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Distributed Real-Time Stability Monitoring Algorithms using Synchrophasors

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Abstract

This paper proposes real-time stability monitoring algorithms using synchrophasor data in distributed architectures. By dividing the computations between a central computer and multitude of local computers at the substation level, the algorithms efficiently detect instability mechanisms in the large-scale power system from wide-area power system measurements. Algorithms for monitoring damping levels of oscillatory modes (small-signal stability), voltage security indices, and angle instability indicators are proposed and illustrated on archived synchrophasor data from real power systems.

I. Introduction

Large-scale implementations of synchrophasors all over the world point to an urgent need for development of real-time applications based on synchrophasor measurements. Technology is maturing in this context in various stability monitoring applications such as oscillation monitoring [1]-[6] and voltage stability monitoring [7]-[9]. Given the rapid growth in the number of available synchrophasor measurements over the past few years, many of the algorithms proposed earlier are not directly able to handle the large-scale nature of future synchrophasor measurements. This paper will focus on distributed synchrophasor algorithms for real-time stability monitoring. These distributed algorithms will share the computations between the substation level and control center level so that they can handle truly large numbers of synchrophasor measurements.

Specifically substation level computations could be done locally at local computers at the substations or within many of the modern Phasor Measurement Unit (PMU) enabled devices such as digital relays and digital fault recorders. Most of the modern PMU devices have advanced computational ability such as internal programming capability including basic signal processing routines such as Fast-Fourier Transform (FFT) computations. Local computations of local measurements at the substations can then send local analysis results to the control center less periodically (say once a second) rather than transmitting the full fidelity digital streaming data which would otherwise choke communication network. The algorithms are thus expected to save communication bandwidth as well as to facilitate distributed computation. The paper will address distributed algorithms for three classes of stability monitoring tools namely for small-signal stability, voltage stability and transient stability.

Oscillation monitoring broadly can be divided into ringdown analysis [1],[2] and ambient data analysis [3]-[6]. In ringdown analysis, power system responses to sudden disturbances such as line openings are decomposed into exponential oscillatory modal components for estimating the dominant mode frequencies and their damping ratios. In ambient data analysis, random load fluctuations in power systems are modeled as white noise inputs and the routine PMU measurements which are system responses to the white noise inputs are analyzed to estimate the dominant modal properties. In both cases, development of distributed oscillation monitoring engines is nontrivial because the oscillation problems typically arise from interaction of generators and controls across many substations. Recent paper [7] proposes a distributed architecture for implementing a frequency domain ambient analysis engine for large power systems. The algorithm called Distributed Frequency Domain Optimization (DFDO) proposed in [7] is consistent with the theme of the present paper and will be discussed in Section II of this paper.

Real-time voltage stability monitoring using synchrophasors is largely divided into two approaches: Thevenin equivalence based methods [8],[9] and sensitivity based methods [10]. Both approaches are reasonably well-suited to distributed architectures. In the proposed paper, a distributed version of the QV sensitivity based voltage stability monitoring algorithm from [10] will be presented in Section III of the paper.

Previous angle stability monitoring algorithms proposed in [10],[11] are mostly targeted towards control center level central implementation. In the proposed paper, specific algorithms such as the phase angle algorithm from [11] will be extended for implementation in a distributed architecture. Details will be presented in Section IV of the paper.

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II. Distributed Oscillation Monitoring

Power system oscillations are typically caused by adverse interactions of system components and system controls. Electromechanical oscillations typically occur in the frequency range between 0.05 Hz and 2.5 Hz and they are generally caused by the existence of poorly damped or negatively damped eigenvalues (oscillatory modes) of the underlying power system dynamics. The modes are classified into local modes (associated with one generator plant), intra-area modes (many generators within a control area) or inter-area modes (across many control areas) [12]. When a problematic mode is detected in a real-time, the classification of the mode into local, intra-area or inter-area kind requires estimation of the associated mode shape [12].

Significant progress has been made in the power engineering literature [1]-[7] in developing synchrophasor based algorithms for estimating the damping levels of dominant oscillatory modes from real-time data. While the frequency values and damping levels of dominant modes in a power system can be estimated from a small set of measurements even locally within specific critical substations, estimation of the mode shape requires wide-area synchrophasor measurements.

