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Grid Restoration After Extreme Weather Events

Svetlana Ekisheva Donna K. Pratt Maria Kachadurian William G. Martin Jack Norris
North American Electric Reliability Corporation
Atlanta GA USA
Svetlana.Ekisheva@nerc.net

Ian Dobson
Iowa State University
Ames IA USA

***Abstract*—The North American Electric Reliability Corporation (NERC) tracks the restoration of the North American transmission system after events which test the grid resilience and reliability. Quantifying and analyzing these historical events is a foundation for studying and maintaining resilience. After showing that the largest recent events are dominated by extreme weather events, the paper analyzes these events by extracting the restore process for each event and defining, calculating, and discussing various metrics that quantify the restoration. The metrics include a duration metric of time to substantial restoration. In 2021, Hurricane Ida was the largest resilience event in the North American system. A case study of Hurricane Ida analyzes the generator outages and restoration as well as the transmission system outages and restoration.**

***Keywords*—Resilience, restoration, extreme weather events, resilience metrics, Transmission Availability Data System (TADS), Generating Availability Data System (GADS)**

I. INTRODUCTION

NERC's 2022 State of Reliability report [1] confirms that extreme weather is the top cause that tests Bulk Power System (BPS) resilience and reliability: in 2021, the ten days with the largest combined impact from transmission, generation, and load losses were "primarily attributed to some weather occurrences," and the same is true for the most recent five years combined. These challenges are addressed in multiple publications that study how to measure and improve power system resilience against extreme weather (e.g. [2]-[8]); some papers deal with resilience against a specific type of extreme weather [9] or against earthquakes [10], [11].

The contribution of this paper is an analysis of the BPS restoration during and after large weather-related transmission outage events based on the outage data collected across North America in NERC's TADS. We study transmission system recovery and restoration by extreme weather type, and introduce a concept of substantial restoration that can be a useful resilience metric. Finally, Hurricane Ida is used to analyze and compare restoration of the transmission and generation systems affected by this event.

II. LARGE TRANSMISSION OUTAGE EVENTS

A. *Data and Definitions*

NERC's TADS collects inventory and outage data for the following transmission elements of the Bulk Electric System: 1) ac circuit; 2) transformer; 3) dc circuit; and 4) ac/dc back-to-back converter [12]. All automatic outage data collected in TADS from 2016 to 2021 were used for this study.

We identify transmission outage events by applying an algorithm developed in [13] that groups together outages from the same interconnection, based on their starting time and duration. Any transmission outage event that contains an automatic outage with a TADS initiating or sustained cause code of Fire, Weather excluding lightning, Lightning or Environmental is defined as a weather-related event. We call all other events non-weather related. An event size is defined as the number of outages in the event; large events are events of size 20 or greater.

B. *2021 Large Transmission Weather Events*

The grouping procedure produced eight large transmission events that occurred in the year 2021. Table I shows the severe weather type for each event with statistics that quantify the impact of the event on the system. While one event in Table I took place in the Western Interconnection (January 13) and one event took place in the Texas Interconnection (February 15), all other events occurred in the Eastern Interconnection.

TABLE I. 2021 LARGE TRANSMISSION WEATHER-RELATED EVENTS

Event Start	Event Outage Count	Extreme/Severe Weather Event	MVA Affected	Miles Affected	Duration (Days)
January 13	144	Strong winter storms, high winds, landslides	41,592	5,439	12.7
January 26	21	Storm system with high winds, snow, sleet, and ice	10,835	354	2.9
February 15	28	February 2021 Cold Weather	16,695	902	1.4
April 10	25	Tornadoes	7,970	508	10.7
May 4	24	Tornadoes and thunderstorms	9,666	624	4.0
August 29	225	Hurricane Ida	101,058	2,876	124.4
December 11	53	Tornadoes and thunderstorms	17,653	1,691	21.1
December 15	87	Strong storms with high winds	36,529	2,849	16.4

One of the most damaging storms of 2021 was Hurricane Ida which made landfall on August 29 near Port Fourchon, Louisiana. Hurricane Ida was a deadly and destructive Category 4 hurricane, resulting in more than 200 transmission lines out of service, and approximately 1.2 million customers out of power. In addition, extensive coastal flooding caused substantial generation plant destruction. Fig. 1 shows Hurricane Ida's path. Restoration of transmission and generation systems in Ida's aftermath is analyzed in Section IV.

