d benefits

# Synchrophasor Technology for Large Power Consumer Network Optimization

Zoran Mihailovic[(1)], Lakshan Piyasinghe[(2)], Lingling Fan[(2)], Zhixin Miao[(2)], Yan Ma[(2)]

[(1)]Jabil Circuit, Inc., St. Petersburg, FL, USA,

[(2)]University of South Florida, Tampa, FL, USA

zoran_mihailovic@jabil.com

Abstract

Synchrophasor technology has been introduced as a research topic back in the mid-eighties of the last century. However, power generation, transportation and distribution (GT&A) community interest in its application in power grid synchronization has been significantly increased after several spectacular, but economically painful, blackouts in the USA during the first decade of the new century. Somewhat simultaneously, emerging renewable energy source technologies, led by wind and solar power harvesting, took a substantial share in electric power generation. The third part of this picture was painted by advances in energy storage and power electronics, including applications such as large data center UPS systems, electric vehicle and industrial battery charging, and vehicle-to-grid power transfer. All of these advances got an essential boost with breakthroughs in new material research, particularly in batteries, super-capacitors, superconductivity, magnetic cores, microprocessor chips and semiconductors. The final part of this picture is communication & control. Fast FPGA-based digital control and Ethernet and wireless communication enable fast execution of complex algorithms and fast data transfer over large distances. Atop of that, GPS technology ensures synchronization of such data in, practically, real time. All of these advances have armored power utility companies with tools to provide and manage more dynamic and efficient power distribution systems than ever before, based on a new, so-called Smart Grid, concept. Syncrophasor technology takes a central part of utilities' SCADA control enhancement. The core of this technology lies in a phasor measurement unit (PMU) due to its measurement data collection, manipulation and transfer capabilities. However, it is only one, power utility side of the equation. The other side is a consumer network. This work is focused on implementing synchrophasor technology into electric demand-response (DR) and intelligent motor control center (IMCC) based power consumption optimization of a large power consumer network with geographically distributed facilities, such as production plants. It will examine a couple of power grid failure pattern scenarios based on known events from a recent past and try to explain how power consumption shifts between geographically remote large power consuming facilities could be used to prevent these failures based on information obtained from PMU network. Another goal is to address control dynamics and stability concerns related to interactions between utility and consumer controls and two separate consumer controls coupled through the grid nodes, and propose an interactive, multi-level control algorithm as a solution. At this stage of the research, the focus is on a simulated network using power grid simulator and some geographically remote low power hardware (up to 5kVA power electronics/motor drive loads) as a proof of system modeling and control design concept. The immediately following step would adjust the same control algorithm to medium remote power level (50kVA-1MVA) loads, simulated using HIL tester. The final step is implementation of the proved concept in a real power system, pending business decisions at that point.

cent US history: 1996 West Coast Blackout WSCC 10 August 1996 [1], [2] and US-Canada Northeast Blackout 14 August 2003 [3] have triggered large-scale root-cause investigation requested by U.S and Canada governments. The results and recommendations from U.S. – Canada Task Force, NERC and other experts have been followed by U.S. Department of Energy (DOE) investments in nationwide electric power grid upgrade research and development, which have spread along both, academia and industry. Synchrophasor technology was recommended as one of promising solutions for real-time signal data collection, especially as it was already present for more than a decade in mostly academic research funded by large utility companies [4], [5].

By reviewing reports about the above-mentioned blackouts, it could be noticed that there were several root-cause commonalities, which could also be noticed in many other worldwide power grid crashes regardless of their proportions. Most observable were: hot summer conditions, human error, misleading system control model due to inaccuracy and obsolescence, tree-top power cable touch-down and reactive energy demand. Power grid failures have been propagating from local transmission line voltage decline in marginally stable power grid sections operating at heavy load of reactive power demanding A/C units, through high-voltage phase-to-ground failures when long-swing power cables touched too high tree-tops causing power oscillations and instability, to cascading large power system disintegration by power line shutdowns, lost synchronicity and subsequent network islanding [1], [2], [3]. Some of these islands have survived and some tripped their safety relays, depending on power and stability of local electric power plant – load interaction.

High temperatures on both blackout dates have caused a high demand of A/C power. This high demand did not exceed the local grid power rating limits, although it was getting close. However, due to the goal of a highly efficient grid based on generation-load balancing, and high reactive energy demand, the grid was operating close to the edge of marginal stability, again, in both cases. Then, another common factor emerged – interaction between heavy swing of power cables and high rise of tree-tops on the cable right-of-passage leading to phase-to-ground failure. Yet another common factor led to an ultimate disaster in both cases – power grid models in control centers did not show a chain of events accurately, which caused operator to miss crucial time periods to apply standard preventive procedures. In both cases, there was enough time to react when the disturbance was still local. In both cases, however, an avalanche of cascading wide area power grid failures was much faster when they could not be controlled.

Model errors have been recognized and addressed by modeling standards and recommendations from Bonneville PA [6], NERC [7] and NASPI [8], presented on numerous workshops and conferences. Well-known WSCC system model failure to capture a large power instability transient is given in Figure 1.

