Reading Diary

Lakshan Bernard

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Contents

Chapter 1

Stability

vanfretti2020decision

L. Vanfretti and V. N. Arava, “Decision tree-based classification of multiple operating conditions for power system voltage stability assessment,” *International Journal of Electrical Power & Energy Systems*, vol. 123, p. 106251, 2020

Write a summary of the paper...

jiang2016novel

T. Jiang, Y. Mu, H. Jia, N. Lu, H. Yuan, J. Yan, and W. Li, "A novel dominant mode estimation method for analyzing inter-area oscillation in china southern power grid," *IEEE Transactions on Smart Grid*, vol. 7, no. 5, pp. 2549–2560, 2016

Write a summary of the paper...

he2016designing

X. He, R. C. Qiu, Q. Ai, L. Chu, X. Xu, and Z. Ling, "Designing for situation awareness of future power grids: An indicator system based on linear eigenvalue statistics of large random matrices," *IEEE Access*, vol. 4, pp. 3557–3568, 2016

Write a summary of the paper...

hatziargyriou2020stability

N. Hatziargyriou, J. Milanović, C. Rahmann, V. Ajjarapu, C. Cañizares, I. Erlich, D. Hill, I. Hiskens, I. Kamwa, B. Pal, *et al.*, “Stability definitions and characterization of dynamic behavior in systems with high penetration of power electronic interfaced technologies,” 2020

Write a summary of the paper...

ghanavati2016identifying

G. Ghanavati, P. D. Hines, and T. I. Lakoba, “Identifying useful statistical indicators of proximity to instability in stochastic power systems,” *IEEE Transactions on Power Systems*, vol. 31, no. 2, pp. 1360–1368, 2016

☆☆☆☆☆ This paper describes how Early Warning Sign (EWS) can be found for bifurcation and system stress. In particular, the EWS is based on the voltage (σ^2) and autocorrelation ($R(\Delta t)$) of bus voltages. Firstly, computationally efficient method for calculating the EWS is presented and tests are performed on the New England 39 bus system. It is experimentally found that $sigma^2$ is a good EWS for load buses and $R(\Delta t)$ is a good EWS for buses close to generators with low inertia. Finding which sytem variable provide the best EWS is still unanswered, and the authors speculate it might be related to a combination of eigenvectors of the state matrix. The EWS is improved to function in the presence of measurement noise by using bandpass filters. Finally, the usefulness of EWS for locating the disturbance in the grid. It was found both $\sigma^2_{\Delta V}$ and $\sigma^2_{\Delta I}$ increased in stressed operation compared with normal operation. The autocorrelation of the line currents (not bus voltages) also can give the approximate location of the stress in the grid.

Theory: Existing power system stability analysis uses deterministic models. Due to renewable generation, electric vehicles, etc., there are stochastic power injections into the grid. Previous literature has studied the impact of this stochasticity on the moments (e.g. variance) of state variables. There is also literature that derives the autocorrelation function of the power system's state vector near a *saddle node bifurcation*. The result was used to calculate the collapse probability. Outside power systems, a phenomenon called Critical Slowing Down (CSD) refers to the tendency of a dynamical system to return to equilibrium slowly as it approaches a critical bifurcation due to change in a *slowly varying parameter*. This slowly varying parameter could be sustained load buildup or gradual increase of power increase in a weak tie line (leading to inter-area oscillations).

Autocorrelation and variance: These are denoted by σ^2 and $R(\Delta t)$ and have the usual mathematical meaning. The general system model is a set of Differential Algebraic Equation (DAE), and we wish to find σ^2 and $R(\Delta t)$ for the algebraic variables (e.g. bus voltage magnitudes). A traditional method is to use run multiple simulations and then use a DAE solver, however this is very time consuming even for offline applications. Instead, the proposed method is semi-analytical since they assume the load injection has known distribution (Ornstein-Uhlenbeck) and use this to simplify the DAE so it can be solved with a Lyapunov equation solver.

