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Practical and theoretical approaches to detecting grid dynamics and stability

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Abstract: Electricity supply systems used to be operated in accordance with strict hierarchical principles. Major power stations controlled the grid frequency and balanced load as well as stabilized voltage levels. In such a system the high inertia of power producers posed a natural limit on the amount of observable dynamic effects and maintained good resilience against Blackout phenomena during overload situations. However, as more and more small, distributed energy producers enter into the picture, inertia is lost and concern for dynamic instabilities grows. This paper gives examples of some dynamic disturbances of electrical grids under stress and points out innovative methods for their quick and sensitive detection, such as Wavelet-based subharmonic oscillation detection. Furthermore, when electrical grids are closer to breakdown they can enter a nonlinear regime where the statistical properties of the state variables become more and more pronounced. We argue that in some situations these statistical fluctuations can be a good early indicator for an upcoming Blackout and propose how to capture breakdown criticality with an appropriate measurement algorithm based on the analysis of voltage statistics.

Keywords: Mechanical Analogon of Inter-Area Oscillations, Blackout Early Detection, GDASys - Complement to WAMS, HVDC+FACTS devices, Oscillations During a Blackout, FFT – Fast Fourier Transform, Stability – Bifurcation Analysis, Voltage Collapse, Stochastic Processes

1. INTRODUCTION

Wide area synchronous power systems offer great benefits for todays deregulated energy markets. Flexible energy transfer across geographical and political borders as well as lower costs through the pooling of generation capacities are some of the key advantages of an interconnected grid. Due to economic pressures, such grids are frequently operated close to their stability limit. In this limit, the presence of dynamic effects such as low frequency oscillations on weak interconnections can rapidly develop into a fundamental bottleneck for power transfer and grid stability.

Interarea oscillations (0,1-1Hz) are present in virtually all large power systems on the transmission level. Under ambient conditions, these modes are well damped, amplitudes are negligible. Stability problems become apparent however only by observing the system behavior after excitations. Examples for excitations are power system faults, line switching, generator disconnection and even the loss or application of loads. An unstable system will enter into a period of machine rotor angle oscillations, with corresponding power flows and oscillatory voltage and frequency variations. Damage to the infrastructure, unwanted trippings and in extreme cases even blackouts are then a danger.

A very recent and dramatic example for this can be found in an official report submitted to the Indian CERC commission analyzing the wide area blackouts that happened on 30th and 31st of July 2012 in the Northern India electricity grid (CERC 2012). Summarizing events during one of the overall largest blackout incidents ever, the report clearly states the presence of unusual and poorly damped low frequency oscillations before, during and after the blackout. Such dynamic oscillatory phenomena are known to cause unwanted protection relay action and trippings which in turn can aggravate stability problems in an already stressed system, eventually leading to blackouts.

Fig. 1. GDASys devices for monitoring oscillatory phenomena in the electrical grid in rack (DMR-D) / mobile version (DA-Box 2000).

Poorly damped oscillations are thus an important indicator for the dynamic stability of the power grid. An early detection of these oscillatory phenomena is the key to

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increased situational awareness. This paper describes two promising approaches for dynamic voltage stability assessment: (1) frequency-domain based Wavelet analysis (2) monitoring the time evolution of the standard deviation of the bus voltage. The authors argue that the corresponding algorithms allow a particularly efficient detection of power system oscillations and stability and give practical measurement examples evidencing their performance. These measurements were taken with GDASys devices as shown in Fig.1.