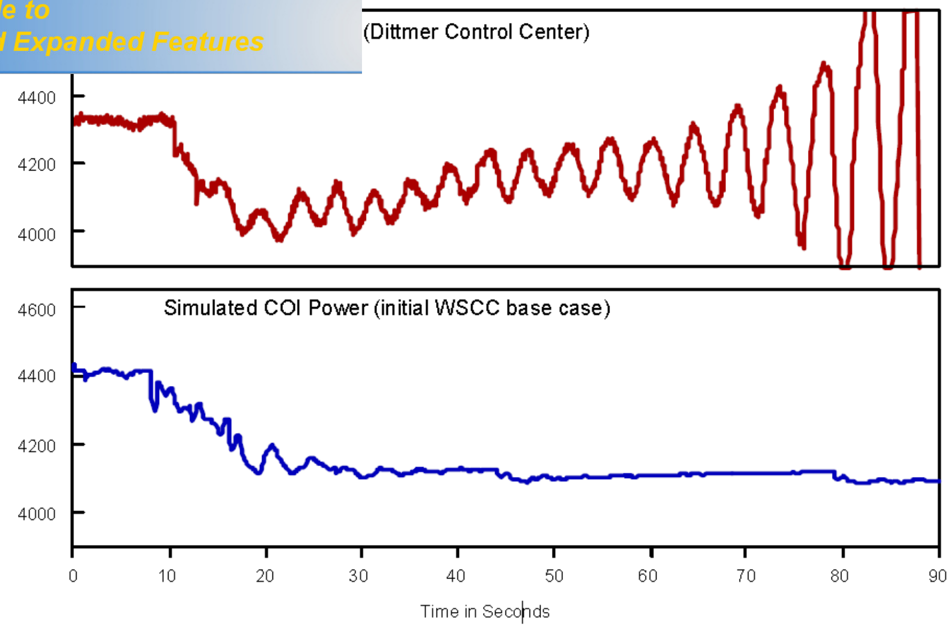


Figure 1: Comparison of observed system response during August 10, 1996 disturbance with response using models in use at that time, extracted from [7]

A key point is that all power grid models should be validated against real measurement on system and component levels and any such validated model should be updated and revalidated when any architecture change occurs in the real system.

Power oscillations can be categorized into three types: local mode, inter-area mode and global mode [9]. Local oscillations belong to a higher frequency range while inter-area and global oscillations are in the lower part of the frequency range (1 Hz and below). Local mode consists of the oscillations of a single generator or a group of generators against the rest of the system while the inter-area and global modes consist of oscillations among a group of generators. These low frequency oscillations can affect the power transfer capability and the stability of a power system.

Common practice in an effort to stabilize the power grid in such situations is to apply load shedding by preventively turning the power off to selected load blocks [10]. Besides, many large electric energy consumers disconnect their facilities for safety reasons when power line voltage drops below under-voltage protection threshold (voltage droop control). However, in both of the above blackouts, these interventions didn't help – load shedding and safety disconnects have happened too late to prevent uncontrollable instability swing. Several methods have been proposed for inter-area oscillation damping and some of them have been applied in recent years. Among most popular solutions are applications of power system stabilizers (PSS) [11], with or without remote power control (RPC) using phasor measurement units (PMU) [12], [13].

Although standard automatic voltage regulators (AVRs) will improve the power system steady state stability, the AVR is unable to provide support to the system stability during transient conditions. Adding PSS into the AVR control will improve the damping of local oscillation modes of the system during transients. A general structure diagram of a typical PSS is shown in Figure 2. PSS receives synchronized phasor measurements from PMUs located in remote areas. PSS uses both local and remote PMU measurements throughout the power network as the inputs of the control loops to damp the inter-area oscillations.

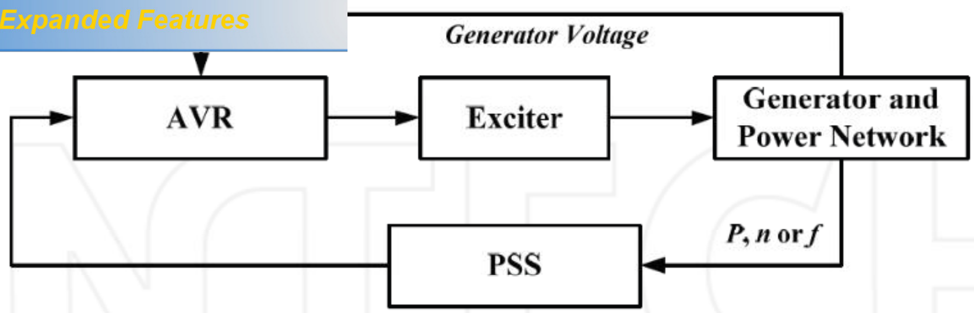


Figure 2: Structure diagram of a PSS

**Motivation**

It should be noticed that the above-mentioned solutions target utility companies offering various improvements in their SCADA control system [14]. Here proposed solution intends to bring an idea of expansion of these methods to large power consumer network of loads, offering consumers an opportunity to contribute with automated load control based on inputs from PMU data. In addition, this method could provide a control tool to local Smart Grid distributers to control and dynamically manage both, energy consumption and generation from renewable power sources, including forced local power grid islanding in an unprecedentedly short disturbance reaction time and response efficiency.

