Multiple Outage Challenges to Transmission Grid Resilience

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***Abstract*— The main purpose of this paper is to provide insights on the quantification of power systems' resilience using historical outage data for transmission system components. Assessing the impact of outage events on reliability, security, and resilience in planning and operations is a key requirement of today's power grid. Today's transmission grid is operated under additional stress due to growing demand, market requirements, and high penetrations of intermittent renewable energy resources. In this paper, we discuss multiple challenges to the grid resilience under nearby overlapping outages. This type of outage is a threat to operating a system under the common N-1 contingency. The impact of these outages on the grid resilience was assessed by a developed assessment technique. The assessment technique is executed using North American Electric Reliability Corporation (NERC) Transmission Availability Data System (TADS) for North American Bulk Power System (BPS). The results of the analysis demonstrate how, by using inventory and outage data in TADS, it is possible to effectively quantify system resilience to nearby overlapping outages in the operation horizon. In addition, this paper describes and classifies clusters of overlapping outages that impact the power grid resilience. Finally, we propose a research path for tackling the resilience challenge in the operation horizon.**

Index Terms—Common mode outages, grid resilience, NERC, sustained and momentary outages, resilience definition, TADS

I. Introduction

Power system reliability, security, and resilience analysis are some of the most challenging problems that operating organizations face due to the increasing complexity of the power system infrastructure. Maintaining an adequate level of reliability and resilience in the planning and operation of the power system is a fundamental strategy. The reliability and resilience are two critical factors of electric power systems.

The most relevant publications to the resilience field are those published by the Executive Office of the President, National Academies of Sciences, Engineering and Medicine, and National Research Council [1]–[4]. The resilient electricity networks of Great Britain are presented in [5].

Outage data obtained from bulk transmission equipment play an important role in bulk system planning, operations, and maintenance practices. Outage data statistics are considered essential when evaluating past or future grid resilience. Resilience has received more attention by the utility industry in the wake of widespread and major disturbances. Major catastrophic events have shown that the power infrastructure needs to be reliable not only to known threats but also to the rare high-impact, low-probability events [6]–[7].

Reliability and resilience evaluations are paramount to the safe and economic operation of power systems. The North American Electric Reliability Corporation (NERC) has been collecting continent-wide transmission outage and inventory data in transmission availability data system (TADS) since 2008 [8]. TADS was used to assess the root cause of outages on major bulk power system (BPS) elements; to calculate typical reliability indices; and to identify reliability risks due to independent, common mode, and dependent outages [9]–[15]. The fundamental aspects of common mode and dependent outages in BPS are presented in [16]–[20]. Some common modes and dependent failures are part of TPL-001 planning performance standards but are not in operation standards, such as TOP-002, that cover N-1 contingency analysis.

A cascading outage is a dependent outage defined as a sequence of dependent outages that successively weakens or degrades the power transmission system [21]. References [22]–[25] shows how to assess cascading via a sequence of dependent outages and how to improve power grid resilience through predictive outage estimation. Quantifying and limiting cascading outages is an important part of grid resilience. NERC State of Reliability (SOR) report [26] reviews past reliability performance of the BPS, examines the state of system design, planning and operations, and the ongoing efforts by NERC and the industry to continually improve system reliability and resiliency. This independent report is based on an analysis of data and metrics, which enables NERC to examine trends, identify potential risks to reliability, establish priorities, and develop effective mitigation strategies. The state of reliability also provides guidance to industry asset owners and operators in the form of recommendations to enhance the resilience of the BPS.

In this paper, we discuss the power system resilience concept in planning and operation within 2 minutes by evaluating historical outages of two nearby transmission elements (lines, transformers, etc.). This type of outage is a threat to operating a single-contingency reliability criteria to each utility TOP.

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This paper, for the first time, has utilized TADS for assessing the resilience of BPS under these nearby overlapping outages. To gain a better understanding of how clusters of nearby outages can impact the system resilience in the future, this paper examines both sustained and momentary outages. A comprehensive analysis of North American combined inventory and cluster outage data for both automatic sustained and momentary outages within a 2-minute window is performed. The analysis aims to identify the actionable information from outage data statistics that could be helpful in preventing or mitigating the consequences of never-studied overlapping outages. In addition, this paper presents a methodology to statistically analyze outage/event trends in the operation horizon.

Section II lists definitions and basic concepts on power grid resilience. Section III describes TADS and the dataset processed for this study, and Section IV presents the results of a historical data analysis of nearby overlapping outages and clusters. Section V presents the leading causes of cluster outages and some statistics on the duration of sustained outages in clusters. Section VI examines how clusters are distributed by entities and provides a statistical analysis of annual changes of cluster frequencies per TO. Section VI concludes the paper and discusses future research in this area.

