Considerations for the Application of Synchrophasors to Predict Voltage Instability

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Considerations for the Application of Synchrophasors to Predict Voltage Instability

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***Abstract*—Growth in electric load, without a corresponding growth in service infrastructure, results in systems operating closer to voltage and frequency instability. While rotor angle stability, or real power stability, can be determined by balancing load and generation, until recent advances in technology, it was difficult to quantify or predict voltage stability. It is well known that fixed and switched shunt capacitors increase the amount of power that can be transferred into a system, but at the same time, this shunt compensation brings the nominal operating voltage closer to the point of voltage instability.**

Synchronized phasor measurements (synchrophasors) are a new technology that provides a tool for system operators and planners to measure the state of the electrical system. Synchrophasors measure voltages and currents, at diverse locations on a power grid, and can output accurately time-stamped voltage and current phasors. Because these phasors are truly synchronized, synchronized comparison of two quantities is possible, in time. These comparisons can be used to assess system conditions.

Implementing a synchrophasor system involves a number of discrete stages. Implementation may involve using phasor measurement and control units (PMCUs) at locations suitable to provide the desired inputs to predictive algorithms, then establishing communication from those sites to a central location for data processing. At the central location, the data from the different locations must be correlated, displayed, and recorded.

This paper discusses the completion of these steps for a unique R&D demonstration project installed by Long Island Power Authority. Long Island Power Authority will use data collected from this project to determine future steps to continue work to improve system reliability by testing a predictive model to preempt steady-state voltage collapse. We discuss concerns, trade-offs made, lessons learned during installation, and initial operation of the system.

I. Introduction

The Long Island Power Authority (LIPA) electrical system has strong connections on the southwest end of the system, the New York City end of the island. Moving away from the west end, there are less interconnections and less available generation. Further complicating matters, from a load management standpoint, the system is compensated with fixed and switched shunt capacitors, leading to a virtually flat voltage profile. A general graph of voltage vs. load is in Fig. 1. LIPA system is unique in the respect that unusually high transmission shunt correction is applied to the system to improve the voltage profile during the peak load conditions.

The key point of the graph in Fig. 1 is that voltage, by itself, gives virtually no warning of an impending system voltage collapse. Switching of shunt capacitors as load increases can have the tendency to raise the voltage and increase the amount of power that can be transmitted. This decreases the system security margin, as shown in Fig. 2.

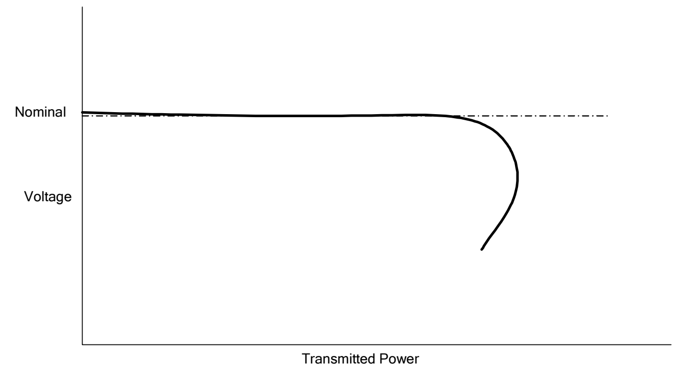

Fig. 1. Typical Voltage Profile With Increasing Load

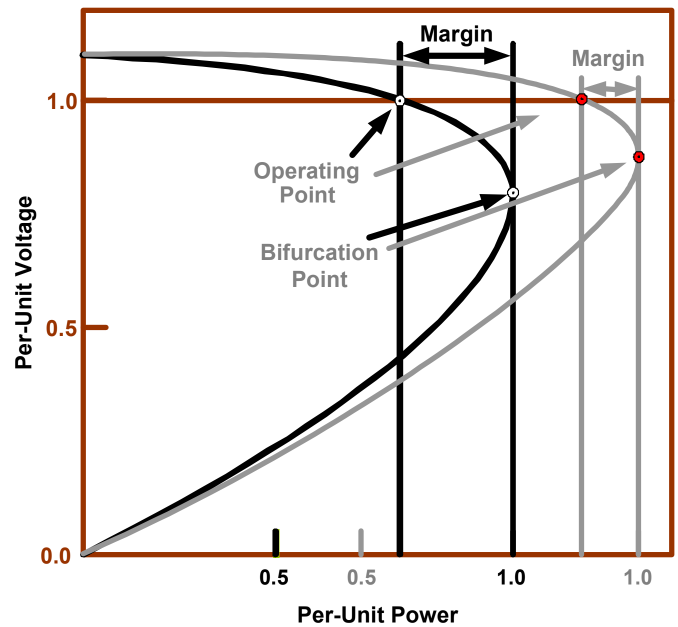

Fig. 2. Decreased Operating Margin With Increased Shunt Capacitance

How the operating characteristic moves from one curve to the other is illustrated using a two-bus system, such as Fig. 3 below:

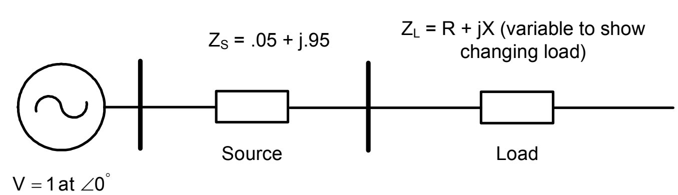

Fig. 3. Two-Bus System for Calculating Voltage and Power

By plotting the varying load as a function of voltage, we can see that a fixed capacitance will increase the load-carrying capacity of the system.

