Power system resilience against extreme temperatures

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***Abstract*—Weather events associated with extreme temperatures cause significant disruptions on North American power system. This paper studies the statistical relationships between temperature covariates and forced transmission and generation outages using detailed weather and outage data in a Midwest location. We derive a functional relationship between transmission/generation unavailability and temperature as well as quantify resilience of the grid against severe temperature events. Overhead and underground circuits are analyzed separately, and conventional generation units are studied by major fuel types for this location. Finally, we investigate a correlation between forced transmission and generation outages and confirm that their largest clusters were caused by extreme weather.**

***Keywords*—extreme temperatures, Generating Availability Data System (GADS), resilience against extreme weather, Transmission Availability Data System (TADS).**

I. Introduction

Extreme weather and natural disasters have been a top risk to North American Bulk Power System (BPS) reliability and resilience, and many of the weather events that impacted both transmission and generation systems were associated with extremely high or low temperatures [1-4]. NERC recently adopted two new reliability standards to enhance grid reliability and resilience under extreme weather conditions: TPL-008-1 establishes transmission system planning performance requirements to ensure that the BPS will operate reliably during extreme weather events, and EOP-012-3 requires that each Generator Owner develop and implement plan(s) to mitigate the reliability impacts of extreme cold weather on its generators [5].

There exists extensive literature that analyzes and/or models relationship between temperature and operation of different parts of power system, e.g. [6] quantifies resilience of thermal power generation to extreme temperatures, [7] proposes resilience assessment of integrated energy system against cold wave disasters, [8] focuses on heat waves impact to resilience of different components of power system. In general, the studies use available outage and weather data with granularity that best serves the purposes of each study. Thus, in [9] an analysis of winter storms Uri and Landon is based on daily customer outage and weather data aggregated by county in Texas. To analyze temperature dependence for forced outages, [10] uses hourly data from the nearest weather station to a given GADS generator, and [11] applies hourly weather data to TADS transmission lines within 50-mile radius from a given weather station in Florida. The latter approach is also used in the current study for both transmission lines and conventional generation units in vicinity of weather station at a major airport in Midwest.

In comparison with the above-mentioned papers that often use simulated/modeled or limited outage data (for a specific component or from a given utility), the unique NERC authority gives the authors opportunity to work with both transmission and generation inventory and outage data reported in TADS and GADS as a part of mandatory data collection from the North American utilities. Even though we study an individual location, the analyzed data represent all NERC-registered transmission and generation owners in this area. The forced transmission and generation outage statistics allow us to quantify impact of temperature covariates and draw conclusions about combined generation and transmission system resilience to extreme hot and extreme cold conditions. Namely, under extreme conditions, the forced outage frequency indicates how well the power system is prepared for cold snap and heat wave events while transmission and generation unavailability gauges the extreme weather impact and enables tracking of system recovery from these events.

II. Data and Method

A. *Weather Data and Weather Time Series*

Weather data originates from a selected Midwest weather station located at a major airport in Velocity Suite for the years 2015-2023. Using a major airport provides hourly temperature data, as opposed to daily, allowing for better alignment with outage data. In addition to hourly weather covariates from the weather station, daily data are aggregated from hourly data in the form of rolling averages or gathered directly from daily data from the weather station. Additionally, tornado data were added for tornadoes with paths within 50 miles of the weather station. No hurricane with a path within 75 miles of the weather station was found for an inclusion in the study. Severe weather events, defined as cold snaps or heat waves, were pulled from the climate zone where the station was located. A heat wave/cold snap is a period of abnormally hot/cold weather generally lasting more than two days.