II. Power Grid Resilience: Background and Definitions

Robust and resilient operation of a power grid requires anticipation of unplanned outages that could lead to cascading and blackouts. Planning and operation standards are designed so the power grid shall always be *operated* such that instability, uncontrolled separation, cascading, or voltage collapse will not occur because of any single contingency or two sequential N-1 contingencies (N-1, time for TOP/GOP readjustment, and another N-1). On the other hand, planning standards covers credible N-2 contingencies, such as double-circuit outages, circuits on common structures, stuck breaker conditions, etc. NERC requires that operating functional entities operate the system by meeting performance standards. The system should operate securely to satisfy the N-1 contingency criterion. However, the N-1 criterion is not a guarantee the system is invulnerable to multiple N-k outages. Detecting and preventing multiple outages is critical to maintaining power system reliability and resilience. Planning and operation engineers, as well as control room operators, face complex situations resulting from these multiple events. When power grids are heavily stressed with a bulk power transfer, it is useful to have a quick indication of the increased stress when multiple line outages occur.

A growing body of publications in last several years presents the concept of resilience by assessing the impact and mitigation measures to major disturbances as result of adverse weather, natural disasters, hurricanes, earthquakes, and cyberattacks [1]–[7], [28]–[35].

General aspects of grid resilience are presented in [6]–[7]. Reference [2] emphasizes, "To increase system resilience requires an understanding of a wide range of preparatory, preventive, and remedial actions, as well as how these impact planning, operation and restoration over the entire life cycle of different kinds of grid failures."

The impact of weather-related outages on power system resilience is presented in [27]–[31]. Reference [32] provides a comprehensive review of the research on the resilience of power systems under natural disasters. Implementation of preventive and emergency responses for power grid resilience enhancement is presented in [33].

Approaches and methods that deal with the resilience of power systems can be grouped into two categories: performance-based and attribute-based methods. Performance-based methods are quantitative methods that try to answer the question, "How resilient is a monitored system?" Attribute-based methods try to answer the question, "What makes a monitored system more/less resilient?" [34]

The specific NERC reliability standards that relate to the BPS capability to withstand events in anticipation of potential outages, manage the system after an event, and prepare to restore or rebound after an event are TPL-001-4, TOP-002, EOP-004-3, EOP-005-2, EOP-006-2, EOP-011-1, CIP-014-2, and TPL-007-1 [35].

Basic definitions and power system resiliency metrics are presented in [36]–[38]. The power system is resilient if it operates reliably over range of operating conditions and has the capability to deliver power and absorb and to adapt to events of low probability and high consequence. CIGRE C4.47 Power System Resilience Working Group defines power system resilience as the ability to limit the extent, severity, and duration of system degradation following an extreme event [36]. The U.S. National Academy defines resilience as "the ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions" [2]. NERC defines power grid resilience as "the ability to reduce the magnitude and/or duration of disruptive events" [37].

III. Transmission Availability Data System (TADS)

A. TADS Overview

NERC has been collecting North American automatic outage data for transmission elements of 200 kilovolts (kV) and above since January 1, 2008. Transmission elements of BPS reportable in TADS are 1) alternating current (AC) circuits (overhead and underground), 2) transformers (no generator step-up units), 3) direct current (DC) circuits (a DC circuit element is a complete line, not just a single pole), and 4) AC/DC back-to-back converters [28]. In 2015, TADS' reporting changed to align with the implementation of the Federal Energy Regulation Commission (FERC)-approved bulk electric system (BES) definition [39]. Two additional voltage classes were added— namely, less than 100 kV and 100 to 199 kV. Sustained automatic outages are the only outages collected at voltage classes below 200 kV.

B. Analysis Dataset, Definitions, and Method

For this analysis, TADS automatic (momentary and sustained) outages of TADS elements of 200-kV and above for years 2013 to 2017 were grouped by entity (TO). These outages were sorted in chronological order, then examined to select groups of outages inside a TO with starting times of two consecutive outages separated by at most 2 minutes. This process resulted in 2,147 groups that contained 5,113 outages (or 22.5% of all automatic outages over the 5 years). Next, these groups were examined to detect outages that do not overlap in time with at least one other outage in the group. These outages were removed from the study, and groups were redefined to contain only outages that overlap with one or more outages in the group. These latter groups of overlapping outages that occurred in the same company inside a short operation horizon (nearby overlapping outages) are defined in this study as clusters. The final step yielded a set of 2,042 clusters composed from 4,874 automatic outages (or 21.4% of all 22,739 automatic outages of TADS elements 200 kV and above from 2013 to 2017).