Existing and ever expanding control of industrial SCADA systems are analogous to power grid SCADA control - it addresses system situational awareness, power consumption optimization, load shedding, voltage droop control, etc. Decision about centralized and distributed control centers is generally based on demand response (DR) strategy in large industrial systems [15], [16]. Atop of it, renewable energy sources have brought new bi-directional dynamics to the power grid systems that require power electronics application to smooth down the transients and keep power flow steady regardless direction it is supposed to take [17]. These power electronics applications shrink the border line between electric power generation and consumption even further, as it is located close to the 13kV/240V power distribution transformers on the low voltage, consumer side. On the other side, renewable energy sources need power electronics to balance generation-load ratio between the sources and power grid, as a consumer. This further justifies the application of multiple PMU measurements to provide power grid data to power electronics unit control optimization. Today, power utility companies and power consumers work separately on power consumption control, each following its own technical and economical requirements. However, the overall system technical and economical requirements in new smart grid environment will push them to work closely together. Sharing PMU information and use it to optimize and protect the electric power grid would be a step in the right direction.

**Simulation Modeling and Analysis**

A major power system failure occurred in the Western systems Coordinating Council (WSCC) system on August 10$^{th}$ in 1996 creating 4 islanded systems within the WSCC system. 7.49 millions of customers were affected due to lose 30,390 MW of loads [1], [2], [6]. The failure occurred due to a number of cascaded events. Initially a 500 KV line sagged close to a tree and flashed over the resulting line to trip. Five minutes later, another line was tripped, in the same time sequential tripping of 13 generators stared tarted the system power and voltage oscillations causing the ransient of this system and preventive control is used as the case study in this work.

Two-area system, presented in [12] and shown in **Error! Reference source not found.**, is chosen to study similar scenarios in a scaled down system. The system consist of two areas connected by a weak tie line consist of two parallel transmission lines. Each area is equipped with two generators, each with 900 MVA and 20 KV ratings. Loads are connected in a way that Area 1 is exporting 413 MW to the Area 2. Three electro mechanical modes can be identified in the system: an inter-area mode with 0.64 Hz frequency and two local oscillation modes with 1.12 Hz and 1.16 Hz frequency values.

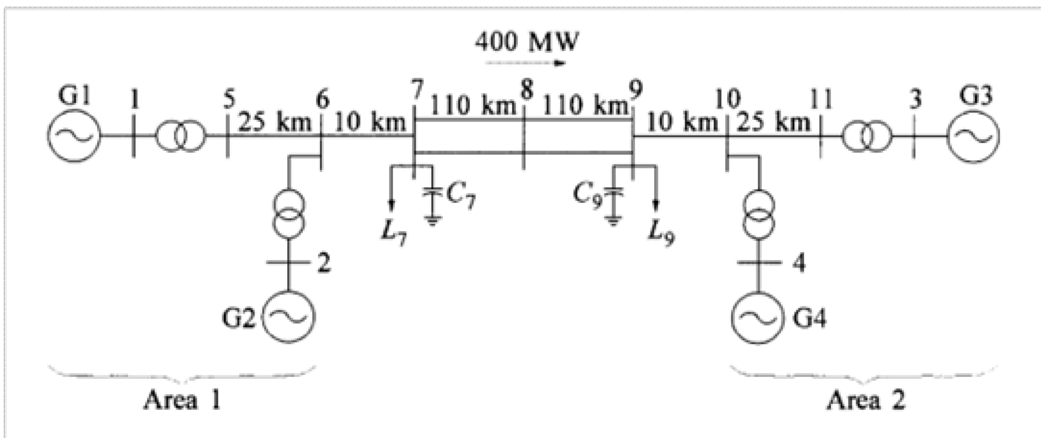


Figure 3: Test System, extracted from [12]

Matlab/Simulink SimpowerSystem model of this power grid segment is presented in Figure 4. It can simulate five control cases: traditional power generator control without PSS, local power system stabilyzer (PSS) control, remote feedback control (RFC), multi-band RFC control and remote feedback load control (RFLC) with load shedding.

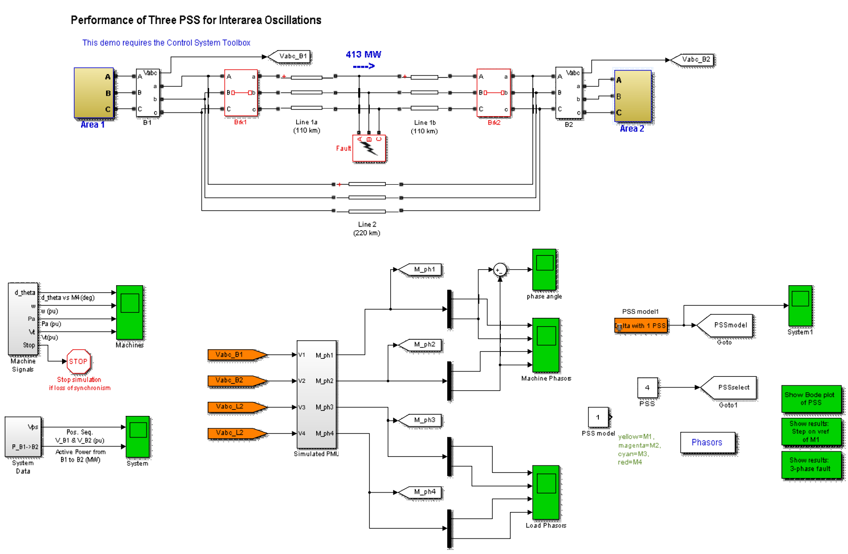


Figure 4: Simulink SimPowerSystem Model of the Test System

s have not been modeled at this point. The loads have been chical blocks. **Error! Reference source not found.** shows the Area 2 generator, controller and load arrangements of the system. Switchable load is used for load shedding simulation.

