



Toward a Systematic Framework for Deploying Synchrophasors and their Utilization for Improving Performance of Future Electric Energy Systems

Final Project Report

Power Systems Engineering Research Center

*Empowering Minds to Engineer
the Future Electric Energy System*



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Part A, B and C

Final Project Report

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PSERC Publication 12-18

May 2012

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Power Systems Engineering Research Center

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Acknowledgements

This is the final report for the Power Systems Engineering Research Center (PSERC) research project titled “Toward a Systematic Framework for Deploying Synchrophasors and their Utilization for Improving Performance of Future Electric Energy Systems.” We express our appreciation for the support provided by PSERC’s industrial members.

We wish to thank all our industry advisors Lisa Beard (TVA- now Quanta Technology), Floyd Galvan (Entergy), Jim Gronquist (BPA), Paul Myrda (EPRI), Antony Johnson (SCE), Mahendra Patel (PJM), Innocent Kamwa (Hydro-Quebec/IREQ), Kip Morison (BCTC- now BC Hydro), Navin Bhatt (AEP), and Reynaldo Nuqui (ABB). Moreover, the project leader of Part B wishes to thank James Ritchie Carroll at Tennessee Valley Authority (TVA) (now at Grid Protection Alliance) for helping the project team with the prototype implementation testing of the PMU based voltage stability monitor at TVA, also, Farrokh “Frank” Habibi-Ashrafi and Armando Salazar at Southern California Edison (SCE) for collaborating with the WSU project team on subsequent research and prototype implementation work of PMU based substation voltage controller for SCE power system. The project leader of Part C wishes to thank Dr. Jianzhong Tong of PJM and Dr. Jay Giri of Alstom Grid.

Executive Summary

This report is motivated by the major opportunities offered by the deployment of near-real time synchrophasor measurements. For the first time it has become possible to consider wide-area synchronized sensing, communications and use for automated control and protection. These opportunities are presenting the industry and the research community with many open questions, not all of which can be addressed in a single report. In this sense the report provides samples of possible uses of synchrophasors for estimation and control. The ultimate objective is to utilize synchrophasors for improving performance of future electric energy systems.

Part A of this report shows how synchrophasor measurements can be used to close the loop and regulate key, pilot point, voltages in each control area and/or regulate the deviations in tie-line flow exchanges between the control areas. The major contribution is a systematic method for selecting the most effective locations for monitoring voltage deviations to be used for closing the loop and for adjusting set points of generators participating in this regulation. It is stressed that while this control scheme has been in place for a very long time in France, the optimal selection of pilot points has remained an open theoretical problem. In this report we introduce a systematic method for selecting the most effective locations for placing synchrophasors to be managing effects of slow voltage deviations around the forecast reactive power demand.

Part A specifically concerns new design of Automated Voltage Regulation (AVR) and Automated Flow Regulation (AFR), which relies on the use of synchrophasors. This control is also known as the Secondary Voltage Control (SVC) and Pennsylvania Jersey Maryland (PJM) currently uses it by the Electricite de France, and, more recently. Its basic purpose is to regulate in an automated way voltage deviations around their schedules that are caused by the relatively slow voltage deviations. The best way of thinking about it is as the sister-function to the Automatic Generation Control (AGC). Instead of regulating single frequency in each control area, it is intended to regulate several voltages to their scheduled values by adjusting the set points of Automatic Voltage Regulators (AVRs) on several generators participating in this scheme. This scheme is necessary to manage the effects of the increased presence of quasi-stationary disturbances causing deviations in voltages around the values resulting from regular 15-30 minute generation dispatch. In particular, these disturbances are caused by persistent hard-to-predict wind power deviations and by the increasingly responsive demand to real-time electricity prices.

Assuming the dynamics resulted from these disturbances could be stabilized by primary control, reliability problems will still remain in forms of system-wide load voltage deviations and transmission line power flow deviations around their scheduled values. It is, therefore, important to maintain load voltages and transmission line power flows within the pre-specified limits as disturbances around scheduled real/reactive power generation dispatch take place.

