SYNOPSIS OF

Data Analysis for Predicting Instabilities in Power Systems

A THESIS

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1 Introduction

Unlike transient faults in a power grid which can generally be attributed to a sudden but tangible anomaly (corrective outcomes of protection mechanisms, sudden failure of a generator or transformer, line faults), steady state instabilities can be hard to detect until they accumulate over time to manifest as a major upset to the grid `CITE HERE FOR FRENCH GRID COLLAPSE IN Augu` or make the grid less robust/more susceptible to collapses [1].

2 Literature Review

For offline analysis of the grids, archived frequency time-series data of several real-world grids via downloaded from these websites and/or papers: [2–10]. Schafer et al's paper [1] was referred to for the analysis of these grids. Their paper analyzes how almost all grids show a significant level of deviation from the commonly used assumption that power demand fluctuations follow the Ornstein-Uhlenbeck's Process in which the state variable follows the Gaussian distribution around a nominal mean and a bounded standard deviation. Adeen et al's paper [11] simulated several Stochastic Differential Equations based on the Ornstein-Uhlenbeck's Process with different values of α (autocorrelation coefficient) and analyzed their Fourier Spectrums to conclude that an increased autocorrelation does in fact lead to a greater amplitude of noise and therefore a higher risk of instability in a power system. Most of the recent literature analyzing the effects of the phenomenon of Critical Slowing Down on various dynamical systems, including but not limited to: power grids, ecological population dynamics, predator-prey ecosystems, prediction of epileptic seizures in patients, climate systems, financial markets, prediction of conversion of vegetation area into deserts, and so on credit the review made by Scheffer et al in [12]. The paper lists out systems in which Critical Slowing Down has been observed and provides accessible mathematical explanations behind its working, such as why there is an increase of autocorrelation and variance of state variables of real-world physical processes as the system approaches a 'critical bifurcation'. The mathematical term has also been appropriately called as 'critical transition' or 'tipping point' by the author of [13], whose paper explains various normal forms of bifurcations (Fold, Hopf, Saddle Node, Transcritical, Pitchfork) via the concept of fast-slow stochastic systems. For developing a working understanding of bifurcation theory, university lecture notes by

[14] and books [15, 16] were utilized.

For real-time/online analysis, authors in [17] have utilized PSAT to simulate a steadily stressed power grid and have demonstrated that the computation of autocorrelation of detrended bus voltages and the computation of variance of detrended line currents can function as reliable Early Warning Signs of increasing instability. The detrending is required in order to filter any measurement noise from the data, which may skew the computed statistical parameters towards bogus values. Authors in [18] test various power grids which are/were driven towards bifurcation and demonstrate that an increase of autocorrelation and variance values of bus voltages (tested in simulation) and grid frequency (tested on the time-series data measured at the Bonneville Power Administration minutes before the blackout of 10 August 1996) can reliably predict the impending bifurcation early enough for mitigating actions to be taken by the grid operator.

3 Motivation and Objectives

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4 Theory

Detrended Fluctuation Analysis: A method of analyzing real-world time series for self-affinity, i.e. how correlated a signal's future value is to it's past values. Say, $x(t)$ is a natural process, then in order to detrend it, it can first be passed via a low-pass filter to obtain

$\texttt{LPF}(x(t))$ and the resultant signal be subtracted from the original in order to obtain the detrended version of the signal $\tilde{x}(t)$ or $d(x(t))$:

$$\tilde{x}(t) \;\texttt{or}\; d(x(t)) = x(t) - \texttt{LPF}(x(t)) \tag{1}$$

Autocorrelation function: A statistical measure of the correlation of a state variable with a time-lagged version of itself, autocorrelation $c(t, \tau)$ of any detrended physical/natural signal $\tilde{x}(t)$ or $d(x(t))$, should decrease exponentially as the time-lag τ is increased.

$$c(x(t), \tau) = \int_{-\infty}^{\infty} x(t)x(t+\tau)dt \tag{2}$$

5 Offline Analysis

Various frequency time-series archives for a diverse set of real-world grids was obtained and analyzed by plotting their bulk distribution probability density functions and autocorrelation decay functions. The data for most European and US grids was conveniently curated by the authors of [2, 3]. For the other regions of the world, [4, 5] had the data for the Tokyo grid, [6, 7] for the Nordic grids, [8, 9] for Continental European grid and [10] for the UK Grid. All time series were collected at sampling rates between 0.5 seconds (Tokyo) and 10 seconds (Continental Europe).