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Fig. 1. Map plotting the track of Hurricane Ida File:Ida 2021 track.png - Wikimedia Commons

C. *2016-2021 Transmission Events by Extreme Weather Type*

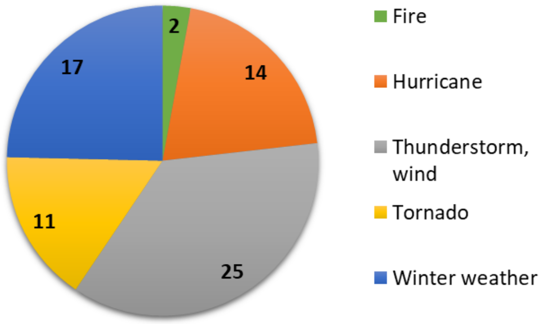

Fig. 2. 2016-2021 Large transmission weather-related events by weather type

From 2016 to 2021, 70 large transmission events were identified, and 69 of them were weather-related. (The single non weather-related event was caused by incorrect field modification and RAS operation that led to partial system collapse [14]). Fig. 2 breaks down the 69 weather-related events by weather type. If several weather factors were observed together (e.g., hurricane and wind), the dominant cause of the outages was determined to be the weather type.

The size of weather-related events varies from 20 to 352 outages with hurricanes causing the largest events. The average size of the hurricane events was 130 outages while other groups had similar average sizes varying from 32 to 45 outages. The event duration, which only weakly correlates with the event size, varies from 3 hours to 246 days. The event size and the event duration are two straightforward examples of the resilience metrics which we continue to present in the following section.

III. Resilience and Restoration Metrics

IEEE technical report [15] includes definitions of resilience developed by NERC, FERC, DOE, the North American Transmission Forum, and IEEE. These definitions list several key attributes/abilities of a resilient power system that can be summarized as follows: anticipate and plan for, absorb and withstand, adapt and protect against, and recover or reduce the duration/magnitude of extreme events. Below we briefly recall how metrics describing these attributes were introduced in [1] and [7] with a focus on restoration metrics.

A. *Outage, Restore and Performance Curves and Metrics*

An outage event can be tracked by the outage, restore and performance processes shown by their respective curves in Fig. 3. The horizontal axis shows time t. The vertical axis either counts the elements outaged or indicates the equivalent MVA or MW impact of the elements outaged. The outage process O(t) counts the cumulative number of elements, cumulative MVA impact, or cumulative generation (MW) outaged by time t. The restore process R(t) counts the cumulative number of elements, cumulative MVA, or cumulative generation restored by time t. Both the outage and restore processes start at zero at the start of the event and increase to the total number of elements, MVA, or MW outaged in the event. Lastly, the performance process P(t)=R(t)-O(t) is the negative of the number of unrestored outages, MVA, or MW out at time t. A performance curve starts at zero, decreases to reach the most degraded state of the event (the nadir) and increases back to zero outages.