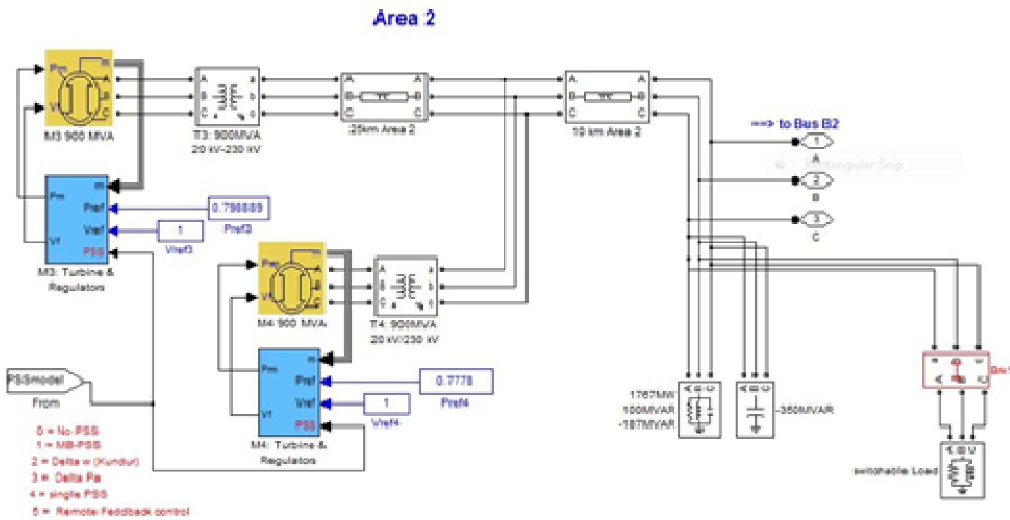


Figure 5: Area 2 subsystem with switchable loads

A three-phase to ground fault (in one of the tie lines) transient have been simulated after one second pre-fault steady-state operation. In Case 1, the system is simulated without any PSS. In Case 2, inbuilt PSS controllers are used to improve the damping of the system. In Case 3, system is simulated with using only one PSS at selected Generator. In Case 4, the system is simulated with adopted remote feedback controllers. In Case 5, the system includes load shedding analysis. The model has been validated by comparison between its Case 1 power failure transient simulation and real data capture of WSCC August 1996 disturbance, Figure 1. Power generation loss in Area 1 of the test system was simulated at 10s, and the tie line power was measured. **Error! Reference source not found.** shows simulation results for comparison with real data from WSCC August 1996 power system failure.

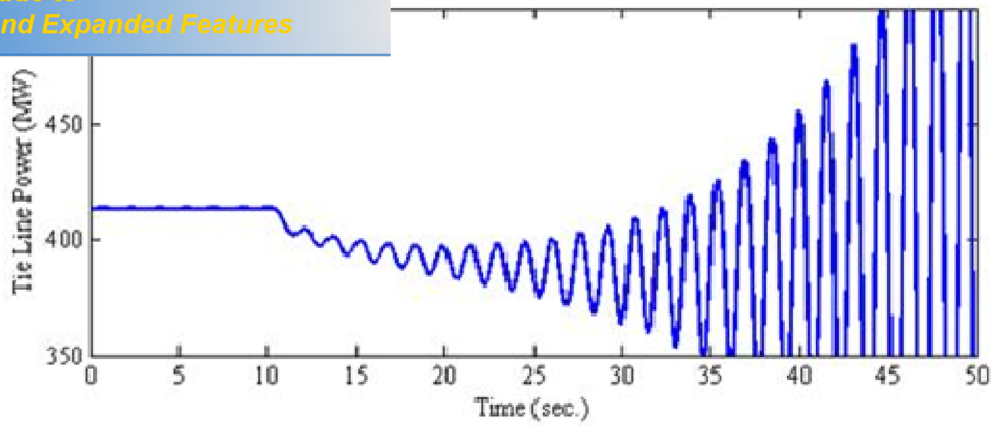


Figure 6: Simulated Case 1 - no PSS

Even thought the test system power is scaled down about 10 times, the results show similar inter-area oscillating behavior in the tie line power, nevertheless the inter-area oscillation frequency of the test system is 0.64 Hz, while the actual WSCC system frequency mode is approximately 0.27 Hz [6].

**Stability Improvement with PMU Data (Utility side)**

Although having PSS for each machine provides better stability for the system, it will increase the complexity of the system control and the cost of implementation. A more economical solution would be to achieve the stability of the system only one PSS. Case 3 simulates such control configuration. Figure 7 shows the tie line power of the system with only 1 PSS activated at a time.

