Statistical Signal Processing for Monitoring the Health of Power Systems

Aarushi Ranjan , IIT Delhi, Aryan Ritwajeet Jha, *MS EE (Power Systems)*

***Abstract*— Power systems are highly tangible and dynamic systems, consisting of a network of electrical components that are fundamental to the adequate functioning of the grid. The grid, which is an interconnected network for power delivery, is ideally represented by a time series of various electrical parameters subject to continuous fluctuations due to the variable nature of power generation. Ensuring stability in the grid is crucial for avoiding bifurcation events, popularly known as a blackout. In this work, we attempt to analyze auto-correlation and other statistical indicators of line voltage and currents in the grid for the prediction of a trend leading to bifurcation in the power systems. We provide a mathematical framework to show early warnings of instability on actual data from the UK, EU, and Indian grids, ultimately drawing upon the Critical Slowing Down (CSD) theory. Our results demonstrate that these statistical indicators can be good predictors and quantifiers for power grid instability.**

***Index Terms*—Signal Processing, Auto-correlation, Grid instability**

I. Introduction

Climate change and Green House Gas (GHG) emissions are among humanity's biggest concerns. Electrical power generation is one of the major contributors to carbon emission. As per IEA data for 2018, out of world's total electricity production, 23% is produced from Renewable Energy Sources (RES), 31% from low carbon fuels, 39% from Coal, 3% from Oil and 26% from Gas. In India, electricity is majorly generated by coal-based plants. In 2019, the electricity generation distribution was: 71.0% Coal, 10.9% Hydro, 7.3% Wind and Solar and the remaining by other sources. India is also targeting to produce 40% of its electricity from non- fossil fuel-based energy resources. [1] The shares of RES, specifically wind and solar, are varying in their power output. In EU the percentage share is 23.2%, UK-23.7%, India 7.3%. The contribution of RES is increasing every year. However, this increase is also leading to issues on grid reliability due to mis-match between demand and actual generation.

The history of power system blackouts suggests that we need a more robust system to predict the trends leading to the collapse. Technically, power systems are known to function near their suggested stability limits, but it is often observed that they are perturbed due to various reasons such as variation in energy generation methods and random change in system properties, leading to instability in the grid. A stable well-operating system therefore, degrades in performance and leads to what is known as bifurcations. While there are several frameworks existing to study the properties and characteristics of deterministic power systems, recent literature suggests that statistical evidence can be studied to find out a trend leading to an instability. The theory of Critical Slowing Down (CSD) suggests that the change in the system stability from stable to non-stable state undergoes a critical point. The knowledge of this critical, if obtained, can help in improving the system stability, and therefore, the social stability and socio-economic conditions in several countries which are currently suffering due to large scale power disruptions. Additionally, with growing consumption of power across the world, there is a quintessential need to integrate renewable resources such as wind and solar power with our existing power generation sources. But, this task is a huge challenge due to dynamic non-Gaussian variability in the power generation process. With a study of grid statistical parameters such as variance and auto-correlation, it is possible to find early prediction trends and assist operators take corrective measures in time. For example, previous analysis in some regions has suggested that as the grid approaches a bifurcation event, the voltage is increased. Similarly, a growing trend of auto-correlation can help in understanding of the region of the grid where a possibility of perturbation might arise or is approaching. While it is not necessary that every statistical measure will linearly give an idea about an approaching instability, it is necessary to understand those that prove practically helpful. Our attempt in our work is to propose a general finding of an approaching instability trend, based on the analysis of auto-correlation state variables in the presence of Gaussian noise. We present a purely mathematical analysis by deriving the statistical values from various real-time power grids such as that of UK, Europe and India.

The rest of the paper is as follows: Section II describes gives a technical introduction to the problem and our approach, Section III describes the method employed to implement the approach, and Section IV comprises the results and insights from the simulations. Finally Section V concludes the paper.

