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Correlation Analysis of Temperature and Frequency Disturbance Events Focusing on Peak Hours and Weather Season in El Salvador: A Case Study from 2022 to 2024

***Abstract*—This study seeks to determine if there is a correlation between higth temperatures and the number of frequency disturbance events in El Salvador's electrical grid. For this analysis, the data are delimited to adjust them to the warmest months over three years (2022-2024) and the hours of the day where the highest temperatures occur. From here, nine cases corresponding to February, March, and April of each year are proposed. Criteria are also described to determine whether there is a correlation in the cases to be studied and, if so, how strong it is. After the analysis was performed, the results show that in three of the nine proposed cases, there is a correlation between temperature and the number of events; moreover, the correlations corresponding to these three cases are classified in the moderate to strong range.**

***Index Terms*—Temperature, Weather, Frequency Disturbance Recorder, Power Grid, FNET/GridEye, El Salvador.**

I. Introduction

The stability of the grid is a fundamental requirement and a constant case study in El Salvador to guarantee the quality of the power supply. Part of the stability of the grid depends on maintaining the frequency close to the nominal value of 60 Hz. This stability can be compromised due to several situations, such as unexpected load losses, transmission system failures, or external environmental factors. Some of these external factors could be related to high temperatures during the warmer seasons of the year. This paper seeks to determine whether there is a correlation between high temperatures and the number of frequency disturbance events in El Salvador's power grid. Since the temperature varies seasonally throughout the year, we seek to determine which months of the year, on average, have the highest temperatures to focus on them. To further delimit the data to be studied, we seek to determine at what times of the day the highest temperatures occur. When determining if there are cases that show a correlation between temperature and the number of events, we are also interested in determining how strong this correlation is, for which we establish a threshold, beyond which we will only take as valid cases those that show moderate to strong correlations. When analyzing the results, we are interested in determining whether there is at least one case in which a significant correlation is established.

II. Monitoring the Frequency of the Power Grid and Assessing the Impact of High Temperatures

A. The FNET/GridEye Project

FNET/GridEye is a low-cost GPS-synchronized wide-area power system frequency measurement network. Highly accurate frequency disturbance records (FDR) developed at Virginia Tech are used to measure the frequency, phase angle, and voltage of the power signal found in ordinary 120 V electrical outlets. Measurement data are continuously transmitted over the Internet to the FNET/GridEye server housed at the University of Tennessee. The University of El Salvador is part of this project, and a FDR-1750 unit is in operation at the School of Electrical Engineering and continues to record data from the power grid [1].

B. FDR (Frequency Disturbance Recorder) meter technology

The Frequency Disturbance Recorder (FDR) is a high-precision device designed to estimate and record the frequency of an electrical power system. It forms a fundamental part of the Frequency Monitoring power grid (FNET) [2], which seeks to gain an in-depth understanding of the dynamics of the power system. Its main purpose is to continuously measure and record the frequency of the power system. Unlike Phasor Measurement Units (PMUs), which are expensive to install, FDRs are designed to be inexpensive, portable, and easy to deploy. This allows for much wider and faster coverage of the power grid to obtain frequency measurements [3] [4].

C. Cooperation Agreement between the University of El Salvador and the Ministry of Environment and Natural Resources

The agreement, established on December 17, 1999, was created to establish mechanisms for participation and technical coordination for developing socioeducational activities in environmental matters, as well as programs, projects, and actions to recover natural resources and the environment. One of its main objectives is to collaborate on technical studies on environmental regulations, monitor pollutant gas emissions, and support research on the environmental impact of activities such as mining and the recovery of environments deteriorated by pollutants.

D. Impact of high temperatures on power grid frequency.

High temperatures impact the frequency of the electric grid by unbalancing generation and demand. This occurs because extreme heat triggers the use of air conditioning, which significantly increases the load. It also increases resistance in transmission lines, affecting efficiency, overloading, and damaging critical equipment such as transformers, putting the supply at risk [5] [6]. Because the relationship between generation and load is closely related to frequency, these effects are reflected in variations in nominal frequency. Studying this phenomenon is crucial for maintaining the stability and reliability of the power grid [7] [8].

