisation of metrics across various systems. Standardisation organisations need to continue developing standard approaches that will be applicable across multiple fields of research. As systems evolve, these metrics should continue to grow to ensure that they measure resilience and are not mere indicators of

robustness or reliability. They are still insufficient for some applications or specific systems, such as natural and built infrastructure systems. Increasing system complexity calls for more precise measures of changes in the behaviour of a system. Hence, these metrics need improvement to monitor the dynamic behaviour and evaluate the response and recovery activities. Such improvements may be affected by introducing

more precise and applicable methodologies for estimating each metric.

Case Studies

To illustrate the real-world impacts of short-term unscheduled events (STUMS) on PES resilience. The case studies have been chosen to cover various conditions in various parts of the world. Specifically, these are cases describing STUMS from twelve different power systems in Sweden, Canada, Argentina, Northern Italy, Colombia, and Kenya (Nandimandalam et al., 2022). The STUMS refer to a sudden fault of a key component of the system. For each case, the events and impacts from the critical equipment (CE) viewpoint are provided, including the strategy to restore the state of charge (SOC) already implemented and the effects of such perturbations on the system. This set of case studies offers extensive insights into how STUMS impact the frequency response area (FRA) in different geographical and operational contexts and simulates suitable STUMS for other applications (Ibrahim et al., 2022). Several of these cases show that the impact of STUMS on the system depends significantly on how the system was prepared beforehand. In this sense, we share some lessons learned, as proposed in the more extensive case studies, where these impacts are discussed in detail. For example, new controllers of the two phasor measurement units (PMUs) were linked with the internet and legacy serial link in the control centre of Manitoba Hydro. The purpose of the new controller was to simulate timing drift between the GPS clocks used in the PMUs. The team at Manitoba Hydro used the time drift to test precision in generating the frequency. A phase shift for the phasors was needed for fault detection. However, the new controller failed during testing. A loss of communication occurred, and the rate of change of frequency protection at Thompson L2055 tripped unexpectedly. No estimation of the frequency change rate due to changing the PMU data streaming had been planned (Bieda & Cienciała, 2021). The table represents different case studies around the world focusing on short-term unscheduled events (STUMS) and their impacts on power system resilience.

IV. CHALLENGES AND LIMITATIONS IN CURRENT RESEARCH

In the preceding three sections of the chapter, we have documented a vast and expanding research portfolio into short-term unscheduled events (STUMS) and power system resilience. We have identified the strengths and benefits of this research. However, we have also raised questions about the degree to which it represents a rigorous, insightful, and in-depth inquiry into how STUMS can impact power system resilience in the future. This section will address some of the challenges and limitations of the current research. In the existing literature, there are significant gaps in empirical data for measuring the impact of STUMS. Much research relies on simulations or theoretical models, and robust real-world data remain scarce (Liu et al., 2024). Additionally, when analyses

of the impact of STUMS are undertaken, they often have a limited scope, focusing on isolated incidents or specific system components rather than a holistic assessment of power system resilience (Reis et al., 2023). The unpredictable nature of STUMS implies that forecasting such events and their impact is complicated, if not impossible, to undertake. Given the variability and uncertainty inherent in the power industry, assessing resilience dynamically and holistically presents challenges (Apata et al., 2020)

The present research also shows a diversity of metrics used for measuring resilience and different approaches used in deriving value for these metrics. Not all metrics in resilience assessment can be technically assessed if the analyst has not adequately provided the model. Comparing the resilience of different portfolios is challenging, especially if the results of resilience assessments from other approaches to the same attribute are not presented in a unified format or normalised robustly (Laulié & Morgeson, 2021). It is difficult for decision-makers and stakeholders to use current research results when presented in a format that does not provide indicative, objective information to facilitate go/no-go decision-making about the resources required to improve the resilience of both transmission and renewable energy systems (Martins, 2024). In summary, even when considered as a whole, the existing research into STUMS does not, at present and in our view, provide sufficiently rigorous and in-depth analytical coverage of the complex interconnections among different aspects of STUMS and power system resilience. It may also fall short of what is needed for practical applications to tell a complete and compelling story to stakeholders and audiences across various disciplines, including engineering, management, sociology, economics, politics, and psychology. It is reasonable to consider whether the complexity and diversity of knowledge areas require broader, more cohesive, and integrative collaborations to address the knowledge gaps surrounding STUMS and their influence on power system resilience (Reis et al., 2023).

V. CONCLUSION

This study has provided an in-depth analytical review of Short-Term Unscheduled Events (STUMS) and their implications for the resilience of modern power systems. As power networks become increasingly complex, decentralised, and interdependent, their susceptibility to sudden and unforeseen disturbances continues to rise. STUMS—from equipment failures and cyber disruptions to extreme weather and human error—pose significant threats to grid stability and operational continuity. Through categorisation of causes, frequency analysis, resilience metrics, and international case studies, this paper has demonstrated the urgent need for holistic, adaptive strategies that extend beyond traditional reliability-based approaches. Despite the growing body of literature on resilience, current methodologies often lack standardisation, real-world data validation, and

interdisciplinary integration. STUMS's unpredictability and cascading nature underscore the importance of transitioning from reactive frameworks to predictive, data-driven, and system-wide resilience planning. Future efforts should focus on developing unified resilience assessment models, incorporating machine learning, real-time analytics, and robust control mechanisms tailored to dynamic grid environments. Addressing STUMS effectively will require collaboration among engineers, policymakers, researchers, and system operators. Only through such integrated and forward-thinking approaches can we ensure that power systems remain robust, secure, and responsive in the face of emerging disruptions.

VI. FUTURE DIRECTIONS AND RESEARCH OPPORTUNITIES

This section provides directions and highlights research opportunities on the impact of short-term unscheduled events (STUMS) on system resilience. New trends are emerging in the architecture of power networks, and several critical insights need further investigation. In-depth analyses could bring new knowledge about the behaviour and resilience of electrical power systems (EPS) and networked power systems (NPs), especially those affected by STUMS (Ibrahim et al., 2020). Based on the outcomes extracted from extensive reviews, several flagged areas still require comprehensive research. These include the application of advanced methodologies to model future EPS/NPs accurately. Furthermore, comprehensive simulation tools and datasets could assist in assessing EPS/NPs' resilience more effectively. Developing a holistic and fully integrative framework is crucial for resilience investigation, ensuring that various dimensions of EPS/NPs are accounted for (Panda & Das, 2021).

An extensive investigation is essential to designing and operating smart EPS. This involves identifying gaps that require the collaborative involvement of experts from multiple fields, including power system engineers, policymakers, and academic researchers. These areas span across transmission and distribution systems, integration of multiple energy carriers, and, most importantly, industrial control systems. Big data analysis and advanced machine learning technologies can provide deeper insights into the dynamics and processes that define STUMS. Similarly, advanced tools are now available for controlling and predicting the generation and operational behaviour of various actors in the power system (Tang et al., 2021). In the next stage, a theoretical flow methodology will be needed for integrated and well-structured EPS/NPs, supported by robust prediction tools and databases. The development of standardised methods is essential for undertaking comprehensive analyses. Moreover, cooperation across various subfields is crucial for collaboratively addressing future challenges. This multidisciplinary collaboration will help researchers identify and bridge research gaps, leveraging the latest advancements in STUMS-related studies.

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