II. Theory

A. Understanding Grid Frequency and Fluctuations

Power systems leverage alternating current to cater to the requirements of homes, industries etc.the AC current alternates between the positive and negative voltage and the oscillations made between them is termed as the electrical frequency. For example, an AC line which oscillates 50 times in a second in a particular region, can be attributed to possess a frequency of 50 hertz. Most equipment used are designed to operate at this fixed frequency rate or tolerance, which makes it fundamental for power systems to keep the frequency stable and supply power in a steady state. However, in practice power systems demonstrate variability for a variety of reasons, which are widely known as grid fluctuations. For maintaining an equilibrium state in the grid, the fluctuations must be kept in a check through power grid monitoring. One of the most important statistical parameters that have emerged of importance in the operation and control of the grid is frequency. Variations in the demand of power and variability at the generation source and fixed energy trading intervals can cause a major effect on the grid. Even the smallest perturbations can lead to immense risk of equipment and infrastructure damage. For example, on January 10, 2019 the grid frequency of Europe varied by a value of 0.2, leading to a bifurcation event.There are various standard grid operators in every country that monitor the grid for any frequency variations. In countries like America, Japan, Korea, the standard fluctuations in frequency occur at 60 Hertz, while it is 50Hz in the UK and other countries. Usually, when grid operators spot a nearing state of instability in the frequency, they activate additional power plants to restore the state of equilibrium. But, from the existing examples of blackouts and increasing stress on renewable sources, it is challenging to stabilize the grid alone with this measure. The need of the hour is to to understand the impact of the frequency fluctuations on the comprehensive dynamics of the grid in different regions, so that corrective steps can be taken in time. However, studying the real data from power grids can be challenging due to the presence of Gaussian or non-Gaussian noise. While existing studies for Gaussian noise focus on only minute deviations in frequency, non-Gaussian ones mostly revolve around deterministic models, which neglect real-time data. To understand the grid dynamics in a better manner, it is fundamental to study and present a comparison of grid frequencies in different regions. This will provide insight on frequency deviations on different kinds of grids, with varying size, and system environments, etc, which we are attempting to answer through our work.

B. Auto-correlation Function in Extracting Events of Instability

Correlation is a function that helps establish an existing relationship between two or more signals. It is used to understand the underlying similarities or instances of overlap between one signal and the other. In case the goal is to find the similarity of the signal with a shifted version of itself, auto-correlation function is used. While it can be found using mathematical, computational and graphical methods, the preferable method depends on the type of expected results. Auto-correlation gives a degree of similarity in time series type of data along with its underlying periodic components. It is expressed using the formula:

$$\int_{-\infty}^{\infty} x(t) * x(t+\tau)\, dt = c(\tau) \tag{1}$$

where, $x(t)$ is the time series, τ denotes the time lag, and $c(\tau)$ denotes the autocorrelation of $x(t)$ for a time lag value equal to τ. In the frequency domain the shift is marked in frequency, n. When used on real data, auto-correlation can help in identifying a periodic signal camouflaged by noise, or a signal's missed out fundamental frequency. In power systems, the auto-correlation function can be used for signal synchronization and measuring the signal energy distributions spread across frequencies though the power spectral density. Since understanding the early signs for a nearing frequency fluctuation in the grid is our main goal, auto-correlation helps in extracting the important events and grid specific time scales during the process of which the power system uncorelates. The increase or decay of auto-correlation for different grids also highlights the underlying process occurring in the grid. For example, a decay in the auto-correlation function with respect to a time lag, for a specific grid might shed light on the inherent stochastic process such as the Ornstein-Uhlenbeck process. Similarly, peaks in the auto-correlation function along with their duration when compared with the frequency trajectories of the grid can provide explanations that are closely responsible for grid instability.

