PHASOR MEASUREMENT-BASED STATE ESTIMATION OF ELECTRIC POWER SYSTEMS AND LINEARIZED ANALYSIS OF POWER SYSTEM NETWORK OSCILLATIONS

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ABSTRACT

Large-scale power systems across the world are facing many challenges for continued secure and reliable operation. Recent major system blackouts such as the 2003 Northeastern US blackout are clear indicators that the systems are being pushed to operate under more stringent conditions. Given the increased number of disruptive disturbances in power systems world-wide, and greater challenges for their uninterrupted operation, it has become clear that improved monitoring and control of power networks is needed.

The application of synchronized phasor measurement units (PMUs) for power system monitoring, control, and protection has recently gained great interest in the power industry. Todays PMUs provide GPS time-tagged phasor measurements of positive-sequence voltages and currents, and have been deployed across wide regions of different power networks. As the deployment of PMUs continues to increase, the development of Wide-Area Measurement Systems (WAMS) across many power networks around the world has become feasible. It is envisioned that as these systems mature and there are more PMUs deployed, WAMS will evolve into Wide-Area Monitoring, Control, and Protection Systems with advanced applications based on phasor measurement data.

This dissertation addresses fundamental research on state estimation and power system oscillations, further advancing this vision of wide-area measurement and control systems.

The first part of this dissertation introduces a new approach for synchronized phasor measurement-based state estimation. We investigate a phasor state estimator (PSE) implementation in a power system where a number of PMUs have been installed on high-voltage (HV) substations, although not necessarily on every HV substation. This new PSE will be built on synchronized phasor data only, and its solutions can be used to supplement a conventional state estimator (SE). This approach is attractive because the PSE is built independent of the conventional SE.

The second part of this dissertation deals with power system oscillation analysis. Most studies of power system interarea mode oscillations focus on the analysis of slow coherent groups of synchronous machine angle and speed variables. It has not been clearly defined how the interarea modes of oscillation propagate through the power network. We bridge this gap by studying the oscillations present in the bus voltage and frequency variables which can be measured by PMUs at the high-voltage transmission network. A technique to compute voltage and frequency oscillations is developed for multi-machine power systems. We start from the linearized model with bus voltages and frequencies as output variables. The columns of the output matrix in modal form then become the voltage and frequency oscillations of the interarea modes. Such an analysis offers new understanding on how interarea modes propagate through a power network. In addition, we propose two methods for visualizing oscillations, one using simple projections, and a second one using surface and contour plots.

In the final stage of this dissertation, motivated by the analysis of power system oscillations resulting from a major disturbance in the U.S. Eastern Interconnection, a new understanding of power system oscillations as observed from network variables (such as bus voltage and line current magnitudes and angles) is provided. Using the electromechanical model of multi-machine power systems, an important characteristic of the electromechanical mode shapes is investigated. By performing eigenanalysis it is shown that machine damping produces phase shifts in the eigenvector matrix. The time delays related to these phase shifts show a strong resemblance to those observed in PMU data. Next, a detailed sensitivity analysis of the network variables is performed. Analytical expressions for the network sensitivities are developed and used to determine linear relationships predicting changes in the network variables as a result of small perturbations. This analysis provides a theoretical understanding for the oscillations measured from PMU data. Finally, the network sensitivities and the eigenvectors are used to obtain the modal components in the network variables. This result provides a rationale explaining the phase shifts observed in the modal components of PMU data.