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B. NERC TADS and Transmission Time Series

Outage data for transmission elements of 100 kV or above are reported by utilities to NERC's TADS. In this study we included forced (i.e., automatic and operational) outages [12] for the years 2015-2023. TADS currently lacks geolocation information, so matches based on similarity between bus names in TADS and substations in Velocity Suite were made to link weather and outage data. Of these matches, Velocity Suite was used to select transmission elements that were at least partially within 50 miles of the weather station. Outage duration was then broken down into an hourly time series to merge with the hourly weather data. If a line had multiple outages within an hour, the starts/ends within the hour are counted, and the duration is summed. The summary columns were then created for metrics such as ac circuit unavailability or the forced outage frequency (the number of outages starts) per line for both cable and overhead circuits.

C. NERC GADS and Generation Time Series

Outage data for conventional generating units by fuel types such as gas, coal, nuclear, etc.) of 20MW or more are reported by utilities to NERC's GADS. In this study we included forced outages and derates (start-up failures, unplanned immediate outages and immediate derates as defined in [13]) for the years 2015-2023. Solar data has only been collected recently, and not enough data are currently available, while wind data for the analysis period are reported in terms of performance only, and do not include outages. Generation plants in Velocity Suite were matched to GADS by EIA codes and then the units associated with those within 50 miles of the weather station were included in the data. GADS outages were transformed into hourly information to combine with the hourly weather data. Generators have the possibility to derate in addition to having an outage, so derates were also included. Where possible, true performance data were used instead of using nameplate rating to give a more accurate accounting of impact of outages or derates. Summary statistics were calculated both by fuel types such as 100 (Fossil-Steam), 200 (Nuclear) and 300 (Gas), and for all units combined (this set includes several minor fuel types not analyzed here separately).

D. Temperature Covariates and Ranking

For the numerical temperature covariates, Pearson's and Spearman's correlations were tested to detect linear and monotonic relationships, respectively, between covariates and the forced outage frequency of ac circuits or generation units.

To analyze categorical covariates, one-way ANOVA with Duncan's grouping was applied to test for significant differences in forced outage frequency between distinct levels of the covariate (e.g., cold snap and heat wave). Finally, to compare and rank all covariates (numerical and categorical) with respect to the explanatory power (Pearson's coefficient R^2) for the forced outage frequency, a one-way ANOVA was repeated for all numerical covariates as well, testing for significant differences in outage frequency between twenty bins defined as follows: bin 1 is the set of hourly observations between a minimum value of the covariate and its 5th percentile, bin 2 is the set of hourly observations between 5th and 10th percentile etc. All statistical tests use significance level 0.05. We also used the bins to create a scatter plot that illustrates the functional relationship between a weather covariate and expected outage frequency. The analyses described above were then repeated for the unavailability (of ac circuits or generation capacity).

III. Temperature Impact to Transmission System

A. Frequency of forced transmission outages

Underground cables comprise 20% of the ac circuits included in the study. They are on average significantly shorter than the overhead lines (3.2 miles and 12.3 miles, respectively). For the years 2015-2023, the average hourly forced outage frequency was 6.65×10^{-6} outages per cable (or about 0.06 forced outages a year) and 1.95×10^{-5} outages per overhead line (about 0.17 forced outages a year). The statistical procedures described in II(D) showed that there is no statistically significant relationship between any numerical or categorical temperature covariate and the cable outage frequency. This is consistent with the fact that the underground ac circuits had no weather-related outages reported over the 9 years and with the North American statistics in [14].

For the overhead ac circuits, ANOVA test found statistically significant differences in outage frequency between levels of the numerical temperature covariates, with the hourly dew point temperature having the strongest relationship with the overhead ac circuits outage frequency (R^2=0.04%).