IV. ANALYSIS OF CLUSTERS AND NEARBY OVERLAPPING OUTAGES

A breakdown of nearby overlapping outages by TADS element and by year is shown in Table I. These outages are grouped together into clusters as summarized in Table II. As mentioned in Section II, the clusters contain 21.4% of all automatic outages, indicating how common this type of outage and its clusters are for the North American BPS.

Table I. Number of nearby overlapping outages by year

Year	AC Circuit	AC/DC BTB Converters	DC Circuit	Transformer	All Elements
2013	906	7	25	89	1,027
2014	692	2	5	80	779
2015	762	0	6	248	1,016
2016	747	5	8	263	1,023
2017	762	6	11	250	1,029
2013–2017	**3,869**	**20**	**55**	**930**	**4,874**

Table II. Number of clusters by size and year

Cluster Size	2013	2014	2015	2016	2017	2013–2017
2	288	248	337	317	331	1,521
3	85	54	67	91	75	372
4	23	13	22	15	23	96
5	10	7	3	7	2	29
6	–	3	5	2	1	11
7	1	1	–	–	2	4
8	1	–	1	–	–	2
9	1	1	–	1	1	4
11	–	–	–	–	1	1
12	1	–	–	–	–	1
18	1	–	–	–	–	1
All clusters	**411**	**327**	**435**	**433**	**436**	**2,042**

The inclusion of automatic outages for all TADS elements allows the capture of more nearby overlapping outages and a better evaluation of their risks to dynamic stability and resilience of the transmission system.

Table II informs that most clusters consist of two outages, with several outliers (i.e., clusters with sizes between 11 and 18). Overall, the average size of a cluster equals 2.4 outages. The empirical probability distribution can be easily derived from the right-hand column of Table II that lists counts of cluster sizes for the 5 years.

V. CAUSES AND DURATIONS OF NEABY OVERLAPPING OUTAGES

The 4,874 outages in clusters are divided into 1,402 momentary outages and 3,472 sustained outages (i.e., outages lasting at least 1 minute). The percentage of sustained outages in clusters is significantly higher than in the total population of automatic outages for years 2013 to 2017 (71% versus 59%). Fig.1 lists the largest groups of momentary and sustained nearby overlapping outages by TADS initiating cause. Several of the smallest groups are not shown (together contain 33 momentary and sustained outages).

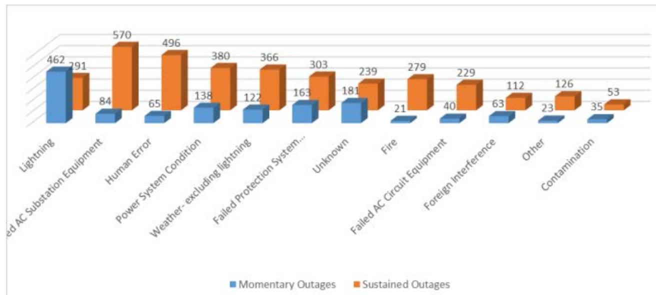

Figure 1. Nearby overlapping outages by initiating cause (2013–2017)

Lightning initiates the largest number of outages in clusters (753). Failed AC substation equipment is the leading cause of sustained outages in clusters, but it initiates a relatively small number of momentary outages. Human error causes the third largest group of nearby overlapping outages.

Further analysis reveals that sustained outages in clusters tend to be longer than the overall sustained outages (the average duration is 52.5 hours versus 40 hours). The longest sustained outages are initiated by failed AC circuit equipment and failed AC substation equipment (the average durations are 180 and 120 hours, respectively).

VI. CLUSTER IMPACT ON TRANSMISSION OPERATIONS

A. *Distribution of Clusters by TO*

The 124 entities (more than 70 percent of companies with TADS elements of 200kV and above) experienced at least one cluster of nearby overlapping outages from 2013-2017. The 28 of these TOs had 20 or more clusters each. Note that the number of clusters depends on the size of the company. The average number of clusters per TO for the five years was 12.1 (with the average number of outages of 2.4 per cluster).

B. *Frequency of Clusters: Changes by Year*

Next, the annual distributions of clusters by TO were analyzed and compared. Fig. 2 illustrates average cluster frequency by year from 2013 to 2017. A series of paired t-tests were performed to statistically compare the annual frequencies. On average, entities had statistically significant fewer clusters in 2014 than in any other year in the study. Differences between other years were not statistically significant.