III. Frequency Fluctuation Observations on Multiple Grids

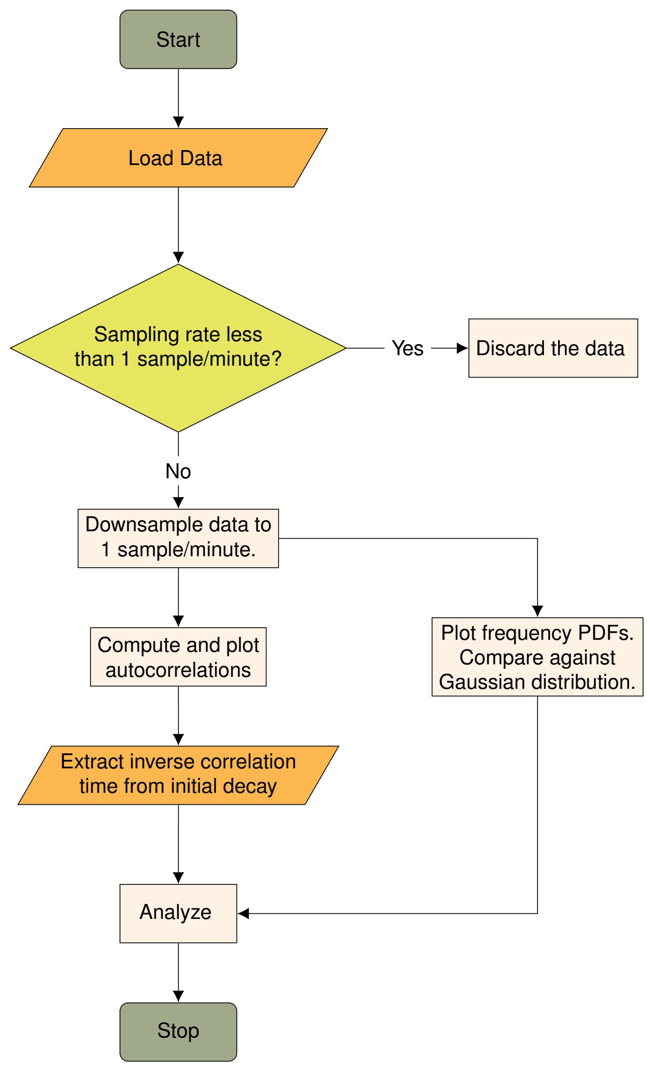

Fig. 1. The above steps, as described in the flowchart were followed for every data set mentioned in this paper. Data cleaning, computations and plotting were done in MATLAB environment.

A. Flow of Processes

The flow of steps undertaken in our work is provided in Fig. (1). The first step was collection of grid frequency data for multiple regions. We were able to collect data of the UK, France, Mallorca (Spain), Japan, Nordic, Continental European, Western Interconnection (US), Texas Interconnection (US) and the Indian grids for our study. In the next step, data pre-processing was done where it was first structured and then checked for reliability, uniformity and sufficiency. Owing to the large size of some datasets (leading to a large computation time), the data were downsampled to 1 sample per minute. Upon these steps, we used the cleaned data to plot and analyze statistical distributions and parameters in order to achieve a better understanding.

IV. Results

A. Frequency PDFs

Auto-correlation of the grid frequencies under nominal conditions demonstrates a perfect coincidence, shedding light on the equilibrium state control of frequency grid operations. However, in case of large deviations, such as the ones occurring on account of frequent trading fluctuations are introduced, whose variance is inversely directly proportional to the size of power grids. Once the distributions are plotted, their respective deviations from standard Gaussian distributions can be recognized by their tails. Authors in [2] have used maximum likelihood estimates to suggest that Levy-stable and q-Gaussian distributions are best fits among all other kinds. Refer to Fig. (2) for the comparison of the Gaussian curve and the actual frequency pdf, for the Continental European grid.

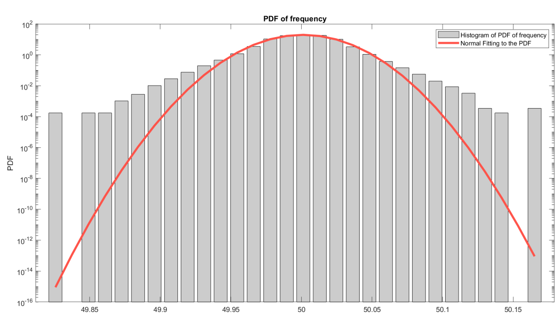

Fig. 2. As can be seen in this pdf plot of the Continental European grid frequency, there is a great mismatch between the actual distribution and the best fit Gaussian/Normal, especially at the tails.

B. Autocorrelations

1) Auto-correlation of French Grid For the year 2019 and Jan 2021: From Fig. (A), we can see the plot for the French Grid frequency auto-correlation with data collection period including the full year 2019 and January 2021. We can observe that there is spike at every 15 minutes block, the peak emerged at every 15 minute block are mainly due to schedule of electricity and trading of energy activity. It starts decaying over period of 15 minutes period.

2) Auto-correlation of UK Grid From Jan 2019 to Mar 2021: From Fig. (A), plot is for the UK Grid auto-correlation with time from Jan 2019 to March 2021. In UK grid also we can observe that there is auto-correlation decay with a jerk at every 15 minutes block, the peak emerged at every 15-minute block are mainly due to schedule of electricity and trading of energy activity.

C. Complete comparison of Five separate synchronous grids

Fig. (3) shows how autocorrelation is in fact, a characteristic of every grid. In fact, as can be seen in the Section (), no two months or years give the same plot even for the same grid. The '15 minute spike' phenomena is most visible for the Continental European and the UK Grids, where trading happens in significant magnitudes every 15 minutes. Other grids such as the Nordic grids show a fairly constant exponential decay.