The plotted bulk distribution PDFs visually revealed insights including any deadbands [19, 20] mandated in their grid operation, their skewness, thickness of their tails, etc. A quantitative study of their moments like kurtosis and skewness was not conducted as was done in [1].

In the plotted autocorrelation decay curves, all grids showed exponentially decreasing autocorrelations $c(\tau)$ for smaller values of τ. In order to confirm if the decrease was indeed exponential with a grid-specific decay constant also called as the inverse-time correlation or t_corr^{-1}, semi-log graphs $(\log(c(\tau))$ vs τ were also plotted. The decay constants were computed by calculating the slopes of the semi-log graphs and it was found that the grids which were bigger, more robust and showed bulk distribution PDFs which were less-deviating from Gaussian distributions, had greater values of inverse-time correlation t_corr^{-1}. This parameter can also be construed as the relative damping strength of the grid for small oscillations α and can be an indicator of the overall robustness of the grid.

6 Online Analysis

On similar lines as [17, 18], we're interested in testing if symptoms of Critical Slowing Down can be detected by a real-time/online analysis of the state variables of a power grid. In other words, we're interested in checking if computing the autocorrelation and variance of real-time PMU data processed over a running window can provide us with Early Warning Signs of an impending instability.

Using the concepts of Bifurcation Theory, a small change in system parameters, such the governor reference power for a generator (P_{Gen}) at certain points, can lead to major upsets in the stability of the power grid. We intend to run a simulation in which a system is purposefully stressed (via a near constant linear load increment) as time progresses but many restrictions/safety mechanisms being lifted with the aim of singling-out the cause of bifurcation to a change in P_{Gen}(s), in order to best demonstrate that the proposed statistical mechanisms (computing autocorrelations and variances) function well as Early Warning Signs even for slow and steady variations of loads, and not just for sudden changes in state variables caused due to sudden corrective protection mechanisms or the machines not being given 'free-range' for chasing load increments due to specified safety limits on maximum allowed generated powers. Below is the set of special conditions for the simulation of the IEEE 9 Bus system:

1. The three load points of the system (Buses 5, 6 and 8) were linearly increased in time, at a rate of $\Delta P\%$ per minute plus a small white noise component $\mathcal{N}(0, \sigma_v)$, with every increment happening at Δt time intervals.

$$P_{L_i}(t + \Delta t) = P_{L_i}(t) * \left(1 + \frac{\Delta P_{L_i}}{100}\right) + \mathcal{N}(0, \sigma_v) \tag{3}$$

   Here, we've assigned ΔP_L values randomly between $8 - 12\%$ for every load bus, $\sigma_v = 0.01$ and $\Delta t = 0.1$ seconds.

2. Simulation ODE solver solves for the new state variables and parameters for the system every 0.01 seconds. This means that the simulation output can be likened to a stream of PMU data whose sampling rate is 100 Hz.

3. Protection mechanisms were disabled. No remedial/corrective action was taken for any drop in bus voltages/grid frequency or any increase in line currents/MVAs.

4. 'Dummy' governors were placed on the three generators (at buses 1, 2 and 3) which can respond instantly to load changes by changing the set reference generation powers P_{Gen}(s) with zero time lag.

5. The generator limits for $P_{Gen_{MAX}}$, $Q_{Gen_{MAX}}$, etc. were removed. Thus the generators had complete freedom to 'chase' the load increments at the load buses, including factoring in the extra line-losses.