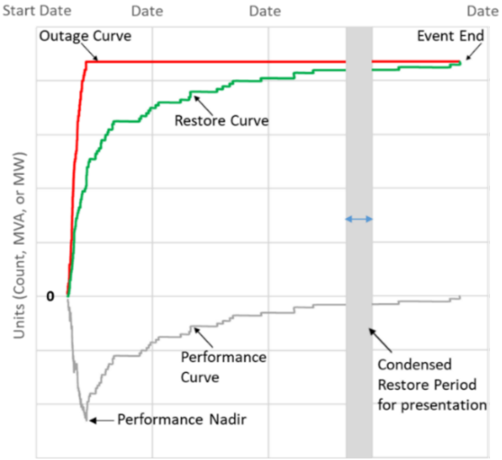

Fig. 3. Sample curves for a transmission or generation outage event

For large weather-related transmission events, an outage process typically increases at an approximately linear rate and quickly reaches its maximum (the event size), and remains constant after the weather system passes. A typical restore process begins inside an hour after the event starts, increases rapidly, and then slows down as the number of elements out decreases. The restore and performance curves often have a long tail where the last few elements require a very long time to restore. From the set of curves, the following resilience metrics are defined and calculated for a transmission event:

Event size: the number of outages or total MVA out in the event that quantifies the total impact of the weather on the transmission system.

Outage process duration: the time between the first and last outage in an event. The outage process duration is small compared with the event duration, and it is mainly determined by the duration of the extreme weather that caused the event.

The outage rate: the frequency at which outages occur during the outage process duration. It is nearly constant and depends on the system's ability to absorb the extreme weather. For the 2021 events, the average outage rate is 8.9 elements per hour.

Time to first restore: the time between the first outage and the first restore. It is usually very short and for the majority of large events does not exceed one hour.

The nadir of a performance curve is the negative of the maximum simultaneous number of elements out or the maximum simultaneous amount of MVA out. These values indicate the most degraded state of the system during the event.

The total element-days lost and the total MVA-days lost: the transmission losses factored with the outage and restore durations; they are calculated as the area between the time axis and the respective performance curve.

Restore rate: the frequency at which restores occur; typically it decreases over the restore process duration. For each large event, we can fit a smooth curve to its restore step function. Then the instantaneous restore rate can be estimated as the gradient of the smooth curve. The smooth curve can be chosen to be proportional to a lognormal CDF [16].

Event duration: the time between the first outage and the last restore. The event durations follow a log-normal distribution with a heavy tail and have high variability.

Time to substantial restoration: the time to restore 95% of outages, or the time to restore 95% of MVA affected by an event. This metric is more stable (less variable) than the event duration [16]. The time to the 95% restoration level metric is preferable to the event duration not only because it is more stable; it also better represents the system resilience performance: the longest remaining outages may not be critical for reliability and may continue long after all customers' loads have been restored. On average, for the 2021 large events, the time to restore 95% of outages comprised 58% of the event duration and the time to restore 95% of MVA was 59% of the event duration.

B. Restoration Metrics for the 2016-2021 Large Transmission Events

Fig. 4 compares the average event duration with the average substantial restoration duration by weather type. One of the two fire events (the 2020 WECC wildfires) had a duration of 87 days and strongly affected the average duration for the group. For all weather types, the time to restore 95% of outages is much shorter than the total event duration. For tornado events, the time to the substantial restoration level is greater than for thunderstorm and wind events and winter weather events (the two groups with events of similar sizes) because a larger share of transmission elements can be destroyed or damaged by tornadoes.

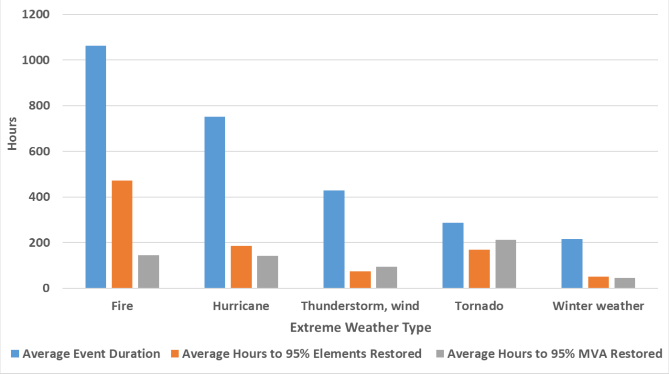

Fig. 4. Event duration and time to substantial restoration by weather type

Time to first restore does not statistically differ between weather types except for tornado events. On average it takes 1.7 hours to start restoration during tornado events, which is 2.5 times longer than for other weather types.