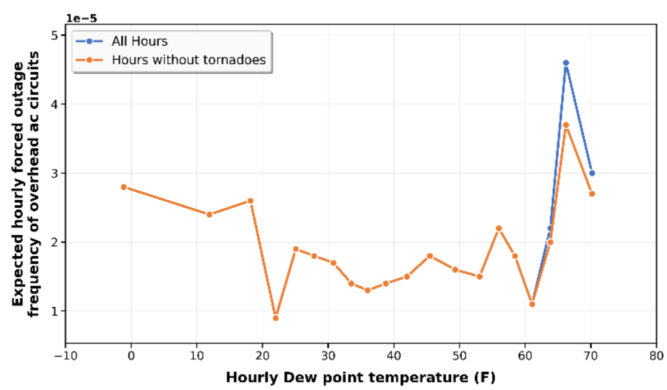

Figure 1. Hourly Dew point temperature and Expected hourly forced outage frequency of overhead ac circuits

Fig.1 illustrates this functional relationship (blue line). The highest outage frequency is observed for the dew point temperature between 65°F and 67°F with the mean of 66.2°F. The hours with this temperature range contain several tornadoes that caused multiple automatic outages of the ac circuits. To filter out the tornado impact, 70 hours with reported tornadoes (for all temperatures) were removed from the dataset and the analysis was repeated. The resulting orange line is also shown in Fig. 1. Duncan grouping test for ANOVA on the reduced data informs that for dew point temperatures below 21°F and at least 65°F the expected outage frequency is statistically significantly higher than for other dew temperature levels. The graph shape in Fig 1 also explains why no statistically significant linear or monotonous relationship between numerical temperature covariates and the overhead outage frequency was detected.

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Additional tests showed statistically similar adverse impact of cold snaps and heat waves as well as no significant difference in outage frequency for temperatures above and below freezing. We conclude that the highest and lowest temperatures have significant and statistically similar impacts to starts of forced outages on overhead lines.

B. AC circuit unavailability percentage due to forced outages

For the 9 years analyzed, the average underground cable unavailability was 0.024%, and the average overhead ac circuit unavailability due to forced outages was 0.073%.

For the underground ac circuits, ANOVA tests detected statistically significantly greater unavailability percentage for: a) hours with heat wave events than for hours with no events or cold snaps, and b) hours with temperature (Dry bulb) above freezing compared with hours with below freezing temperature. The ANOVA tests also found statistically significant differences in cable unavailability between levels of numerical covariates, with the average temperature for a day having the strongest relationship with unavailability (R^2=1.5%).

For the overhead ac circuits, ANOVA tests detected statistically significantly greater overhead circuit unavailability a) for hours with cold snaps events than for hours with heat wave events or no severe events, and b) for hours with temperature (Dry bulb) below freezing compared with hours with above freezing temperature. The ANOVA tests also found statistically significant differences in unavailability between levels of numerical covariates, with the average temperature for a day having the strongest relationship with unavailability (R^2=2.0%).

Fig.2 shows a blue graph connecting the average daily temperature and the expected cable and overhead line unavailability. Duncan grouping test for ANOVA informs that underground cables have statistically significantly higher expected unavailability during average daily temperature at least 76°F. These findings are consistent with the fact that the greatest percentage of cable unavailability (2.4%) was observed over 13 consecutive hours during a heat wave event.

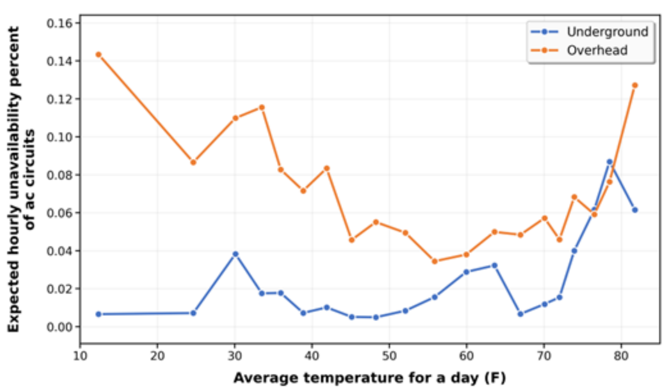

Figure 2. Average temperature for a day and average ac circuit percentage of unavailability due to forced outages

An orange curve in Fig.2 illustrates a functional relationship between the average daily temperature and the expected overhead line unavailability. The Duncan grouping test for ANOVA shows that bin 1 with average daily temperatures below 20°F has statistically significantly higher unavailability than other levels. Next, bin 20 with temperatures at least 80°F has statistically significantly higher unavailability than all other bins except bin 1. Therefore, we conclude:

- While temperature does not impact cable outage starts, higher cable unavailability is consistently observed for the highest levels of temperature values.
- Both extreme low and extreme high temperature impact overhead circuits outage initiation and unavailability, with statistically higher unavailability for extreme low than for extreme high temperatures.