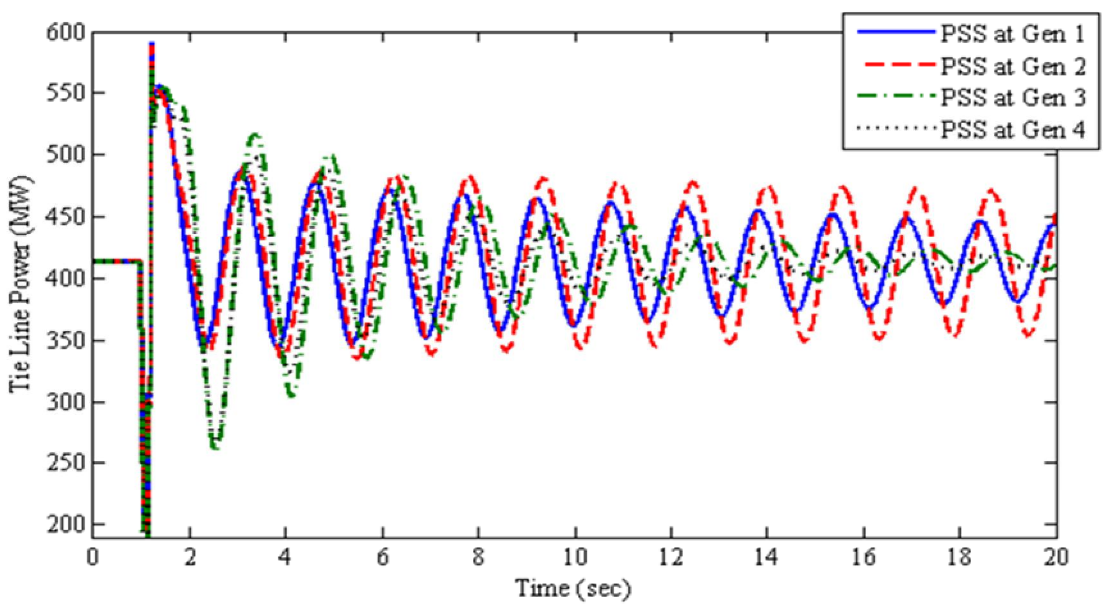


Figure 7: The tie line power of the system with a single PSS installed

amping for the inter-area oscillations so that it is the optimal

Case 4 remote feedback controller (RFC) has been modeled according to controller design from [12], Figure 8. It can be utilized to overcome the above inter-area oscillation transient issue. A local machine is selected in Area 2 and the remote machine is selected in Area 1 to compensate the inter-area oscillations. Synchronized phasor measurements using PMU at generators G1 and G3 have been used to calculate electrical power of each machine in synchronized time. The division of electric power from the mechanical power of each machine is fed to the remote feedback controller. The output of the controller is fed to the Generator 3 AVR.

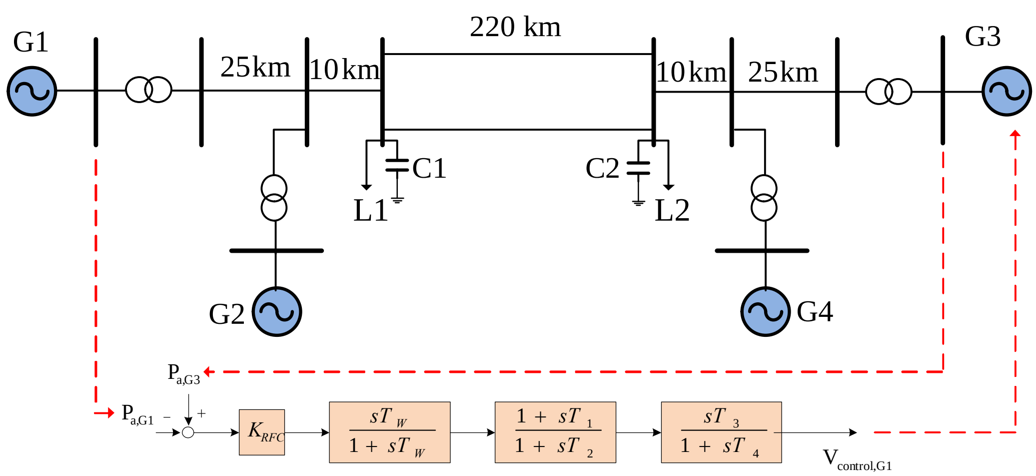


Figure 8: Test system with the remote feedback controller

Figure 9 shows the tie line power oscillations are well damped with the remote feedback controller.

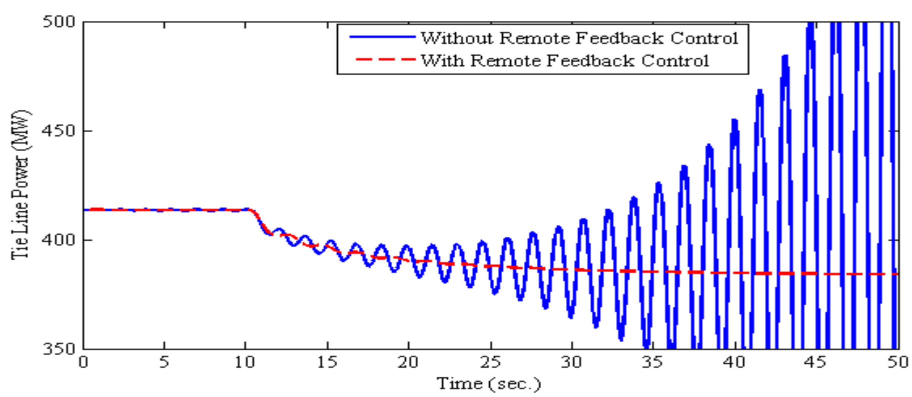


Figure 9: The tie Line power of the system without a controller vs remote feedback control at Gen 3

Comparison between single PSS system and RFC retrieves faster oscillation damping, Figure 10.