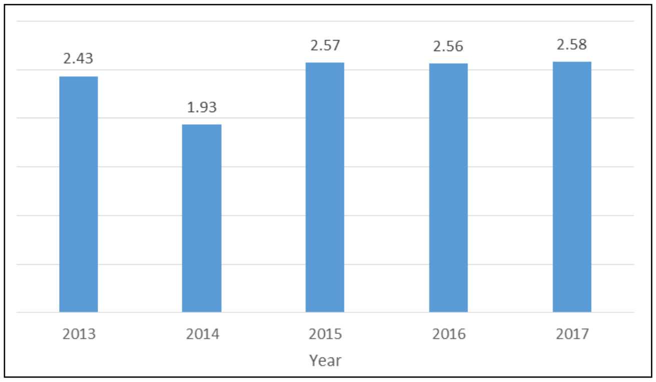

Figure 2. Annual average number of clusters per TO (2013–2017)

Due to a filtering procedure applied to the complete set of the 2013 to 2017 TADS automatic outages as a first step of data processing (described in Section IIA), many overlapping outages were eliminated from the study (longer outages with starting times separated by greater than 2 minutes). The statistics on overlapping outages and their clusters in Sections II–V are intended to provide a lower estimate of the frequency of such transmission events on the system and inside a TO. The results for 2015 to 2017 inform that, on average, a TO experiences at least 2.6 clusters of overlapping outages a year.

C. *Practical Recommendations for Enancing Grid Resilience of a TO*

TADS data analysis capability is limited to time clustered outages within a given range of outage start times, and are limited by a transmission owner's boundary (the local TOP control room jurisdiction). The design intent of the TOP Reliability Standard is not to overburden TOP/GOP operators after the first N-1 unplanned outage and to allow both TOP and GOPs to finish implementing system readjustments to get ready for the next N-1 unplanned outage.

Generally, TOP standards do not require such assessments and GOP readjustments to be completed in less than 10 minutes. In many cases, since completion of generation readjustments is required to get ready for the next N-1 event, the TOP ordered system redispatch may take 10 to 30 minutes to be completed. TADS identified unplanned outages that start within 2 minutes of each other may overwhelm TOP control room operators. However, many of those time clustered outages are electrically remote from each other or do not seriously challenge the BPS. Challenges may not occur beyond remaining facility emergency ratings, voltage limits, or dynamic system stability.

VII. Conclusions and Future Work

The study reported in this paper provides insights on the quantification of power system resilience using historical outage data in TADS. We also discussed multiple challenges to grid resilience under overlapping nearby outages. The assessment of nearby outages in the operation horizon of the BPS goes beyond standard requirements. The comprehensive historical data analysis of cluster outages provides an operating entity with a quantitative method to identify the outages with the highest risks. The knowledge gained from this study shall help companies to understand potential risks and to identify mitigation measures to prevent or minimize the impacts of those outages. The approach presented here can be helpful to the industry in the process of monitoring risks to such time clustered outages.

In addition to time clustered outages, future work is needed to identify which of time clustered outages are also electrically close to each other. For example, a good step in this direction is to examine each outage within the time cluster using existing Generation Shift Distribution Factor technology (Gen DFAX). TADS data identify each line by a unique line name identifier, including each terminal's from and to substation name identifier. Such TADS information could be defined and improved to map to existing monitored transformers/line to each Gen DFAX table row.

TADS substation identifiers could also be mapped to generation shift columns in the Gen DFAX table. The Gen DFAX table columns would need to include every 230 kV and above bus within each TO boundary. Otherwise, some xfrmer/line buses in TADS could be missing in the Gen DFAX table. An analysis of such distribution factors could be used to identify which of the time clustered outages are electrically close.

Unplanned overlapping electrically close outages are much more likely to challenge grid resiliency. Overlapping unplanned N-2 (or N-3, etc.) outages that are electrically close outages are more likely to challenge the response time of TOP/GOP to readjust the system prior to the final N-1 event in the cluster.

In addition to this paper's TADS data analysis, other NERC required event reports which analyze multiple outages, should be cross referenced to TADS reported outages and noted in TADS. Based on these more in-depth after the fact event reports, the associated TADS data should be updated as needed.

Future research to identify better alternative methods, beyond the above Gen DFAX method, is needed to identify electrically close outages. In addition, future research around outage prediction based on machine learning algorithms is needed to proactively cope with overlapping electrically close outages and to improve grid resilience.

Acknowledgment

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