Computational Challenges in Stability Monitoring of Power Systems Using Large Number of PMUs

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Widespread installations of Phasor Measurement Units (PMUs) (or synchrophasors) are underway in the North American power grid, enabled by the recent Federal investment into smart grid infrastructure projects for electric power industry. There are over 500 PMUs in the western power grid, several hundred PMUs have been installed in the eastern power grid, and these numbers are expected to grow rapidly in the future. By providing a synchronized glimpse into the dynamic state of the large power grid, the availability of PMU measurements is leading to active research on a new class of real-time stability monitoring and control algorithms. Such real-time stability monitoring algorithms detect early signatures of oscillation problems, voltage instability phenomena, and angle instability mechanisms, for alerting power grid operators as well as for triggering closed loop stabilization controls.

In the present day implementations, these real-time stability monitoring algorithms are typically limited to handling a handful of PMU measurements because of inherent computational complexity of internal calculations. On the other hand, the power system is becoming increasingly complex from larger presence of renewable energy sources and more sophisticated power electronic controls in customer loads throughout the system. These newer devices and controls are introducing new types of instability phenomena in power systems such as wind farm related oscillations and Fault Induced Delayed Voltage Recovery (FIDVR) which are becoming increasingly difficult to model and to monitor. To understand the nature and cause of the instability mechanisms, and to fully utilize the large number of PMU measurements already available in the eastern and western power grids, there is an urgent need to develop new class of computational algorithms to solve some of underlying fundamental large-scale mathematical problems in the analysis of PMU data.

An alternate approach would be redesigning the PMU processing algorithms themselves to render them friendly towards parallel implementations [1]. As an example, oscillation monitoring algorithms can be designed in hybrid formulations [2] wherein the estimation is shared among the substation level computations (close to PMU locations) and at a control center type central processor. Algorithms that encourage efficient *sharing of information rather than data* among substations and control center need to be developed for fully utilizing the computational capability of the substations in the future and for intelligent management of the communication network requirements. Algorithms that integrate the stability monitoring properties of the power grid together with the constraints of the communication network will be crucial for extracting all of the critical information that can be derived from the thousands of PMUs in the field in the near future.

To illustrate the complexity of the stability monitoring problem, we will discuss the computational challenges encountered in some of the PMU based oscillation monitoring algorithms. In real-time oscillation monitoring, there are two classes of analysis tools: ambient modal estimation and event modal analysis. In ambient modal estimation, the power system is typically assumed to be continuously perturbed by Gaussian white noise type of random load fluctuations. Analysis of the PMU measurements lead to outputs of the power system under small-signal random perturbations, and the underlying small-signal model is estimated by various kinds of algorithms towards extracting the modal properties of poorly damped oscillations present in the system. In event modal analysis, the system response following a medium or large disturbance is scrutinized for extracting the dominant modal characteristics of a small-signal model of the power system by analyzing appropriate portion of the system response. The analysis in both classes of problems can be carried out either in time-domain or in frequency domain.

Many of the popular time-domain oscillation monitoring algorithms such as Stochastic Subspace Identification (SSI) method [3],[4] for ambient analysis, Matrix Pencil algorithm [5], Hankel Total Least Square (HTLS) [6], and Eigenvalue Realization Algorithm (ERA) [7] for event analysis require the computation of a Singular Value Decomposition (SVD) for extracting the critical modal information from the noisy PMU data. SVD has also been applied in real-time voltage stability analysis of power system using PMU data recently in [8]. In present day implementations of the tools in power industry, SVD computation stands as the major computational bottleneck in implementing these algorithms. The size of the matrix requiring SVD grows linearly with the number of signals being processed in the oscillation monitoring algorithm.

As an example, running each time-step of the SSI algorithm based on the covariance matrix formulation involves computing SVD on a dense matrix of size (300*m) X (300*m), where m is the number of PMU signals being processed, if we assume a PMU sampling rate of 30 samples per second and a moving window size of 10 seconds [9]. As noted above, there are already over 500 PMU measurements being collected in the western power system. For processing say, one signal from each of the 500 PMUs, the size of the matrix becomes 150,000 X 150,000. Computation of the SVD for such a matrix using standard SVD algorithms is clearly infeasible because the computational complexity is $O(N^3)$. In a real-time implementation, the computation has to be completed within the moving window time period of 10 seconds assumed above. This SVD problem is infeasible using a conventional approach because of the memory and speed limitations of current computers. We need fundamentally different formulations and algorithmic methodologies for solving the mathematical challenges in emerging PMU based stability monitoring algorithms. As the number of PMU installations continues to grow, the consequent increase in the size of the matrices is only expected to exacerbate the computational demands.

Fortunately the SVD problem discussed above is not unique to power system applications alone. There is an extensive literature in other science domains such as in image processing and compressed sensing where new algorithms have been developed for computing the SVD of large-scale matrices [10]. However, the characteristics of the stability monitoring algorithms that require the SVD formulation are different from these other application domains. The structure and requirements of the SVD computation in specific algorithms such as SSI and HTLS need to be carefully understood in developing efficient computational methods for solving the large-scale SVD problems in PMU based analysis algorithms.

For instance, in the SSI SVD decomposition above, our interest is mainly in solving a small subset of principal singular values (say 100) of the large-scale matrix. This is because each principal singular value physically points to a dominant oscillation mode in the power system. Even for a large-scale power system, only a handful of the oscillatory modes are expected to get “excited” at any point of time from underlying physics of the power grid. Therefore, the SVD problem can be reduced from the full 150K X

150K matrix into a much smaller matrix (say 100 X 100) while preserving the principal singular values of the large matrix during the reduction using novel algorithms. These algorithms will need to be developed carefully exploiting the algorithmic construction of the matrices that require SVD in the power system area. An additional challenge is to update the singular values and vectors from one time step to another, while utilizing the fact much of the data is unchanged as we step in time. Solutions developed should be capable of harnessing the high performance computing capabilities available from current and future generation supercomputing platforms. Once developed, these new techniques can be broadly applied into other complex systems with similar characteristics involving sensors collecting temporal data.

In the 1970s and 1980s, significant progress was made in power systems by the introduction of sophisticated sparse matrix algorithms in computational tools for power-flow analysis and transient stability simulation. As we move into real-time PMU-based power system analysis tools for emerging power grid applications, we expect that the efficient solution of large-scale SVD problems will be a fundamental building block for efficient real-time algorithms that can handle high-speed measurement data from the large number of PMUs.

As we move forward to processing thousands of PMU measurements in future power systems, there is a need for both the design of new distributed stability monitoring algorithms as well as for efficient solution of big data-related SVD-based solution methodologies.

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