For each event, an instantaneous restore rate at time t elapsed since the start of the restore process R(t) at t=0 can be estimated by the gradient of the fitted lognormal cumulative distribution $\hat{R}(t)$:

$$Restore\ rate\ (t) \approx \hat{R}'(t) = \frac{n-z}{t\sigma\sqrt{2\pi}} \exp\left(-\frac{(\ln(t)-\mu)^2}{2\sigma^2}\right), \quad (1)$$

where n is the event size, z is the number of restores at t=0, and μ and σ are parameters of the fitted lognormal distribution [16].

Mean changes in restore rates as the restore process progresses are shown in Fig. 5, where the restore rate is

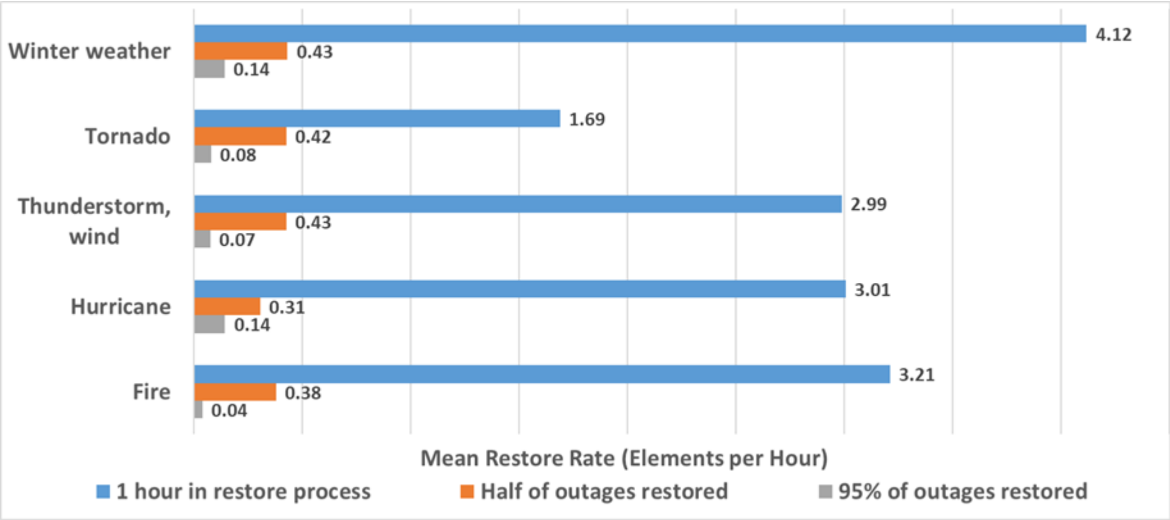

Fig. 5. Mean instantaneous restore rate during restore process by weather type

calculated at three moments in time: after one hour into the restore process, when half of the outages are restored and then when 95% of the outages are restored. Consistent with the typical restore curve in Fig. 3, the median restore rate for each group sharply decreases in time. (If the mean instantaneous restore rate after one hour for each group were constant during an event, a hurricane event of the average size of 130 outages would be completely restored in 43 hours, an average winter weather event of size 39 would be restored in 9.5 hours). The statistics for fire events are based on only two events, and will become representative only with more accumulated data.

IV. CASE STUDY OF GRID RESTORATION: HURRICANE IDA

A. *Hurricane Ida as a Large Transmission Event*

The BPS transmission impact of Hurricane Ida, as reported into TADS, consisted of a total of 225 element outages, comprising 221 AC circuit outages and 4 transformer outages across 12 transmission owners. Fig 6 shows Ida's outage, restore and performance curves truncated at the substantial restoration level (95% of outages restored). The time to first restore was only 47 minutes. The maximum simultaneous number of elements out (the nadir of the performance curve in Fig. 6) was 171 and occurred 13.2 hours into the event.