III. Data collection and preprocessing

A. Frequency data acquisition

The recorded data for El Salvador's power grid frequency were obtained from two sources. The first, using the FDR-1628 unit, provided by the University of Tennessee at Knoxville as part of the FNET/GridEye [4] project and in collaboration with the Autonomous University of Mexico (UNAM). This unit recorded data for the period from September 2022 to May 2023. The second source of data was provided by the Transaction Unit (UT) and its SCADA unit, hereafter referred to as SCADA-UT. The frequency data provided by SCADA-UT range from January 2022 to December 2024. The most noticeable difference between the two types of data is the sampling period, which is 4 seconds in the case of the data provided by the UT and 100 milliseconds in the case of the data recorded with the FDR unit.

B. Temperature data acquisition

The temperature data used were extracted from the climate data package provided by the Cooperation Agreement between the University of El Salvador (UES) and the Ministry of Environment and Natural Resources of El Salvador (MARN). The data provided by MARN are average records of 24 hours of different climatic variables over several years. For the purposes of our analysis, we focus on the maximum temperature (hereafter referred to as temperature only). Thus, the data extracted from the source files correspond to the maximum temperature. The period of the data to be analyzed is based, among other parameters, on the period of the SCADA-UT frequency data (since these have a wider time interval than those obtained by the FDR-1628 unit) and runs from January 2022 to December 2024.

C. Data preprocessing

When comparing the frequency data recorded by the SCADA-UT and FDR-1628 units, a key difference is their sampling periods: 100 milliseconds for FDR-1628 and 4 seconds for SCADA-UT [9]. Figure 1 visually compares these two data sets. Initially, the FDR-1628 frequency data were in UTC and were converted to UTC-6 to match the El Salvador time zone. As can be seen in Figure 1, there is a noticeable delay of 4 seconds in the SCADA-UT data compared to the FDR-1628 data. However, this delay is considered insignificant for the intended analysis.

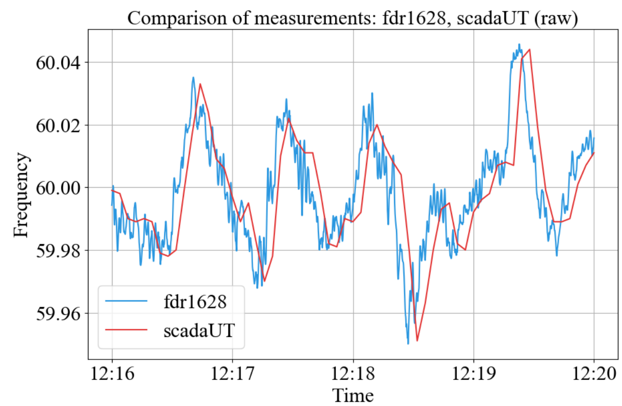

Fig. 1: Comparison between frequency data collected by FDR-1628 and SCADA-UT on May 18, 2022: FDR unit with 100 ms period vs. SCADA-UT unit with 4 s per period.

After validating, organizing, and cleaning both sets of frequency data, they undergo processing to generate a list of frequency disturbance events and their classifications. The classification criteria for these events are established based on existing studies, standards, and regulations [10].

A frequency disturbance event is defined by frequency variations of ± 0.05 Hz, a threshold recommended by the Regional Commission for Electrical Interconnection (CRIE) [11] to be met for 90% of the time. The specific classifications of these events are detailed in [1].

- Slight: The maximum frequency deviation ranges from 0.05 to 0.12 Hz.
- Moderate: The maximum deviation is in the range of 0.12 to 0.60 Hz.
- Critical: The maximum deviation is greater than or equal to 0.60 Hz.