This algorithm is particularly useful in the planning stage, to choose which variables give the best EWS in different test cases. During real time deployment, the operator can only estimate the variance and autocorrelation (since he does not have infinite data points). As such, an index $q_{95/80}$ is defined such that: if $q_{95/80} = 0$ then the statistic (variance or autocorrelation) p.d.f. significantly changes as the system becomes more unstable; if $q_{95/80} = 1$ then the statistic's p.d.f. does not change as the system reaches instability.

Choosing EWS: Based on simulations it is found that not all variables (e.g. bus voltages, line currents) provide useful EWS. Thus it is a planning task to choose which variables to monitor in real time. From the New England 39 bus system it was found that for voltages σ^2 was most useful for load buses, while $R(\Delta t)$ is useful for buses near generation with low intertia. For line currents it was also found that σ^2 is useful most lines but $R(\Delta t)$ is only useful for lines connected to low inertia generators. A hypothesis to be tested is: "line current autocorrelation is closely tied to the way generators respond to perturbations as the system approaches bifurcation".

There is still work linking the good variables for EWS with the eigenvalues/eigenvectors of the state matrix of the system. Especially regarding $R(\Delta t)$ this link is unclear, but for σ^2 good variables for EWS seem to be linked with eigenvectors of the covariance matrix. This is a possible future extension to this research.

System stress: The other key use of EWS is to locate regions of the grid that are stressed. This was performed by considering to types of case studies: transmission line tripping and capacitor tripping. The methodology was to calculate the difference between the statistic during stress and during normal operation. Similarly the ratio between stressed and normal operation is calulated. It was found that variances of voltage and current magnitudes show larger increases near the stressed area of the power system, compared to the variances elsewhere. The line current autocorrelation is also a useful statistic to locate stress but voltage autocorrelation is not useful (and a mathematical argument is presented as to why). The ability of the EWS to not only detect the onset, but also the location of the stress is promising for intervening action.

Recommendations: 1) Improving the EWS to be resistant to measurement noise; 2) Developing a probabilistic index of system stability; 3) Test these algorithms on real data; 4) Improve semi-analytic method for real-time use.

meegahapola2020review

L. G. Meegahapola, S. Bu, D. P. Wadduwage, C. Y. Chung, and X. Yu, "Review on oscillatory stability in power grids with renewable energy sources: Monitoring, analysis, and control using synchrophasor technology," *IEEE Transactions on Industrial Electronics*, pp. 1–1, 2020

☆☆☆☆☆ This is a recent review paper on oscillatory stability. It contain 100+ references and covers established theory and open research questions relating to Power Electronic Converter (PEC) renewable energy generation.

Applications: Using synchrophasors for analysing oscillatory stability is well established in literature but further work is required to cope with PEC induced oscillations. The challenges introduced by PEC generation include: Frequency regulation/control; Voltage control; Oscillatory stability; Power quality (harmonics, flicker, etc.).

Over the past few years, research has been conducted into how PEC devices impact the damping performance of the power grid. Types of PEC studied include: Doubly Fed Induction Generator (DFIG); Permanent Magnet Synchronous Generator (PMSG); Non-linear loads such as Variable Speed Drive (VSD); Switch mode power supply; and Light Emitting Diode (LED) drives.