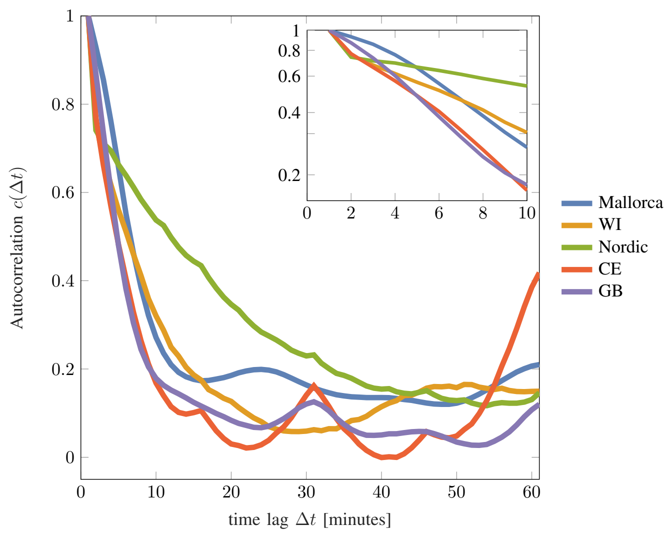

Fig. 3. Autocorrelation decay of different synchronous regions. Initially, all grids show a characteristic exponential decay, but later, some grids, such as the UK and Continental European grids, show regular peaks.

D. Inverse correlation time

Authors in [2] have deduced how the decay of autocorrelation is in fact a representation of the grid damping, i.e. more damping equates to a faster decay. Plotting the first 10 minutes of autocorrelation decay for ever grid in the inset in (3) in semi-log axis, we can see that each grid has its characteristic decay. This decay is mathematically represented as the slope of the semi-log plot line. The inverse-correlation times have been tabulated in Table (I). These values are all in the same magnitude range, which is intuitive, as the synchronous machines in every grid wouldn't be significantly different.

V. Conclusions

The grid frequency probability distribution deviates significantly from the popularly Gaussian model. Authors in [2] have suggested that models with higher degrees of freedom,

TABLE I
INVERSE-CORRELATION VALUES FOR DIFFERENT GRIDS

Grid name	Inverse-correlation value τ^{-1} $[min^{-1}]$
Mallorca	0.0654
Western Interconnection	0.0498
Nordic	0.0235
Continental Europe	0.0829
Great Britain	0.0879

such as q-Gaussians (four degrees of freedom) and Levy-stable functions (three degrees of freedom) are able to model the higher order moments of frequency, such as Skewness (asymmetry of the frequency pdf around nominal value) and Kurtosis (heavier tails in the pdf) better than the Gaussian, with its two degrees of freedom. In this paper, we graphically verify that the grid frequency pdfs indeed deviate from the Gaussian distribution.

Authors in [3] have suggested the use of statistical parameters such as autocorrelation and covariance for predicting Critical Slowing Down (CSD) of the grid. In the paper they have used the parameters on node voltages and line currents. In this paper, however, we have used the parameters on grid frequency, on similar lines as [2]. For European grids, this showed an interesting result: the autocorrelation shows a spike every 15 minutes, but especially every 30 and 60 minutes, due to electricity trading after a new dispatch is agreed upon. Unlike generation, the state variables of the dynamic system can not adapt instantaneously, and thus the system requires time to settle to the new steady state equilibrium. Thus electricity trading is a prominent cause of system instability in a grid, among other factors such as low system inertia, low damping, and increasing penetration of renewables.

Finally the autocorrelations also give us valuable insight into the grid damping ratios. From the initial (first ten minutes) of the autocorrelation, the inverse-correlation time can be computed, which is proportional to the grid damping ratio. This is an important insight for power grid operators whose concern is modifying grid damping in order to damp out any excessive oscillations, thereby protecting from any possible instabilities in the grid.