Ultimately, the processed data are consolidated into a single, cleaned, and sorted CSV file. Figure 2 exemplifies a frequency disturbance, showing El Salvador's power grid frequency behavior on May 18, 2022, around 18:46 UTC-6. This event, reported by the Regional Operating Entity (EOR) [12] [13], involved tripped transmission lines that caused El Salvador's grid to disconnect from the Regional Electric System [14].

After all data types are adjusted and cleaned, two primary CSV files remain: a disturbance event quantity file and a maximum temperature data file.

IV. Formulating hypotheses and defining the methods

The methodology for validation for moderate to strong correlations between temperature and the number of frequency disturbance events is represented in Algorithm 1.

A. Delimitation of the cases to be analyzed

This section outlines the criteria for establishing the time interval and analyzing the cases. The SCADA-UT frequency

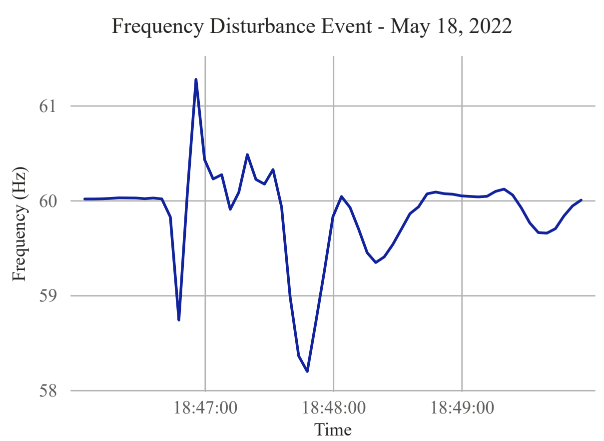

Fig. 2: Frequency disturbance event in El Salvador's power grid on May 18, 2022: Failure caused by tripping on transmission lines.

data set, covering January 2022 to December 2024, is the largest available and thus defines the initial and end study period.

To determine the warmest period for temperature analysis, given that El Salvador's hottest months (over 32°C) typically occur from early to mid-year [15], the three warmest months on average were selected throughout the 2022-2024 time frame. Figure 3 illustrates the six months with the highest temperatures during this period.

The analysis revealed that February, March, and April are the three months with the highest temperatures from 2022 to 2024. These months will be referred to as "cases." With three months per year over three years, there are nine cases, sequenced from Case 1 (February 2022) onward.

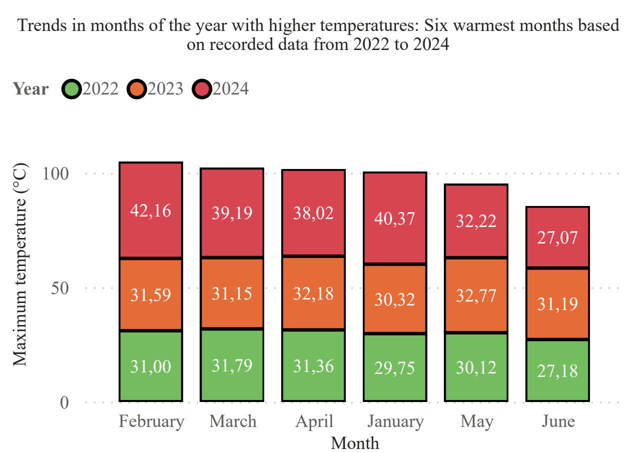

Fig. 3: Six Warmest Months Based on Temperature Data (2022–2024).

It is crucial to exclude periods of significantly lower temperatures within a day from the analysis to avoid erroneous data. For the final criterion, a range of average daily hours with the highest temperatures will be defined. As MARN's climate data are averaged over 24 hours, an external database was used [16]. Figure 4 exemplifies this using Monday, 21 March 2022, in San Salvador, showing that temperatures typically rise around 9:00 AM and fall back to similar levels at 6:00 PM. This behavior was observed to be nearly consistent across various scenarios during the study months.