IV. TEMPERATURE IMPACT TO GENERATION SYSTEM

A. Frequency of forced outages and derates

A conventional generation fleet in this location is typical for the Midwest composition of unit types. Gas turbines/Jet engines (simple cycle operation) are the largest group in both the number of units and the total generation capacity. The second largest group in 2015 was Fossil-steam (coal) units with majority of units retired by the end of 2023. The third largest group by the total capacity is nuclear units. These three generation types together with the total conventional generation fleet we will consider in more detail; the smaller groups in the number of units and capacity are combined cycle block and multi-boiler/multiturbine units.

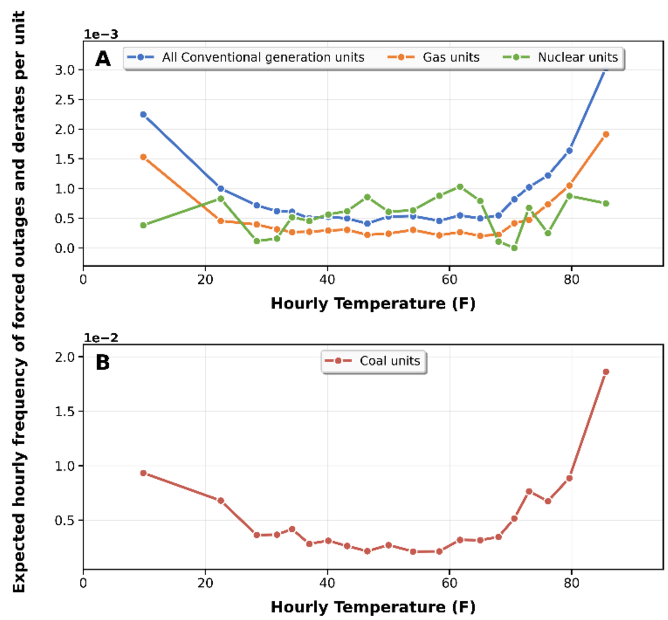

Figure 3. Hourly dry bulb temperature and Expected hourly frequency of forced outages for (A) conventional generators and (B) coal units

The mean hourly forced outage frequency for conventional units was 9.1 × 10^{-4} outages/derates per unit (i.e., 8.0 outages and derates per year). The gas and nuclear units had statistically similar average outage frequencies of 5.1 × 10^{-4} and 5.6 × 10^{-4} outages/derates per unit, respectively, and the coal units had the highest average frequency of 5.2 × 10^{-3} outages/derates per unit.

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For the outage frequency of gas and coal units as well as all conventional generation units, all numerical temperature covariates are found to be statistically significant covariates. For each of these generator groups, the hourly (dry bulb) temperature is the most impactful numerical temperature covariate (R^2=1.0%, 1.4%, and 2.2%, respectively). In contrast, no numerical temperature covariate is significant for the hourly outage frequency of nuclear units. Fig. 3 (A) illustrates a functional relationship between the hourly temperature and the expected forced outage frequency for all conventional, gas and nuclear generation units included in this study. The same relationship is illustrated in Fig. 3(B) for coal units separately because of their significantly higher outage frequency.

To summarize results of ANOVA with Duncan grouping test for the temperature levels shown in Figs. 3 (A)-(B) and for categorical covariates, we list conditions with statistically significantly higher expected number of forced outages and derates.

- For all conventional generation units/gas units: the hourly temperature above 82°F followed by the hourly temperatures below 19°F; cold snaps; tornadoes.
- For coal units: the hourly temperature above 82°F; heat waves; tornadoes.
- For nuclear units: no statistically significant relations between forced outages and temperature.