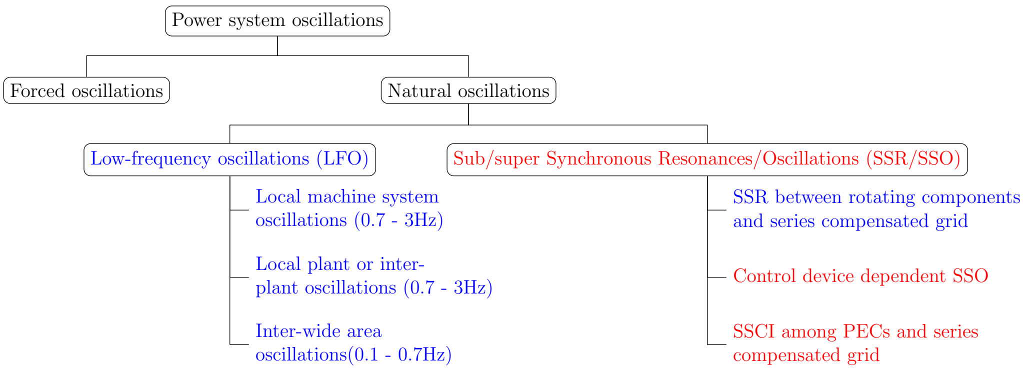
Synchrophasors vs SCADA: For this type of research, synchrophasors have superceded the capability of SCADA systems, primarily due to their high accuracy and high speed data transfer capabilities. The broad categories of research in synchrophasors can be divided as follows:

- Synchrophasor Research
  - Phasor Measurement Units
    - Phasor estimation algorithms
    - Communication protocols
  - Power System Applications
    - Measurement/monitoring
    - Protection
    - Control
    - PMU placement
    - Model validation

This review also includes a nice summary of definitions relating to PMUs. Phase Locked Loop (PLL) is the fastest estimation technique but accuracy decreases under harmonic distortions. Quadrature demodulation is described as very accurate and DFT based methods are most commercially available.

Individual PMUs feed into a Phasor Data Concentrator (PDC) and large networks have multiple PDCs in a hierarchy (local → regional → coorporate). It is at the PDCs that real-time situational awareness algorithms (e.g. to monitor voltage stability, transient stability, oscillatory stability) are deployed. Note local PDCs have less delay but limited view of the grid, whereas the coorporate/central has a full view of the network but longer delays. The review paper did not mention the order of magnitude of these delays.

Classification: The types of power system oscillation are depicted below:



Forced oscillations arise from cyclic oscillating sources (e.g. fluctuations of renewables). LFO involves synchronous generators and has extensively been studied. SSO/SSR was defined by the SSR working group (from the IEEE Power System and Dynamic Performance subcommittee) in 1976 and revised in 1979, 1985, 1991 and 1997. Recently, wind and solar generation is causing new types of SSO/SSR. Thus SSO/SSR is reclassified into three sub-categories:

1. SSR between rotating components and series compensated grid. This includes Induction Generator/Machine Effect (IGE/IME), Torque Amplification (TA), and Torsional Interaction (TI).
2. Control device dependent SSO. This includes the steam/hydro against fast response controllers, and Sub Synchronous Torsional Interaction (SSTI).
3. Sub Synchronous Control Interaction (SSCI) among PECs and series compensated grid. These are newly observed oscillations that need to be adequately dampened.

Monitoring methods: Traditionally, time domain simulations were used for modal analysis, however, this is no longer practical because: increased quantity of PECs has complicated dynamic models with time-varying parameters, 'black-box' controllers, and large computational burden for real time applications. For example, model-based approaches were unable to identify the oscillation in the 1996 USA blackout. The future is using PMUs for real time monitoring of power system dynamics.

The first group of methods aim to *estimate the oscillation mode and/or the oscillation mode shape*. The typical data collected by the PMU is called ambient, while the post-fault data is called ringdown.

Method	**Mode**	**Shape**	**Data**
Stochastic subspace system identification	Y	Y	Both
Prony analysis	Y	Y	Ringdown
Matrix pencil	Y	Y	Ringdown
Phase locked loop method	Y	Y	Ringdown
Frequency domain decomposition	Y	Y	Ambient
ARMAX model	Y	Y	Ambient
Continuous modal parameter estimator	N	Y	Ringdown
Principal component analysis	N	Y	Ringdown
Moment matching method	N	Y	Ringdown
Kalman filtering	N	Y	Ringdown
Cross spectrum analysis	N	Y	Ambient
Channel matching method	N	Y	Ambient
Transfer function	N	Y	Ambient
Minimal realisation	Y	?	Ringdown
Eigensystem realisation	Y	?	Ringdown
Fourier transformation	Y	?	Ringdown
Hilbert-Hung transformation	Y	?	Ringdown
Wavelet transformation	Y	?	Ringdown
Variable projection	Y	?	Ringdown
Spectral analysis	Y	?	Ambient
Yule-Walker method	Y	?	Ambient
LMS adaptive filtering	Y	?	Both
Robust recursive least squares	Y	?	Both