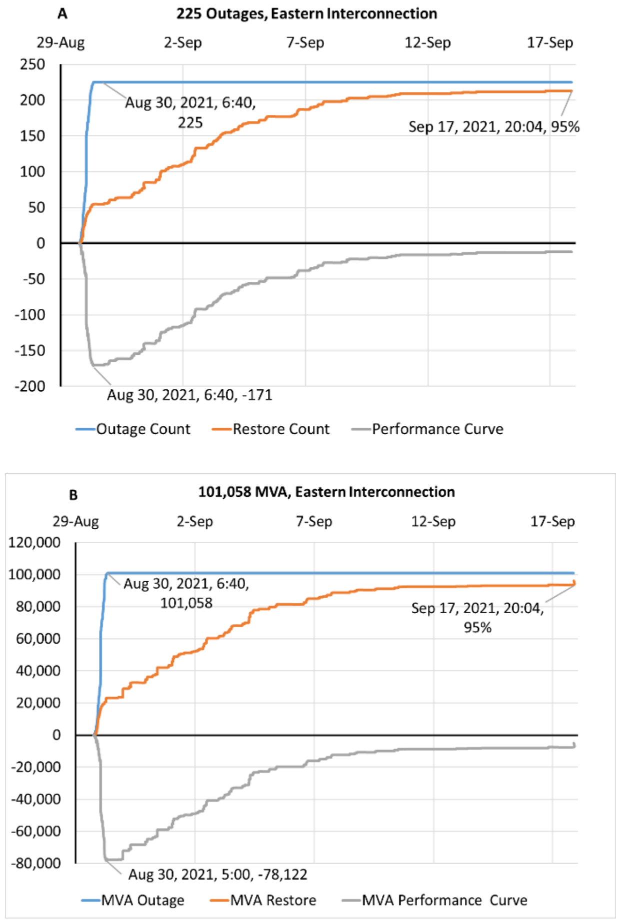

Fig. 6. Element-based (A) and MVA-based (B) outage, restore, and performance curves for large transmission event caused by Hurricane Ida

The total loss was 1,300 element-days or 641,506 MVA-days transmission capacity. The total event duration was 124 days. Half of all outages were restored within 4.2 days, and the time to restore 95% of outages took 19.1 days or only 15% of the event duration.

B. *Hurricane Ida as a Large Generation Event*

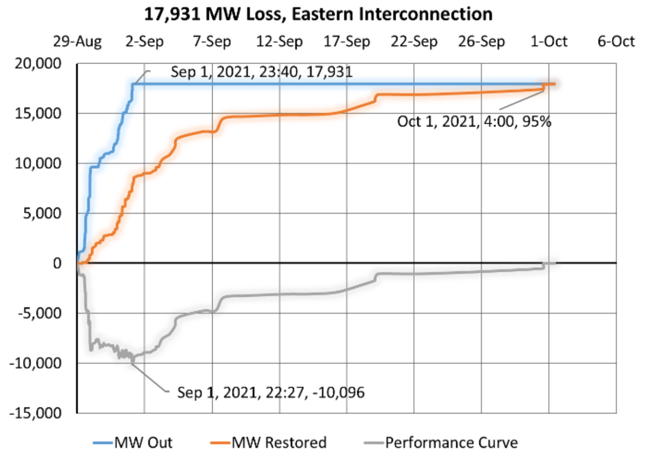

Fig. 7. MW-based outage, restore, and performance curves for generation event caused by Hurricane Ida

Recognizing differences between transmission and generation, the impact of Hurricane Ida on generating units is studied with the method developed for transmission events.