B. Generation capacity unavailability due to forced outages and derates

The mean hourly percentage of unavailable capacity for conventional units was 3.5%; for gas, nuclear and coal units it was 2.7%, 1.2%, and 9.1%, respectively. Noteworthy the maximum hourly unavailable capacity attained 48.1% for all generation units, 78.2% for gas units, 94.0% for nuclear units, and 100% for coal units.

For unavailable capacity percentage of each generation group, all numerical temperature covariates are found to be statistically significant. For all generators combined, for gas and coal units, the minimum temperature for a day is the most significant numerical temperature covariate (R^2=7.4%, 5.1%, and 4.8%, respectively). For nuclear units, the most significant temperature covariate is average temperature for a day (R^2=1.6%).

Fig. 4 (A) illustrates a functional relationship between the minimum temperature for a day and the expected percentage of unavailable capacity due to forced outages and derates for all conventional generation units combined, gas and nuclear units. The same relationship is illustrated in Fig. 4(B) for coal units separately because of their significantly higher unavailable capacity.

To summarize results of ANOVA with Duncan grouping test for the temperature levels shown in Figs. 4 (A)-(B) and for categorical covariates, we list below conditions with statistically significantly higher expected generation capacity unavailability.

- For all conventional generation units/gas units: the minimum daily temperature below 9°F; cold snaps.
- For coal units: minimum daily temperatures above 69.8°F; heat waves; tornadoes.
- For nuclear units: minimum daily temperatures between 37°F and 45°F.

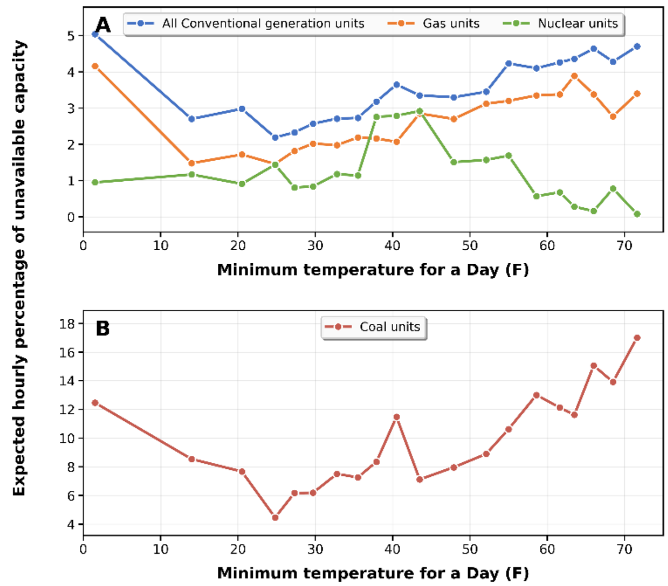

Figure 4. Minimum temperature for a day and Expected hourly percentage of unavailable capacity for (A) conventional generators and (B) coal units

The results summarized in IV indicate that both extreme low and extreme high temperatures test reliability and resilience of the local conventional generation system as well as generators of each type except nuclear units by causing a statistically significant increase in the number of outages and slowing down the system restoration.

V. Correlation between Transmission and Generation Outages and Extreme Weather

Next, we investigate the critical issue of the relationship between forced transmission and generation outages. The only two statistically significant correlations were found between forced underground circuit outages and forced outages of the generation units (gas, nuclear, coal, and combined conventional generators: between overhead line outages and coal unit outages/conventional generation outages combined. ANOVA test also found significant differences in the number coal unit outages at different number of overhead circuit outages (ordered association). The same held true for the combined outages of conventional generation units.

For this location, no mutual cause-effect relationship between forced transmission and generation outages is found based on TADS and GADS outage causes; instead, the largest clusters of simultaneous outages happened during natural disasters and were caused by them. Fig. 5 shows the results of ANOVA's Duncan grouping tests for the total number of forced transmission and generation (T&G) outages for a) the hours with and without tornadoes (left), and b) hours with and without severe weather events (right). There are statistically significantly more outages during tornadoes (on average 6 times more) than during hours without tornadoes. This impact

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we detected for transmission and generation outages separately and described it in IV.