APPENDIX A
AUTOCORRELATION PLOTS FOR COMPLETE DATASETS

ACKNOWLEDGMENT

The authors would like to thank Dr. Monika Aggarwal, Professor of Electrical Engineering at IIT Delhi for her valuable inputs, both inspirational and analytical into the this work. The figures were made using `Tikz`. The program available on MATLAB File Exchange [4] was used for converting the MATLAB figures into `Tikz`. Data sets used in this paper are freely available on references [5], [6] for the Continental Europe grid, [7], [8] for the Nordic grid, [9], [10], for the Japanese grid, and [11] for all other grids. Tabia Ahmad, PhD EE (Power Systems), IITD mentored one of the authors, Aryan and supplied data for GB, NRLDC, RTE grids and suggested useful literature to research from, including [2], [3], [12], [13].

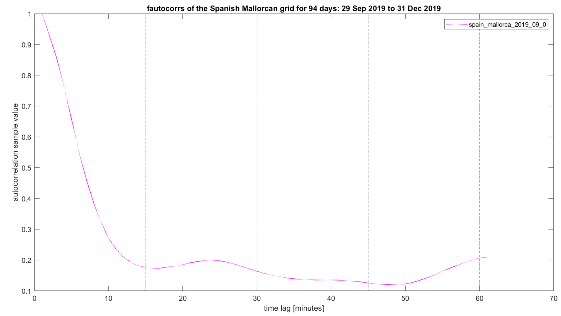

Fig. 4. Autocorrelation values for the Mallorcan Grid for 94 days, from 29 September 2019 to 31 December 2019.

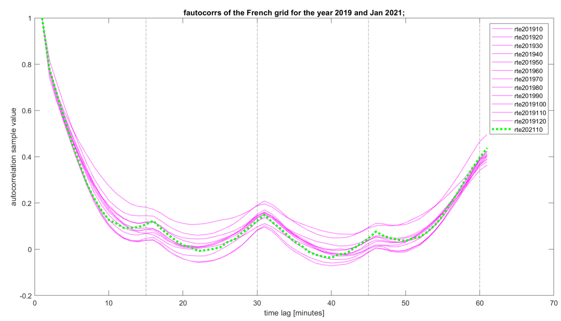

Fig. 5. Autocorrelation values for the French Grid (a part of the Continental Europeans synchronous region) for 12 months of 2019 and 1 month of 2021. Note that the general trend is similar for all months, but different months can be distinguished by offsets caused by external factors.

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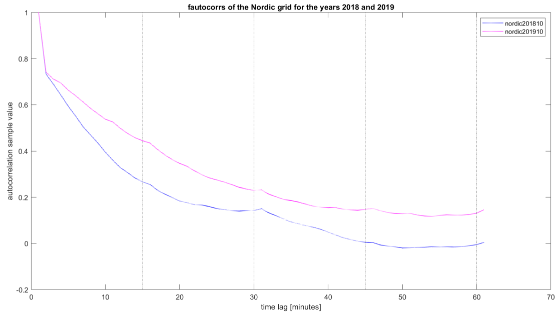

Fig. 6. Autocorrelation values for the Nordic Grid for the years 2019 and 2020. Note that the general trend is similar for both years, but different years can be distinguished by offsets caused by external factors.

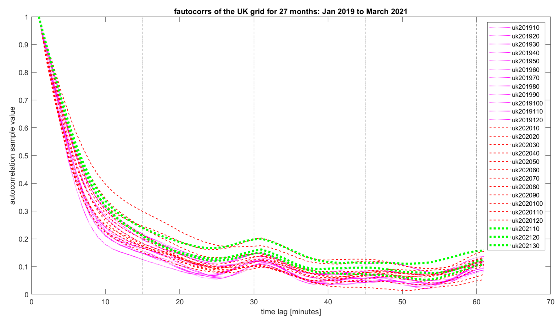

Fig. 7. Autocorrelation values for the UK Grid for 27 months, including the years 2019, 2020 and first three months of 2021. Note that the general trend is similar for all months, but different months can be distinguished by offsets caused by external factors.

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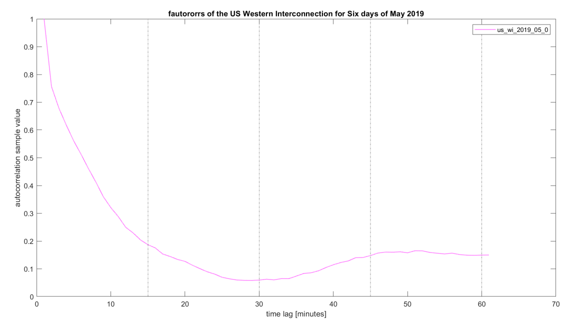

Fig. 8. Autocorrelation values for the US Western Interconnection Grid for 6 days of May 2019.