The implementation of AVR/SVC for purposes of regulating voltage and flow deviations can be done using measurements provided by the Phasor Measurement Units (PMUs). PMUs could provide accurate and fast sensing of key output variables of interest. We pose the problem of PMU-enabled AVC and AFC as an engineering design problem which for the given number of PMUs computes the best locations of PMUs and the control design gains based on these measurements in order to ensure that the voltage and/or flow deviations remain within the pre-specified limits. We describe in this report how to pose systematically the problems of robust Automated Voltage Control (AVC) and Automated Flow Control (AFC) design based on selecting the best locations for placing the PMUs and the corresponding feedback control gains. The underlying mathematical formulation is the minimization of L_∞ norm representing the measure of the worst-case deviations. Once the problem is posed, a Linear Programming (LP) algorithm is used to find numerical solutions which minimize this objective function; simulations are carried out to show the result of using the LP method. In the latter part of this report, a design of decentralized AVC for very large-scale power systems has also been formulated. This is based on a multi-layered clustering algorithm for decomposing the system into several weakly interconnected reactive power control zones. These zones can be computed once and/or can be dynamically recomputed operating conditions vary. For dynamically clustered approach generally a higher number of PMUs is required. The results are illustrated by simulating potential performance of the proposed designs using an equivalent Northeast Power Coordinating Council 36-bus system. The results indicate that the *N-1* reliability criteria can be met by combining the economic dispatch for scheduling resources given demand forecast, and by relying on an automated feedback to ensure that voltage and line flow deviations remain within the pre-specified limits in between scheduling intervals. This is done without having to know the exact location and magnitude of disturbances.

Part B of this report proposes a synchrophasors-based substation voltage controller. Novel algorithms for direct estimation of QV line sensitivities from real-time streaming PMU data are proposed first. The algorithms are shown to be effective in detecting voltage insecurity scenarios in the power system. Voltage Security Index proposed at each bus is useful to classify voltage strong buses versus voltage weak buses in terms of reactive power support at the bus. Next, initial formulation of a substation voltage controller is proposed. The controller uses QV sensitivity values from Section 2 to carry out local power-flow like calculations to predict expected bus voltage levels after discrete switching actions. The substation controller then coordinates the switching of local VAR devices to manage the discrete VAR devices at the substation towards maintaining voltage schedules for different voltage levels at the substation. Future research is indicated on two-level control formulations that may include central higher-level coordinator and many local substation controllers.

Finally, Part C of this report is concerned with a development of a practical method to identify the external line outages using the data available to internal power system operator in real-time, namely real-time data from internal system as well as measurements from those external buses with PMUs. In an inter-connected power system, state estimator has real-time access to the measurements, and topology of the area under

study, while its real-time knowledge about external system measurements and topology is very limited. One way to have real-time access to external measurements and topology is through phasor measurement units (PMUs).

Errors in external network topology may have significant impact on accuracy of internal state estimation and subsequent real-time contingency analysis (especially contingency analysis). Identification of any type of change in the external network topology will be impossible by using only internal system real-time measurements. However, recent availability of external system synchronized phasor measurements will facilitate identification of certain external topology errors, especially if they are strategically located with respect to the available phasor measurement units. The proposed method is developed and presented in two parts: In the first part the problem of external topology change is formulated using DC power flow assumptions. Once the formulated problem is solved successfully, the method can be extended to the more realistic AC power flow formulation. In the second part, the developed method is extended to the non-linear case of full A.C. solution. In addition to the internal system measurements, few phasor measurements installed in the external system are also assumed to exist in this part. The proposed method utilizes an integer programming method to identify the changes in external system based on real-time data received from internal system along with real-time data from external phasor measurement units. The linear (D.C.) decoupled model of the power system will be used initially to formulate the external network topology-tracking problem and develop its solution method.

It has been important for the proposed method to address all possible conditions in the external system. The proposed method is required to accurately detect an external load change as an external topology change and vice versa. Different possible scenarios which the proposed method would be able to identify can be listed as follows: a) External topology change with constant external operating conditions; b) External operating change with constant external topology; c) Change in neither external topology nor external operating conditions; and, d) Change in both external system operating conditions and external network topology.

The proposed method utilizes an integer programming method to identify the changes in external system based on real-time data received from internal system along with real-time data from external phasor measurement units. The linear (D.C.) decoupled model of the power system will be used initially to formulate the external network topology tracking problem and develop its solution method.

The proposed method's performance is tested using the IEEE 30 bus and 118 bus test systems.