For instance, in the case of sustained oscillations at a generator plant from a problematic local mode, neighboring generating units may also be responding to these oscillations albeit at smaller amplitudes. If the oscillation monitoring is done purely based on local measurements, there is a danger that several of the neighboring generators may take corrective actions such as reduction of MW outputs unnecessarily which could cause havoc for system operation. Therefore, oscillation monitoring should utilize as much of available wide-area synchrophasor measurements as possible to pinpoint the source of the problem and for suggesting appropriate corrective actions. Simultaneous processing of a large number of PMU measurements is suggested for the future in better understanding oscillatory properties of the intra-area modes in power systems.

In this section, a distributed oscillation monitoring algorithm from [7] called DFDO is summarized. DFDO divides computations between substation computers and a central computer towards simultaneous handling very large of PMU signals simultaneously in oscillation monitoring. A flow-chart of DFDO is presented first in Fig. 1.

Main computational steps such as Fast Fourier transforms and estimation of modal data from PMU measurements by using signal processing algorithms are done in a distributed fashion at the substation computers. The central controller estimates the overall system power spectrum density from the substation FFTs, finds the dominant modes and selects specific substations to do the local estimations for each mode, and finally computes the system mode frequency, damping level, mode shape and energy estimates by suitably combining the local results from the substations. This type of supervisory role for the central computation allows the methodology to handle large number of PMUs in the estimation process. Among many available measurements, the central controller only selects a subset of measurements for carrying out local estimations for each mode so that the procedure is adaptive to effectively handle changing system conditions. Next the methodology is applied to actual recorded data from August 10, 1996 western American blackout. More details on this case study as well as other examples can be seen in [7].

On Aug. 10th 1996, a major blackout occurred in the WECC system [13], [14]. Time-plot of a major California-Oregon tie-line flow during the event is shown in Fig. 2. It shows poorly damped oscillations in the MW flow after Keller-Allston line tripping and growing MW oscillations after Ross-Lexington line tripping. For lack of available phase angle measurements, active power measurements from 9 PMUs have been taken as inputs for DFDO analysis. The moving window length is 180 seconds and refresh rate is 10 seconds [7].

First, DFDO has been tested on the data before tripping of Keeler-Allston line (t=0 to 400 seconds). DFDO finds the dominant mode at 0.2722 Hz average frequency with 0.0028 Hz standard deviation and has mean damping ratio at 5.59% with 0.63% standard deviation (Table I). Then, Prony analysis [1],[2] has been applied to the system response during 20 seconds after Keeler-Allston line tripping (t=400 to 420 seconds). Prony analysis finds the dominant mode at 0.2690 Hz with 2.59% damping ratio. Mode shape for this mode found by Prony is shown in Fig. 3 (top subplot).

Finally, DFDO has been applied to the time window between Keeler-Allston line tripping and Ross-Lexington line tripping (t=430 to 700 seconds). The mode estimated by DFDO has average frequency at 0.2507 Hz with 0.0011 Hz standard deviation and average damping ratio as 1.70% with 0.54% standard deviation. Estimation and mode shape results from DFDO are presented in Table I and Fig. 3 (bottom subplot) respectively. By checking DFDO results with the results of Prony Analysis and FDD [6], it is clear that they match well. Mode shape estimations provided by DFDO are similar to the ones from Prony Analysis.