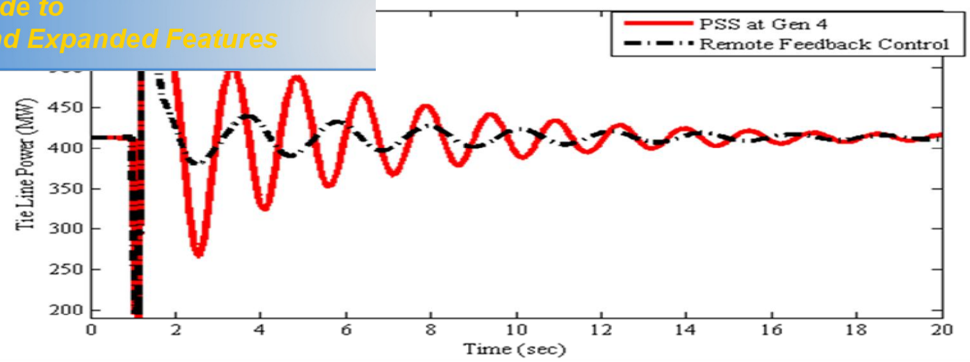


Figure 10: The tie line power of the system with a single PSS at generator G4 vs. Remote feedback control at generator G3

**<u>Stability Improvement with PMU Data (customer side)</u>**

In order to show importance of load shedding, , Case 5, another transient scenario was simulated with a tie line trip of the test system. A 3 phase to ground fault in one of the tie lines is simulated after 10 seconds of steady-state. The breakers were activated after 8 cycles and the line was kept open afterwards. Figure 6 shows the tie line power with different operational scenarios. It can be seen that the system will go unstable even with remote feedback control. However the results show the load shedding from the customer side can significantly improve the system stability. The customer can use PMU data to detect the fault condition and start load shedding to increase the damping of the system.

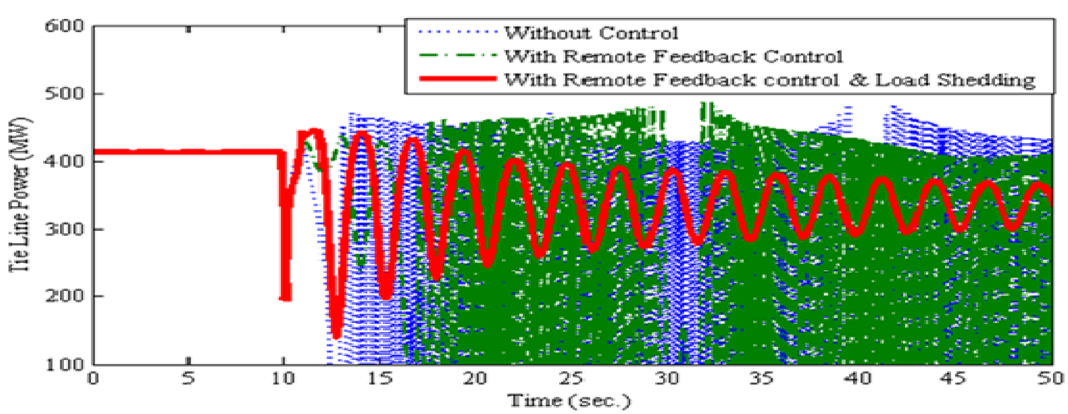


Figure 11: Line trip after 10 seconds with and without load shedding

Different percentages of Area 2 load have been shed one second after the failure to see the effect to system damping. Expectedly, system damping improves with the higher percentage of load shedding. However, higher shedding leads the customer to face more losses. Hence the proper mechanism has to be implemented to obtain the optimal value. As a case providing a reasonable damping, 10% load shedding was selected for the remaining case studies presented here.

ing of the load shedding. It can be seen a slight improvement edding. However, the system won't be able to keep its stability with longer delays of load shedding. In this case, load shedding after seven seconds was too late.