It should be noted that while autocorrelation was used in both online/real-time and offline/postmortem analyses, the two usages were different in:

- their mode of procuring and processing input data (a running window of an incoming stream of data vs previously stored months/years worth of time series),
- the degrees of freedom allowed for its two parameter variables (which out of t and τ is allowed to be constant),
- their theoretically expected output data (autocorrelation is should decrease exponentially with respect to time lag τ but increase with time t if that the system is being progressively stressed with time)

7 Summary and Conclusions

Offline/Postmortem Analysis

- Frequency time-series for months/years of data obtained from various real-world grids were converted into probability distribution function plots and autocorrelation decay plots ($c(\tau)$ vs τ plots).
- Visual inspection of the probability distribution function plots provided many insights into the presence of long-standing steady-state instabilities in the grid as well as the grid's resilience against any additional instability causing agents. Generally the more robust grids such as the RTE (France) and Continental European grids are mostly Gaussian except that they have heavier tails, whereas the smaller or island grids, such as the Mallorcan (Spain) grid can have multiple peaks, skewed distributions and thus an overall visible deviation from Gaussianity which explains their higher susceptibility to steady-state deviations and thus a greater degree of vulnerability to grid failures.
- For most grids, the autocorrelation functions exponentially decay with respect to time lag τ for smaller values of τ but certain grids show significant deviation from the expected norm. For example the Continental European and UK grids show a spike in autocorrelation decay function at time lags of every 15 minutes. This spike, which indicates an inherent instability causing agent in the grid systems, can be attributed

to their 15 minute power trading intervals. Unlike the amount of transacted power which is suddenly varied every 15 minutes, the power grids, being dynamical systems cannot instantly adjust to the new power settings and thus the sudden imbalance of supply and demand leads to transients in the grid state variables.

- Autocorrelation decay curves of other grids (Nordic, Japan, US-Western Interconnection) initially decrease exponentially but later follow between a very slowly decaying or almost constant curve with respect to τ. This can be attributed to measurement noise in the frequency detection.
- From the initial exponential decay of the curves, semi-log graphs were plotted and their inverse correlation times ${t_{corr}}^{-1}$ were obtained. As per the Ornstein-Uhlenbeck Process this inverse correlation time can be likened to the damping constant α of the grids. As per our theoretical expectations, the bigger and more robust grids had higher values of α compared to the smaller, islanded grids.

Online/Real-time Analysis

- The IEEE 9 Bus System was progressively stressed in a time-domain simulation until 'bifurcation was achieved' [18]. In terms of implementation, 'bifurcation' was concluded to have taken place when the simulation solver could no longer converge to a solution without violating convergence thresholds. PSSE 34.3 simply calls out this occurrence as 'Network Not Converged'.
- The bus voltages were detrended with the help of a low pass filter, and their variance σ^2 as well as autocorrelations $c(t, \tau)$ with a fixed time lag $\tau = 1$ instance were computed over a running window.
- A new statistical parameter, called the Modified Kendall's τ Correlation Coefficient (MKTCC) was employed to check if the increase in the autocorrelations and variances was statistically significant. The reason for using a modified version of the normally used Kendall's τ Correlation Coefficient was to accommodate for the degree of certainty/confidence in predicting the correlation apart from the absolute value of correlation itself.
- Both autocorrelation and variance were found to be appropriate Early Warning Sign Indicators for an impending bifurcation, predicting the event minutes earlier.

8 Future Work

The grid analyzed for online/real-time analysis should be bigger, in order to demonstrate spatial variation in the early warning sign indicators for different buses/areas and for singling out areas which are more vulnerable to steady state instabilities.

Despite the successful application of statistical analysis to detect symptoms of Critical Slowing Down in various phenomena [12], autocorrelation and variance are not certain indicators for the same, at least by themselves [21]. In order to tackle that, statistical parameters other than autocorrelation and variance can be investigated for their feasibility as Early Warning Signal indicators. Even for the same statistical indicators, changing the length of the running window, time lag τ, sampling rate etc. can have a significant effect on their effectiveness. Thus an 'optimal' set of parameters could be researched for, which may be different for different grids, but shouldn't vary for a particular grid once computed. On similar lines, grid state variables other than bus voltages, line current/MVAs, grid frequencies may be investigated.

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