Even though the stochastic subspace system identification can estimate the mode and the mode shape with both types of data, it has a high computational cost. The key improvements to this group of methods are: 1) past research has exclusively targeted LFO - the new oscillation modes (e.g. power resonance caused by renewables interaction with voltage source converters and HVDC controllers) are still to be solved; 2) there is interest in algorithms that work for both ringdown and ambient data; 3) most research does not consider data cleanliness issues (e.g. how to cope with missing packets); 4) the oscillation mode shapes are not enough to identify the source of the oscillation; and 5) these methods do not show how damping is distributed throughout the grid - hence they can only be used for monitoring purposes.

The second class of methods to monitor oscillations are called *energy flow tracking*. The idea is to calculate the damping torque coefficent $K_D(f)$ for each device in the network. For a Single Machine Infinite Bus (SMIB) there is rigorous theory justifying how to calculate the $K_D(f)$ using the cross-energy spectral density and angular velocity of the terminal voltage. Recently there is a renewed interest in this type of method because: 1) it is computationally efficient; 2) the source and cause of the oscillation is identified by having negative $K_D(f)$; 3) the theory is general enough that it can deal with a wide frequency of oscillations - not just LFO. The room for improvement is that the theory has still not been extended from SMIB to a real power system so this method is currently restricted to local application. It is unclear how to extend this theory to find the system oscillatory stability margin.

Non-fundamental phasors: Originally, PMUs were designed to monitor the fundamental phasor. When the reporting rate is high (e.g. 100Hz) it is possible to analyse variations in the fundamental phasor to find the presence of sub synchronous oscillations. The is current research interest in algorithms that can extract the frequency, damping coefficient, amplitude and phase angle of any sub synchronous oscillations present. There are four standard methods: Prony, Hankel total least squares, eigensystem realisation and matrix pencil. All these methods feature a data matrix which is processed and end with a least square solution. It is also found that the Fourier transform can be used to extract the frequency and damping of sub synchronous oscillations.

During sub-synchronous oscillation based events, there can also be super synchronous interharmonics. Even with a reporting rate of 100Hz, these interharmonics cannot be identified by solely analysing the fundamental phasor. Instead, the conventional DFT based phasor estimation algorithm inside the PMUs should be updated. This is also an active field of research including Synchronised Measurement Devices (SMD) and the Improved Iterative Taylor Fourier Multifrequency (I2TFM).

Damping systems: When poorly damped, oscillatory modes (esp. LFO inter-area) limit the power transfer along lines which can cause a failure in the system. The majority of the literature tackles inter-area oscillations (viz. sub synchronous oscillations).

The first technique is to treat the inadequate damping of oscillations as a small signal problem and use a linearised model of the system. Traditionally, this involved a Power System Stabiliser (PSS) that provides a control signal to an Automatic Voltage Regulator (AVR). The drawbacks of this approach are: 1) validity of linear model around multiple operating points; 2) robustness of the designed controller to work under multiple operating conditions; 3) model uncertainities; 4) computational complexities; and 5) simultaneously damping local and inter-area oscillatory modes.

The majority of techniques are called *robust and adaptive controllers* because they handle model uncertainities and adaptively update to cope with a variety of operating conditions. State of the art techniques include: the H_∞ controller; multiagent H_∞ controller; mixed H_2/H_∞ controller; dual Youla parameterisation based adaptive controller; and the multi-polytopic adaptive controller. Consideration must also be given to communication delay arising from remote signal - this is taken in consideration by the: networked predictive control approach; phasor power oscillation damping controller; enhanced adaptive phasor power oscillation damping controller; Smith predictor based H_∞ controller; recurrent neural network based controller; stochastic subspace indentification based controllers.