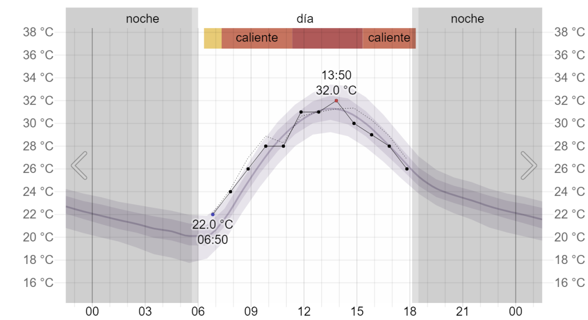

Fig. 4: Temperature on a warm day. March 21, 2022 in San Salvador [16]

For the latter criterion, the time interval to be studied is set between 12:00 and 16:00 hours of the day (four hours). The table I shows a summary of the specific cases to be analyzed.

TABLE I: Analyzed Cases According to Year, Month, and Time Range

Year	Month	Time Range	Case
2022	February	12:00 – 15:00	1
	March	12:00 – 15:00	2
	April	12:00 – 15:00	3
2023	February	12:00 – 15:00	4
	March	12:00 – 15:00	5
	April	12:00 – 15:00	6
2024	February	12:00 – 15:00	7
	March	12:00 – 15:00	8
	April	12:00 – 15:00	9

B. Hypothesis Statement

Before the analysis, the hypotheses are defined [17] [18] [19].

- H_0 (Null hypothesis): There is no significant correlation between the number of frequency disturbance events and higth temperatures in the period from 2022 to 2024, either in the month of February, March, or April.
$$H_0 : r = 0 \tag{1}$$
- H_A (Alternative hypothesis): There is a significant correlation between the number of frequency disturbance events and higth temperatures in the period 2022 through 2024, whether in the month of February, March, or April.
$$H_A : r \neq 0 \tag{2}$$

If in at least one of the cases a statistically verifiable correlation is found, it is considered sufficient to discard the hypothesis H_0 and proceed to test the hypothesis H_A. [19]. The significance level parameter $alpha$ to be used in the following analyses is set at 0.05, and the p-value is calculated to validate the following. [17] [20] [21]:

- If $p < alpha$ and the correlation is moderate or strong, the correlation is considered statistically significant; therefore, we reject the hypothesis H_0.
- If $p \geq \alpha$ there are considered to be insufficient data and the correlation is statistically insignificant; therefore, hypothesis H_0 is not rejected.

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Due to the above, only the cases where the hypothesis H_0 is rejected will be analyzed. The parameters to define whether the correlation is strong or moderate are explained later.

C. Statistical methods

The Pearson coefficient is calculated using the following equation [22] [23].

$$r = \frac{\mathrm{Cov}(x, y)}{\sigma_x \cdot \sigma_y}, \quad -1 \leq r \leq 1 \tag{3}$$

Algorithm 1: Validation algorithm for moderate to strong correlations between temperature and number of frequency disturbance events.

Result: Correlation validation and classification (None/Weak/Moderate/Strong)

1. Set significance level $\alpha \leftarrow 0.05$;
2. Take the case to be analyzed;
3. Calculate sample size of the case $n \leftarrow$ Number of events;
4. Compute degrees of freedom $DF \leftarrow n - 2$;
5. Calculate covariance: $\mathrm{Cov} \leftarrow \frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})$;
6. Compute Pearson coefficient: $r = \frac{\mathrm{Cov}(x,y)}{\sigma_x \cdot \sigma_y}$;

if $r \notin [-1, 1]$ **then**
  return "Invalid Pearson coefficient";

7. Calculate t-statistic: $t \leftarrow r\sqrt{\frac{DF}{1-r^2}}$;
8. Compute p-value using t-statistic value with DF degrees of freedom;

if $p > \alpha$ **then**
  return "No significant correlation";
else
  if $0.10 \leq |r| < 0.30$ **then**
    return "Weak correlation (discarded)";
  else
    if $0.30 \leq |r| < 0.50$ **then**
      return "Moderate correlation";
    else
      return "Strong correlation";

Where:

- $\mathrm{Cov}(x,y)$ is the covariance between the independent variable and the dependent variable.
- σ_x is the standard deviation of the independent variable x, in our case the maximum temperature.
- σ_y is the standard deviation of the dependent variable y, in our case the frequency disturbance events.