2. THEORETICAL CONSIDERATIONS: EFFICIENT DETECTION OF GRID OSCILLATIONS

Traditionally, grid operators use SCADA systems to monitor and control their network of power lines. This involves measuring average values of important operational parameters with a periodicity of a few seconds. The measurement data is then sent to a centralized supervisory station for review. To enable the analysis of dynamic effects in the grid, one has to drastically increase the measurement data rate. Suitable measurement tools for this purpose are offered by a “Grid Dynamics Analyzing System” as described in W. Haussel et al. (2004) and M. Hofbeck et al. (2008a,b). The variant in the top part of Fig. 1 consists of the core measurement unit DMR-D, a Windows-based industrial PC for data storage and a communication unit supporting a wide range of industry standard protocols. The mobile version of the device and a separate communication device is shown in the lower half of the picture. The devices offer a usable bandwidth between 5 mHz and 98 Hz at a high resolution of 5 mHz.

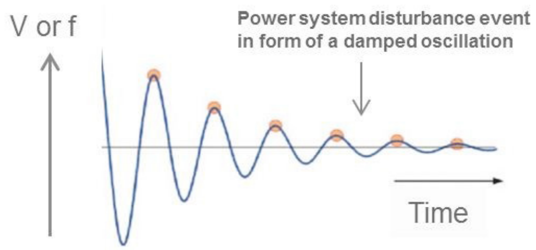

Fig. 2. GDASys damping monitor principle. Power systems disturbance model, a damped sinusoid.

Another distinguishing characteristic is the usage of highly sensitive methods of frequency domain analysis. Here, the well-known Fourier- as well Wavelet-analysis is available. The Wavelet analysis is employed to realize a function called damping monitor. Its task is to detect oscillatory disturbances on the power line that deviate from nominal system voltage or frequency behavior. By means of high precision Wavelet-based Prony analysis, the damping monitor searches the full usable frequency spectrum for power system disturbances matching the fundamental model of a damped sinusoid (Fig. 2). Its output consists of the measured time stamp, frequency, amplitude, duration and the damping factor of a detected disturbance. Such an oscillation could for example be related to a malfunction or some dynamical interactions between generators or loads. The damping monitor gives a precise answer as to what kind of disturbance occurred and when, how large it was and how long the disturbance was measurable. The usage of Wavelet- instead of conventional Fourier analysis here is not merely incidental but of utmost importance for true early detection: the choice of a proper Wavelet allows a significantly improved detection time because the time frequency uncertainty relationship is more favourable in online measurement situations. This will be demonstrated below in a measurement where inter-area oscillations were observed in near-real-time after a sudden generation loss.

Whenever a dynamic deviation of system parameters from normal has been established, the problem to assess the criticality of the state of the system starts. Assessing the actual proximity to voltage breakdown for a complex system such as an interconnected electric grid is a difficult task and so far no single universally efficient and well-accepted assessment scheme is known. However, recent research into complex systems inside and outside the domain of electrical grids indicates that statistical tools such as autocorrelation and variance measurements of key observables can serve as useful indicators during the transition into breakdown. Particularly one body of research brought forth by d. Podolsky et al. (2013), G. Ghanavati (2013, 2014) and E. Cotilla-Sanchez (2012) points out a phenomenon called "critical slowing down" which is characterized by increasing fluctuations in the system, particularly in the nonlinear regime close to breakdown. G. Ghanavati (2013) shows, based on simulations of power systems approaching critical bifurcations, that especially the statistical *variance* in bus voltages can be a good indicator of the proximity to Blackout.

Below the authors of this paper show real data measured in the German transmission system during the blackout which occurred in Turkey in March 2015. While this Blackout did not affect the European or German power system in a critical way, the data employs similar statistical analysis methods and shows that very sensitive event detection is possible. Corresponding measurement devices based on statistical algorithms thus show very good promise as power system instability early warning tools.

The following sections present measurement results obtained during large disturbances in various actual power networks by means of measurement equipment of the A. Eberle GDASys family of devices. The purpose is to demonstrate in practice the efficiency of Wavelet- and statistical variance/standard deviation-based measurement algorithms for power system dynamics assessment.

3. PRACTICAL RESULTS: OSCILLATION DETECTION

The following two case studies demonstrate the practical application of a Wavelet-based damping monitor during major power system disturbances.