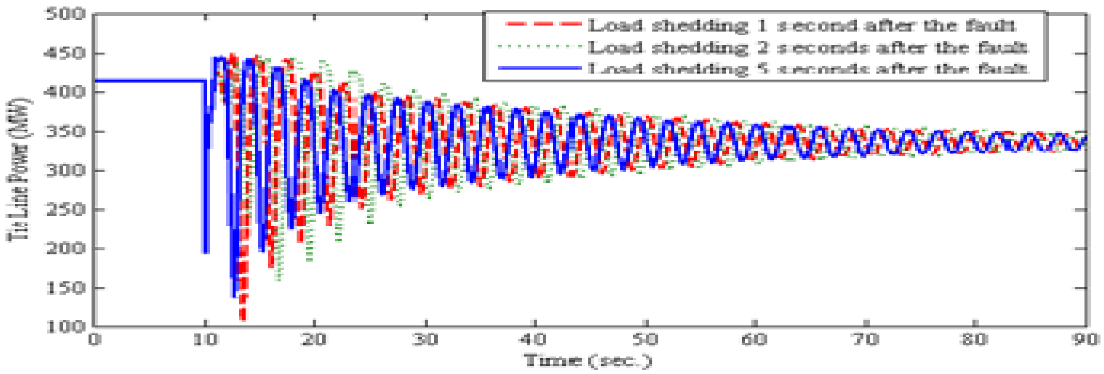


Figure 12: Tie Line power with load shedding with different delays

**Large industrial remote feedback load control (RFLC)**

Demand response is a part of the electric demand-side management (DSM) and it is focused on demand reduction or shifting in order to optimize power consumption with existing resources and slow down demand for building new power generation units [15]. Contrary to residential and commercial power loads, industrial load shedding is more complex due to various specific parameters such as production, operation/resource and inventory constraints, and maintenance schedules. Large industrial facilities already apply SCADA control systems to distribute loads and operation of various system units, from industrial motor drives [16] to production lines [15] and renewable energy sources [17]. Due to specific operating requirements, it is not possible to optimize power grid operation with such dynamic systems without letting these consumers to be involved in its dynamics control.

The main idea how to accomplish such unprecedented utility-industry coordination task is to use synchrophasor technology to send PMU data not only to power generation and transportation control centers, but also to interested consumers. Dynamics of power grid and consumer load control loops have to be tightly controlled to avoid eventual oscillations due to mismatched controls. Extension of the RFC control to active load control should be this gluing factor between two control systems. The test system model from Figure 4 shows PMU I/O signal extensions to power load phasors in both, Area 1 and Area 2. Load control using power electronics unit, Figure 13, brings flexibility for load shaping. It should be noted that a single high voltage high power AC/DC/AC PE unit at the grid edge represents many down-steam power electronics (PE) units controlled by control signal PE_ctr.

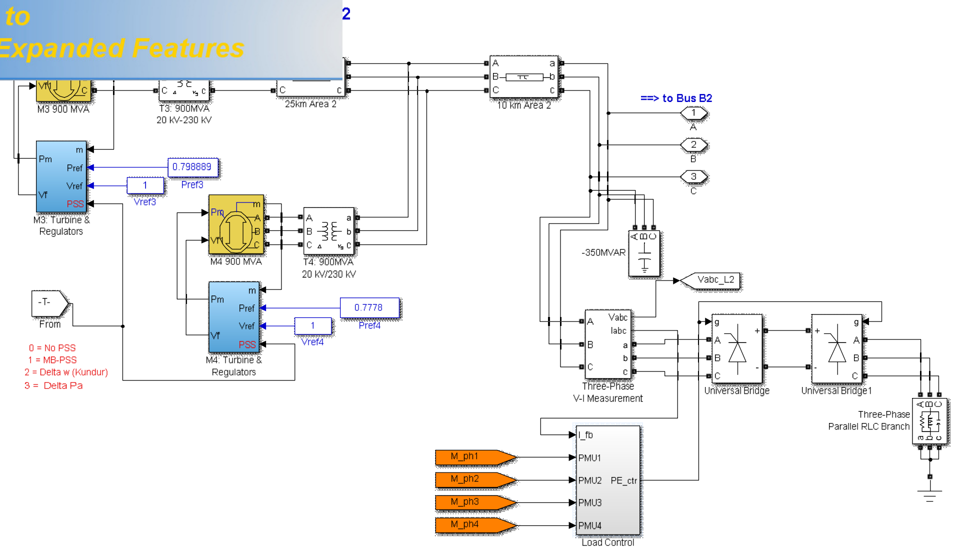


Figure 13: Area 2 remote feedback load control

Architecture of the Load Control unit is shown in Figure 14. Control principle is to apply external PMU data dependant loops to regular current, power and voltage feedback control loops. It was shown previously that there is enough time and information to act preventively to any power grid disturbance using load shedding with RFC, based on timely PMU measurement information. This is not classical relay on/off type load shedding, but rather dynamic feed-forward-type control with time constants much larger than the ones of the internal feedback loops, but still small enough to allow efficient load control for power grid stability. Power grid utility companies still have the final say about the ultimate load shedding decision. However, they should still keep this window of opportunity for a soft load shedding by consumers as an inner control loop as a preventive action for the large scale system failure.

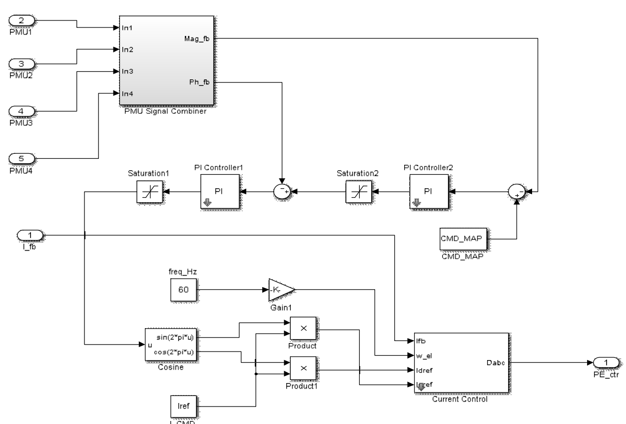


Figure 14: RFLC load controller architecture

Received PMU phasor signals are inputs to the PMU signal combiner, which output is compared to preset command map. PMU signal combiner could be as simple as phasor data concentrator (PDC) data stream organizer or specific data manipulator for given power load. In any case, the output should correspond to the command map. Command map should be a combination of calculated/expected PMU signals for safe power grid operation at the segment from which the PMU phasor signals have been collected. It includes

s two different, but interrelated feed-forward signals, which
uter loop to each other.