The independent variable corresponds to the maximum temperature, and the dependent variable corresponds to the number of events. Although the order of these variables does not matter in the calculations, it is prudent to clarify it. To calculate the covariance value, the following equation is used [23] [24].

$$\mathrm{Cov}(x, y) = \frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y}) \tag{4}$$

Where:

- n is the number of observations (the sample) for each case.
- x_i and y_i are the individual values of the variables x and y, respectively.
- $\bar{x}$ and $\bar{y}$ are the arithmetic means of variables x and y, respectively.

To determine the sampling distribution, we calculate the degrees of freedom (DF) using the equation (5) [18]. [23].

$$DF = n - 2 \tag{5}$$

Where.

- n is the number of observations (the sample) for each case.

Another parameter required to calculate the p-value is the statistical test value (or t-value), for which the equation 6 is used [20] [23].

$$t = \frac{r\sqrt{n-2}}{\sqrt{1-r^2}} \tag{6}$$

Where.

- r is the Pearson coefficient.
- n is the number of observations (the sample) for each case.

With the value t and the degrees of freedom, we can calculate the p-value [19] [21]. The p-value was calculated using a Python script with input values t and DF for each case. Since ruling out the H_0 hypothesis requires that the value of Pearson's coefficient be significantly different from zero (positive or negative), it is most appropriate to perform a bilateral t-test. [20] [21]. The significance level parameter $alpha$ is set to 0.05 [23] [20].

In case hypothesis H_0 has been ruled out, either by at least one correlation found in the cases under study, we proceed to determine the effect threshold of r. The criterion to be applied in this case is shown in Table II [25]. Only cases showing a moderate or strong correlation will be considered and those with a weak correlation will be discarded.

TABLE II: Classification of the Magnitude of the Correlation Coefficient

Magnitude	Absolute Value of r	Classification
Small	0.10 – 0.29	Weak effect
Medium	0.30 – 0.49	Moderate effect
Large	$\geq$ 0.50	Strong effect

V. Correlation Analysis and Results

Once the correlation criteria, the variables involved and the study period have been defined, the analysis is carried out. It should be clarified that, since the temperature data have a 24-hour period, the number of events will be related by 24-hour periods, so that each of the events within one of these intervals will have the same temperature value. The example in Table III shows the disturbance events of January 7, 2022.

TABLE III: Start Time of Events and Corresponding Maximum Temperature

Start time event (UTC-6)	Max temperature (°C)
7/1/2022 12:26	29.7
7/1/2022 12:35	29.7
7/1/2022 13:33	29.7
7/1/2022 15:00	29.7
7/1/2022 15:13	29.7

To begin the analysis, the covariance between the two variables under study is calculated for each of the months in question. Subsequently, the individual Pearson coefficient is calculated for each month, which is represented by the variable r.

TABLE IV: Pearson Correlation Results for Each Case

Case	Pearson's coefficient (r)	Sample (n)	Statistical test value (t)	Significance level (α)
1	0.42	375	8.94	0.05
2	0.65	310	15.01	0.05
3	0.09	250	1.42	0.05
4	-0.17	362	-3.27	0.05
5	0.04	285	0.67	0.05
6	0.02	250	0.32	0.05
7	0.17	206	2.46	0.05
8	0.14	194	1.96	0.05
9	0.55	139	7.71	0.05

The sample value n is the number of events in each month; From this value, the degrees of freedom (DF) are calculated. The significance level has been adjusted to a value of 0.05. To calculate the p-value, there are multiple ways, such as making use of tables; despite this, the calculation was performed with the help of a Python script. Once the $p - value$ of each case has been obtained, we proceed to classify the cases applying the criteria shown in Table II and subsequently evaluate the hypothesis H_0.