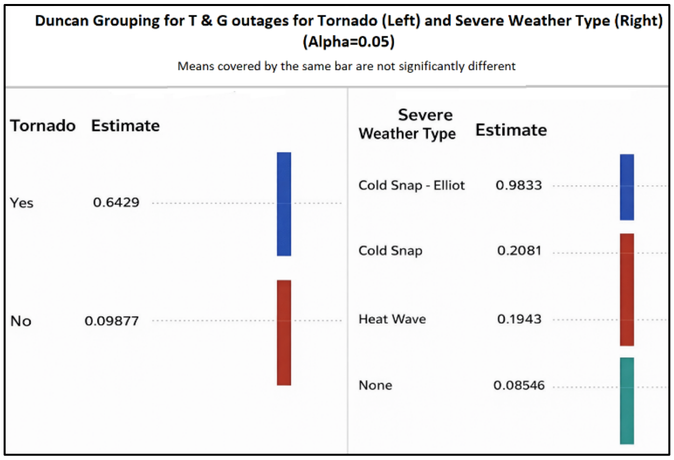

Figure 5. Duncan grouping tests for the total transmission and conventional generation forced outages and derates for tornadoes and severe weather

In the right-hand chart in Fig. 5 the hours during Winter storm Elliot were separated from all other cold snap events to highlight an impact of this most significant extreme weather event that hit the area over the 9 years. During Elliot, the hourly number of transmission and generation outages was statistically significantly greater (on average almost ten times) than during other cold snaps. The cold snaps (without Elliot) and heat waves caused statistically similar increases in the number of outages compared with moderate temperature hours. These fundings are aligned with the study findings for both transmission and generation systems.

VI. Conclusions and Discussion

In this location, temperature does not impact underground cable outage frequency; however, higher cable unavailability is consistently observed for the highest levels of temperature values. For overhead transmission lines, both extreme low and extreme high temperature impact overhead circuits outage initiation and unavailability, with statistically higher unavailability for extreme low than for extreme high temperatures. System operators should prepare for extreme temperature impacts on the transmission system, taking extra caution for overhead transmission during periods of extreme cold weather and underground cables during periods of extreme hot weather. This further reinforces the need for NERC reliability standards TPL-008-1

The results summarized in section IV indicate that both extreme low and extreme high temperatures test reliability and resilience of the local conventional generation system for all unit types (except nuclear units) by causing a statistically significant increase in the number of outages and system unavailability. This further validates the observations in NERC reports [1-4] and reinforces the need for generator owners and operators to prepare units for periods of extreme temperatures as required by NERC Reliability standard EOP-012-3.

Section V investigates the relationship between transmission and generation outages. The analysis determines that the largest clusters of simultaneous transmission and generation outages are caused by extreme weather events such as tornadoes, cold snaps, and heat waves.

The functional relationships for significant temperature covariates illustrated in Figs.1-4 provide the industry with essential information about reliability and resilience of a localized transmission and generation system under full range of historical temperatures. For example, Fig.3 (A-B) shows a wide hourly temperature range (between ~10°F and ~65°F) with stable and reliable performance of gas, coal, and overall conventional units. There are no statistically significant differences in expected forced outage frequency across this range. This is a "reliability zone." Temperatures outside this range, however, are associated with statistically significant increases in the number of outages. These are zones where the generation system is stressed and its resilience is tested. They indicate areas for improvement and can help prioritize investment strategies for system hardening, as well as extreme event response and long-term planning. Unavailability profiles for diverse types of generation demonstrate the difference in generation performance during cold snaps and heat waves and inform utilities in building a more resilient and balanced generation fleet, optimizing generators retirement schedule to keep the system reliable and resilient.

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