**Conclusion**

The goal of this R&D effort is to define the opportunity and describe the basis for dynamic load control for power grid stability and optimization. A simulation model used for this analysis has been validated against the WSCC August 1996 disturbance by showing similar behavior after three-phase to ground short circuit failure. Several control algorithms, such as PSS and RFC have proved to be efficient in power oscillation damping. However, the ultimate oscillation damping method was still power load shedding. With the emergence of smart grids and application of SCADA and other centralized and distributed control systems in the industry, it seems natural that power grid control and consumers' load control could synchronize into an efficient, large scale electric power optimization system. Developed and here presented simulation model is only a lump model representation of the larger power grid RT-Lab model. PMU dynamics and transportation latency delays have also been neglected in this study. The next step is to integrate a system of several remote PMU hardware units, establish communication with RT Lab power grid simulator (approx. 300 nodes) using a small PDC network using OpenPDC software and following IEEE C37.118 and/or IEC 61850- 90-5 standards, simulate a control center PMU-based decision making, and communicate back the commands to load relay controllers. Another RT Lab simulator would serve as a power load network simulator and the same path would be established for the load soft control by using power electronics controls. Finally, the two systems would merge following the principles which basis has been presented in this technical paper.

References


[1] NERC: "1996 System Disturbances," North American Electric Reliability Council, Princeton, NJ, August 2002

[2] Vaithianathan (Mani) Venkatasubramanian and Yuan Li: "Analysis of 1996 Western American Electric Blackouts," Bulk Power System Dynamics and Control – VI, Cortina d'Ampezzo, Italy, August 2004, pp. 685-721

[3] NERC Steering Group: "Technical Analysis of the August 14, 2003, Blackout: What Happened, Why, and What Did We Learn?" Report to the NERC Board of Trustees, July 13, 2004

[4] A. G. Phadke: "Synchronized Phasor Measurements - A Historical Overview," Virginia Tech, Blacksburg VA, Transmission and Distribution Conference and Exhibition 2002: Asia Pacific. IEEE/PES, Volume:1, October 2002, pp. 470-479

[5] Jaime De La Ree, Virgilio Centeno, James S. Thorp and A. G. Phadke: "Synchronized Phasor Measurement Applications in Power Systems," IEEE Transactions On Smart Grid, Vol. 1, No. 1, June 2010, pp. 20-27

[6] Dmitry N. Kosterev, Carson W. Taylor, William A. Mittelstadt: "Model Validation for the August 10, 1996 WSCC System Outage," IEEE Transactions On Power Systems, Vol. 14, No. 3, August 1999, pp. 967-979

[7] NERC Model Validation Task Force of the Transmission Issues Subcommittee: "Power System Model Validation," North American Electric Reliability Council, Princeton, NJ, December 2010

Initiative: “Model Validation Using Synchrophasors Technical Reinvestment Act of 2009, NASPI Model Validation Technical Workshop, October 22, 2010

[9] Kundur, Prabha: “*Power system stability and control,*” Eds. Neal J. Balu, and Mark G. Lauby. Vol. 7. New York: McGraw-hill, 1994.

[10] C. Mozina: “Undervoltage Load Shedding,” Power Systems Conference: Advanced Metering, Protection, Control, Communication, And Distributed Resources, Clemson, NC, March 13-16, 2007, PSC 2007, pp. 39-54

[11] Fang Liu, Ryuichi Yokoyama, Yicheng Zhou, Min Wu: “Study of Oscillation Damping Effects of Power System Stabilizer with Eigenvalue Analysis Method for the Stability of Power Systems,” Modeling, Simulation and Identification ed. By Azah Mohamed, Sciyo, Chapter 4, Aug. 2010 (www.Intechopen.com)

[12] Aaron F. Snyder, Nouredine Hadjsaid, Didier Georges, Lamine Mili, Arun G. Phadke, Olivier Fawon, Sylvain Wet: “Inter-Area Oscillation Damping with Power System Stabilizers and Synchronized Phasor Measurements,” Power System Technology Proceedings, POWERCON’98, Beijing, China, Vol. 2, August 1998, pp. 790-794

[13] Yang Zhang and Anjan Bose: “Design of Wide-Area Damping Controllers for Interarea Oscillations,” IEEE Transactions On Power Systems, Vol. 23, No. 3, August 2008, pp.1136-1143

[14] Mark Adamiak, Rich Hunt: “Application of Phasor Measurement Units for Disturbance Recording,” GE Multilin, Protection & Control Journal, 8th Edition, Spring 2009, pp. 7-13

[15] Salman Mohagheghi and Neda Raji: “Dynamic Demand Response,” IEEE Industry Applications Magazine, Vol. 21, No. 2, March/April 2015, pp. 54-62

[16] David C. Mazur, John A. Kay and Kenneth D. Mazur: “Intelligent Motor Control,” IEEE Industry Applications Magazine, Vol. 21, No. 2, March/April 2015, pp. 30-37

[17] Deepak Divan, Rohit Moghe and Anish Prasai: “Power Electronics at the Grid Edge,” IEEE Power Electronics Magazine, Vol. 1, No. 4, December 2014, pp. 16-22