The results show that of the total of nine cases analyzed, three cases show that there is a statistically significant correlation. Of these three cases, one exhibits a moderate correlation, while the remaining two cases show a strong correlation. Figure 5 shows the scatter plot corresponding to case 2

TABLE V: Hypothesis Test Results

Case	DF	p-value*	Hypothesis H_0
1	373	0.00	Rejected
2	308	0.00	Rejected
3	248	0.15	No Rejected
4	360	0.15	Rejected
5	283	2.00	No Rejected
6	248	0.75	No Rejected
7	204	0.01	Rejected
8	192	0.05	No Rejected
9	137	0.00	Rejected

resulting from the correlation analysis, which illustrates the general direction and strength of the correlation between the two variables studied.

TABLE VI: Correlation Results and Hypothesis Outcomes

Case	r	Correlation classification	Hypothesis H_A
1	0.42	Moderate	Accepted
2	0.65	Strong	Accepted
9	0.55	Strong	Accepted

Since there is at least one case that meets the stated restrictions, we reject hypothesis H_0. These results, in turn, support the hypothesis H_A. Table VI shows the final cases that meet the statistical tests to be considered significantly correlated, according to the results of the correlation analysis. In the case of the months that show a significant correlation, this correlation is positive for all cases (there are no cases with a positive correlation and others with a negative correlation), which gives us greater homogeneity in the results.

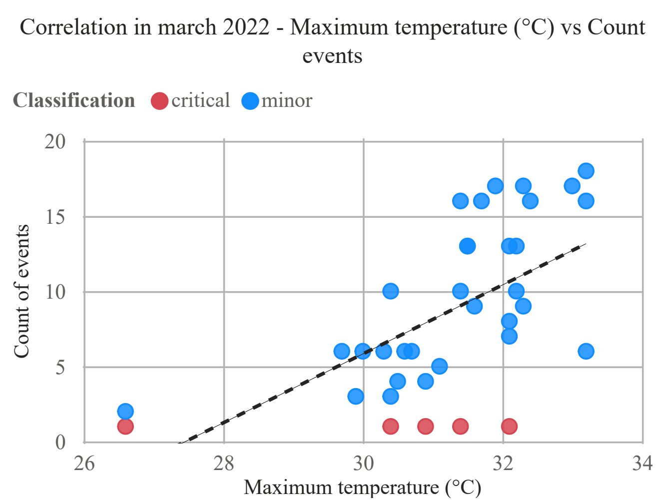

Fig. 5: Dispersion Analysis: Relationship between Number of Cases and Maximum Temperature for Case 2.

Conclusions

The results of the statistical tests show a correlation between maximum temperatures and the number of frequency disturbance events in El Salvador in cases 1, 2, and 9. Each of these cases presents a p-value less than 0.05 (the significance value established to consider a correlation) and an r-value greater than 0.30, which classifies these correlations as moderate to strong. The warmest months of the year were correctly selected for this analysis. Each of the three validated cases with significant correlation (case 1 with r=0.42, case 2 with r=0.65, and case 9 with r=0.55) corresponds to one of those months. However, to obtain a more robust conclusion, it would be ideal to analyze data from additional years. The correlation results with r values greater than 0.5 were obtained considering hours with higher daytime temperatures. This could suggest that during these hours the use of cooling devices such as air conditioners increases energy demand, which in turn could generate variations in the rated frequency. This analysis can be extended if other climatic variables are taken into account, such as wind speed, precipitation, or relative humidity. To obtain better results, it is recommended that the study be extended with more years of data on both the temperature and frequency of the power grid.

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