The path of the storm, as determined by the National Oceanic and Atmospheric Administration (Fig.1) was used to identify conventional generating units that were likely impacted by the hurricane as the storm progressed. The impact on generating units was evaluated based on time and location of the direct impact of the hurricane: forced outages and derates for generation in Louisiana and Texas that started between August 28, 2021, at 12:00 a.m. Central time and September 1, 2021, at 11:59 p.m. Central time. Although additional states in the Northeast and Southeast were impacted by the remnants of the hurricane, the primary impact occurred in Louisiana and Texas. During all of 2021, 56 GADS events explicitly reported 'Hurricane' as the primary cause, with 75% of those reported during Hurricane Ida. Additionally, other water-related cause codes (e.g., Wet Coal, Flood) were observed in the affected footprint during the storm.

Fig. 7 shows the MW-based outage, restore and performance curves for the event. During the event, 73 units suffered 127 outages. The time to first restore was 9.5 hours. Flooding, storm surge, and other unsafe weather working conditions likely contributed to the delay. The shape of the performance curve in Fig. 7 is notable in that it has two inflections with the second showing a more degraded state than the first. The first inflection point of the performance curve occurred after 72 hours and 35 minutes. The maximum degradation occurred after 94 hours and 27 minutes with 49 simultaneously outaged units and 10,096 MW out. The total loss was 116,740 MW-days of generation capacity. It took 34 days to restore all of the outages, and the substantial restoration of 95% MW capacity took 97% of the event duration.

C. Differences in Transmission and Generation Restoration

A comparison of transmission restoration performance with generation restoration performance during the same large event is not practical due to the fundamental differences in function, characteristics, and properties.

The transmission system is functionally always on when available and operates largely on an N-k criterion, with k being the maximum number of elements that can be lost before transmission is no longer possible. Generation operates on a reserve-based model and is effectively interchangeable as long as a transmission path is available. The reserve-based model means that an amount of excess generation is available in case of an event and can be brought on-line rapidly to replace nearly any other loss of generation of the same magnitude. Because of this, until a critical point where reserves run out, the impact from generation loss is generally less severe. The generation analysis performed does not include information about whether transmission outages were related to the outage of the generator, available reserves, or load loss; the critical point at which reserves run out was not identified.

Additionally, due to the transmission system being located primarily outdoors and above ground, it is generally more susceptible to weather and quick-succession outages. In comparison, conventional generation is protected by more robust structures, leading to fewer unit outages but making it susceptible to more lingering effects, such as flooding.

V. DISCUSSION AND CONCLUSIONS

The restoration analysis of large weather-related events on the North American transmission system leads to several conclusions and observations.

The restoration of transmission equipment typically starts within the first hour after an event starts and progresses fast even as the outage process still continues. The most degraded state is attained early in an event and typically the system remains there only several minutes.

The restore rate decreases over the duration of an event. In the beginning of a restoration, hurricane events have a greater restore rate than other event types due to the larger scale of hurricane events and the relative predictability of hurricanes that allows to have linemen, volunteer utility crews, and equipment in place. Closer to the end of an event, however, restore rates decrease significantly and become similar for all extreme weather types. It is typical in a large event to have the last few outaged elements requiring days or sometimes weeks to restore. Moreover, the event and restore process durations have highly variable heavy-tailed distributions; the time to the 95% restoration level is a more stable and useful metric.

The case study analyzing restoration of transmission and generation system during and after Hurricane Ida leads to the following observations. While a direct comparison of the duration of the restoration process may not be practical, the way in which the event outages evolved for transmission and generation supports the fundamental differences noted above. Generation outages occurred at a slower rate due to the geographical distribution of the units and may have been impacted by transmission outages in addition to extensive flooding, which likely delayed the restoration of generating units.

This introductory analysis of Hurricane Ida shows how the method developed for transmission resilience against extreme weather can be adapted to large generator outages, while recognizing the different characteristics of generation outages. This case study can serve as a foundation to develop metrics that would track grid resilience. To fairly assess whether resilience is improving or declining, these metrics must also incorporate weather data that would categorize extreme events by weather type, severity etc.

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