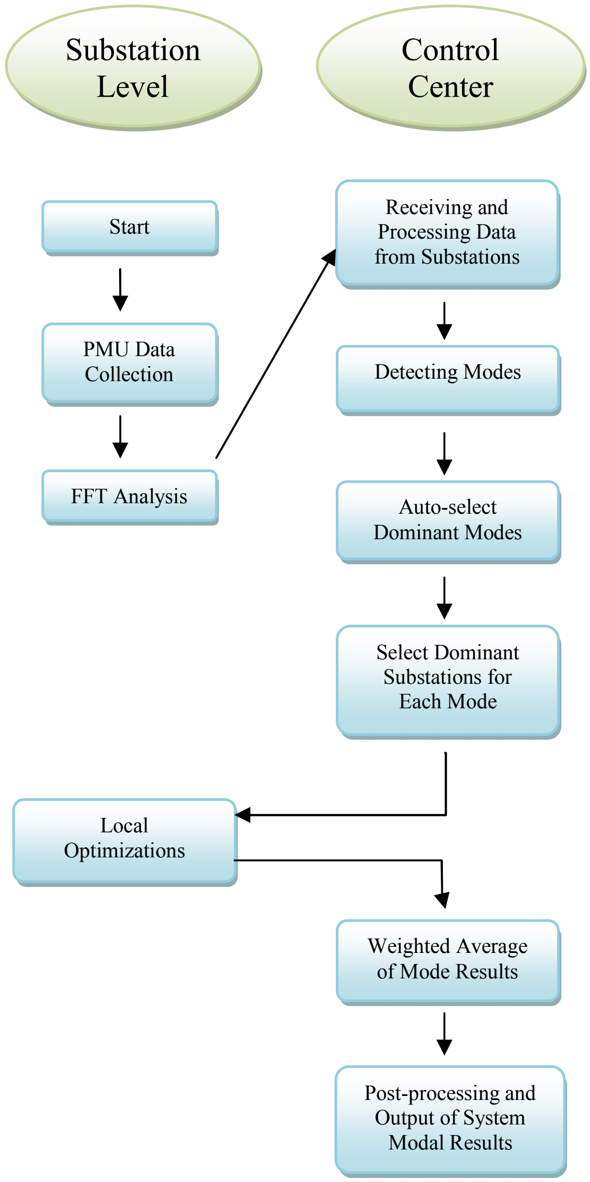

Fig. 1. Flowchart for DFDO [7]

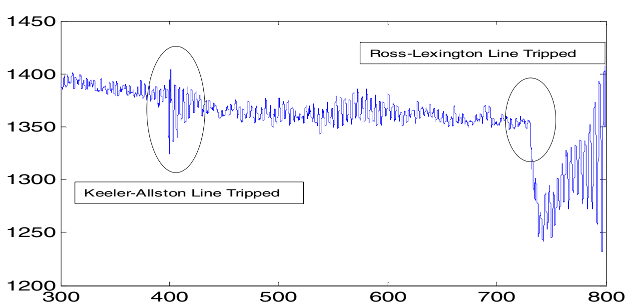

Fig. 2. Active power-flow (MW) on Malin to Round Mountain Tie-line 1 during Aug. 10, 1996 blackout

TABLE I. RESULTS SUMMARY FOR WECC AUG. 10TH 1996 EVENT

Algorithm	Freq. (Hz)	Freq.Std. Dev. (Hz)	Damping Ratio(%)	Damping Ratio Std. Dev. (%)
Prony	0.2690	--	2.59	--
DFDO (before)	0.2722	0.0028	5.59	0.63
FDD (before)	0.2710	0.0012	4.47	1.15
DFDO (after)	0.2507	0.0011	1.70	0.54
FDD (after)	0.2510	0.0002	1.60	0.18

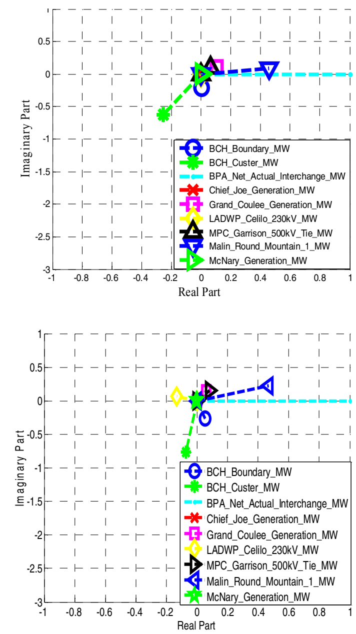

Fig. 3. Prony (top) vs. DFDO (bottom) mode shape results prior to Ross-Lexington tripping

III. Distributed Voltage Security Monitoring

Voltage instability phenomenon is caused by lack of adequate reactive power support in some part of the system. It can be caused by sudden loss of critical VAR support devices including generators, loss of transmission lines and unexpected growth in reactive power demands. It is important to detect the proximity of system operation towards voltage instability so that operators can be alerted to take appropriate actions to correct the problem well-in-advance.