The final category of synchrophasor based damping control mentioned uses Flexible AC Transmission System (FACTS) devices such as Thyristor Controlled Series Capacitor (TCSC) and Static VAR Compensators (SVCs).

Real power grids: A comparison is made between: Statnett Power Oscillation Monitoring System (Nordic Energy Network), SGCC WAMS Platform (China), Swissgrid WAMS (Swissgrid), Southern California Edison Company (Southern California), Manitoba Hydro (Manitoba) and Tennessee Valley (Knoxville Tennessee). These example show that the monitorred oscillatory modes are <2 Hz hence corresponds to the LFO. The Statnett Power Oscillation Monitoring System is highlighted since it was implemented in parallel with SCADA data (fault recorders). It is reliable with communication latencies upto 300ms.

Big data: Synchrophasor data is saved on databases. Big data has large volume, variety and velocity - thus covers synchrophasor databases. The most common big data technique used on synchrophasor databases is data mining, in particular classification and regression approaches are most common. Typical application include Dynamic Stability Assessment (DSA); instability prediction; state estimation; and protection. Parallel processing is also essential to deal with synchrophasor data streams, so there is active research in 'upgrading' conventional algorithms by finding more efficient decompositions, exploiting sparsity, splitting the data into smaller blocks, etc.

The application for dynamic event detection is also highlighted. One algorithm consisted of using Finite Impulse Response (FIR) filters to find line outages. Event location was also considered in a offline hierarchical clustering approach to group coherent generators. Detecting transient events has also been considered using Detrended Fluctuation Analysis.

Very interesting research has also been conducting in using advanced statistics on synchrophasor data. The main aim is to design statisical indices to predict stability issues in power networks. The first example uses autocorrelation and variance of bus voltages to produce early warning signs of separation events. The second example uses Linear Eigenvalue Statistics (LES) for situational awareness in power grids, especially enabling anomaly detection.

Recommendations: There are five main recommendations:

1. Monitoring mixed oscillation issues caused by PEC, not just LFO.
2. Extending energy flow tracking from SMIB to real power grids.
3. Dealing with synchrophasor data cleanliness.
4. Monitoring sub synchronous oscillations from fundamental phasor data.
5. Use of big data for oscillatory stability monitoring.

Chapter 2

System Strength

gu2019review

H. Gu, R. Yan, and T. Saha, "Review of system strength and inertia requirements for the national electricity market of australia," *CSEE Journal of Power and Energy Systems*, vol. 5, no. 3, pp. 295–305, 2019

Synchronous generators (SGs) are still making major contributions to the re-stabilization of a power system following voltage/frequency disturbances, attributed to their inherent capability of providing system strength and inertia. However, SGs powered by fossil fuels are operating to a lesser extent and scheduled for decommissioning in the National Electricity Market (NEM) of Australia due to the accelerating increase of low bidding priced asynchronous generation of wind and solar, which leads to the reduction and even in some cases, a shortage of system strength and inertia. This paper comprehensively reviews the requirements of system strength and inertia in the NEM from an operational security perspective. Australia is the first country that established the regulation rules of system strength and inertia to accommodate issues of an emerging high penetration level of non-synchronous renewable generation.

Chapter 3

Example Chapter

einstein1935can

A. Einstein, B. Podolsky, and N. Rosen, “Can quantum-mechanical description of physical reality be considered complete?,” *Physical review*, vol. 47, no. 10, p. 777, 1935

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Since this a LaTeX document, it is quite easy to enter math mode to write equations, for example:

$$\sin^2\theta + \cos^2\theta = 1$$

It is also possible to have tables and even draw diagrams using TikZ.