In previous research [10], a voltage security assessment index Γ_i for bus i has been defined as the slope of the QV curve

$$\Gamma_i = \frac{\Delta Q_i}{\Delta V_i} = \sum_j^n \frac{\Delta Q_{ij}}{\Delta V_i}$$

where ΔQ_{ij} represents reactive power change for each transmission line or transformer connected with this bus. ΔQ_i is an incremental change in bus reactive power injection at bus i. Methods for computing Γ_i from real-time PMU data has been developed in [10]. The methodology has been implemented for prototype testing at several North American utilities [15]. It can be shown that the index Γ_i becomes close to zero when the system becomes voltage insecure at bus i. Specifically, by comparing Γ_i at different buses, the relative strength of the buses with respect to voltage security can be assessed. For instance, in case of voltage insecurity, the bus with the lowest Γ_i index is likely located closest to the critical bus for mitigating the voltage instability. The computation of the voltage security index Γ_i is purely based on local measurements of bus voltage magnitude and line VAR flows at that bus [10], and can be implemented independently at each substation. The substations then send the indices Γ_i to the central computer periodically say every 1 second.

At the central level, the indices from various substations are analyzed and any vulnerable buses can be detected. In case of voltage insecurity, by comparing the relative strengths of different buses in the problematic portion of the system, the central computer can determine the best location for mitigating control actions such as switching of VAR devices and load shedding whenever needed.

IV. Distributed Angle Stability Monitoring

Transient stability deals with whether the interconnected power system can remain synchronized following large disturbances. Here we assume that the system is in a dynamic state following some unknown large disturbance possibly an unexpected high order contingency. The critical questions are as follows: a) Is the system transient stable or unstable? b) In case of transient instability prediction, which part of the system is accelerating and which part is decelerating? and c) How much generation is to be tripped if any and how load is to be shed if any needed? PMU based algorithms for answering these questions have been presented previously in [11]. In this section, we will discuss one of these methods called Phase Angle Algorithm which is well-suited to the distributed monitoring theme of this paper.

First recall that the center of angle reference frame for a power system is defined by [12]:

$$\theta_{COA} = \sum_{i=1}^{N} \frac{H_i \theta_i}{H_i}$$

where θ_i denotes the internal rotor angle of machine i and H_i stands for the interia constant for machine i. It is argued in [11] that the center of angle can be very well approximated by external PMU measurements in the form of

$$\theta_{COA} \approx \sum_{i=1}^{N} \frac{P_{Gi} \delta_i}{P_{Gi}}$$

where δ_i represents the external bus voltage phase angle at bus i, and P_{Gi} stands for the MW power output of generator i. When any of the angles δ_i starts to deviate significantly from the system center θ_{COA}, that is an indication of impending angle instability [11]. The sign of $\delta_i - \theta_{COA}$ indicates whether the machine is accelerating away (positive sign) or decelerating away (negative sign) respectively [11].

The phase angle algorithm of [11] is readily suited for a distributed implementation. Each substation connected to major generating units sends the measurements δ_i, and P_{Gi} to the central computer. The central computer calculates θ_{COA} and sends back θ_{COA} to all these substations. At each substation, the phase angle algorithm of [11] is then applied. That is, whenever the magnitude of $\delta_i - \theta_{COA}$ goes above a preset threshold, the local processor starts accumulating the integral area of $\delta_i - \theta_{COA}$ over time, and like in protective relays, the area is reset if the magnitude of $\delta_i - \theta_{COA}$ swings back down below the threshold at any time. When the area accumulated from $\delta_i - \theta_{COA}$ has gone past a predefined critical value, the substation i predicts a potential transient instability and reports a transient stability alarm from bus i to the central computer. By monitoring the substation alarms, the central computer can them arm specific substations to take corrective control actions. The sign and magnitude of the accumulated area for substation i can be used to determine whether generation tripping is needed (positive $\delta_i - \theta_{COA}$) or load shedding is required (negative $\delta_i - \theta_{COA}$) respectively. Additional details and examples will be presented in a future paper.

V. Conclusion

The paper proposes a distributed frequency domain algorithm DFDO for ambient noise based oscillation monitoring of multiple modes from many PMUs. Test results on known test systems and archived PMU test data show the method could be effective when the global system results are combined from parallel local optimizations at individual PMU level. As the number of PMU installations in North America grows to thousands of devices in the near future, it is important to develop distributed algorithms that can exploit the very large number of cores available in modern computational servers.

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