Comparing the voltage/power profile for two different systems, one with no shunt compensation and one with 75 percent shunt compensation, we can see the following two graphs (Fig. 4 and Fig. 5):

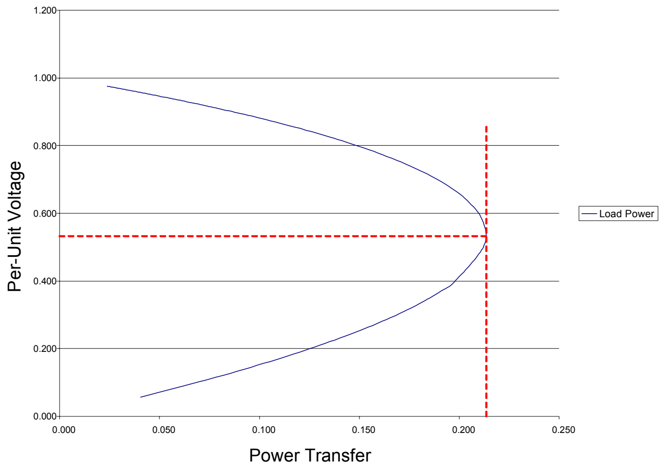

Fig. 4. Voltage Power Profile With No Compensation

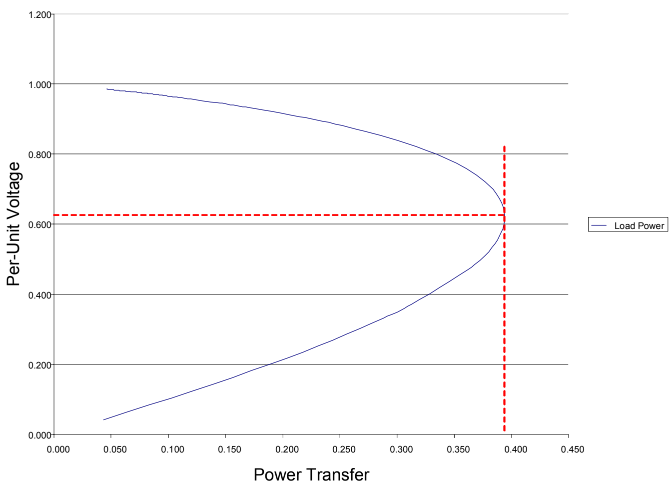

Fig. 5. Voltage Power Profile With 75 Percent Compensation

Notice that the curve has the same general shape, but that the load transfer is almost double, and the point of voltage collapse has moved from 50 percent to 60 percent peak voltage.

The system can be modeled with voltage and power calculations made to predict how close the point of voltage collapse is to the operating point. One problem with this approach is that it is very difficult, or impossible, to know how many shunt capacitors are in service at a given time. Even if there is precise application of voltage controls on the capacitors, there can be no certainty that the capacitor control switch will function, or that the capacitor will have an intact fuse. Anecdotal evidence suggests that typical systems may have as many as 50 percent of distribution shunt capacitors out of service when controls or models indicate they should be active.

The method used for capacitor bank control may also make system models difficult to apply. Depending on the practices of a particular utility, capacitor banks can be controlled using voltage, Var loading of the distribution line, time of day, temperature, or other quantity. In order to have the type of rising voltage profile seen in Fig. 1, there must be a leading power factor on at least some section of the distribution system.

Transmitted power in an inductive system can be characterized by the equation:

$$P = \frac{V1 \bullet V2 \sin \delta}{X}$$

Where V1 and V2 are the system voltages at the sending and receiving ends respectively, δ is the phase angle separation between the two different voltages, and X is the system impedance between the two points measured. This ongoing LIPA R&D demonstration project is attempting to determine those measured values that indicate impending system voltage collapse.

Measuring the phase angle across a system, in this case Long Island, can provide an indication of the total power transmitted. Of course, changes in the system configuration will change the impedance, which would change the phase angle for the same power transmitted. Eventual analysis of the collected data will require knowledge of the system configuration for correlation with the phase angle data. For a simplistic application of how this information could be used, consider the two-bus system of Fig. 3. If the load impedance were unknown, it could be determined by knowing the exact magnitude and phase angle of the voltage at the source and the load bus.

One approach to using synchrophasor information in just this fashion is described in [2]. By simplifying a radial system similar to that shown in Fig. 6, the Equation (1) solves for the maximum power transfer (combined real and reactive) from the source to the load, with θ = load power angle measured simultaneously with V_s measured at the source. (This equation assumes X is very large compared to R so that resistance can be neglected).

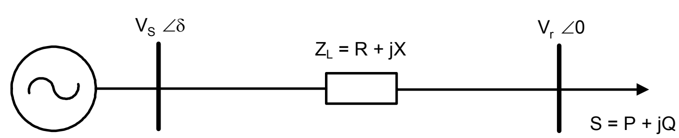

Fig. 6 A Simple Power System

$$S_{max} = \frac{\left(1 - \sin(\theta)\right) V_s^{\,2}}{2\cos(\theta)^2 X} \tag{1}$$

The value of synchrophasors is even more strongly demonstrated by considering that if the system impedance is known between the source and the load, then the power factor of the load can be determined by measuring the voltage magnitude and angle at both the load and source locations.

II. Measurement Locations

Two sites were selected for measuring phase angle. While the phasor measurement and control units (PMCUs) selected can measure both voltage and current, in the initial stage of the installation, only voltage is being measured. Transmitting only the positive-sequence voltage phase angle keeps the bandwidth of the communications system to a minimum. In an approximation of the simple two-bus system of Fig. 3, the sites of the phasor measurements to be taken were selected at East Garden City station and Buell station.

East Garden City is a 138 kV station that is close to the major ties between Long Island and the main Eastern Interconnection. Buell station is two buses removed from East Garden City on the 23 kV distribution network, as shown in Fig. 7.

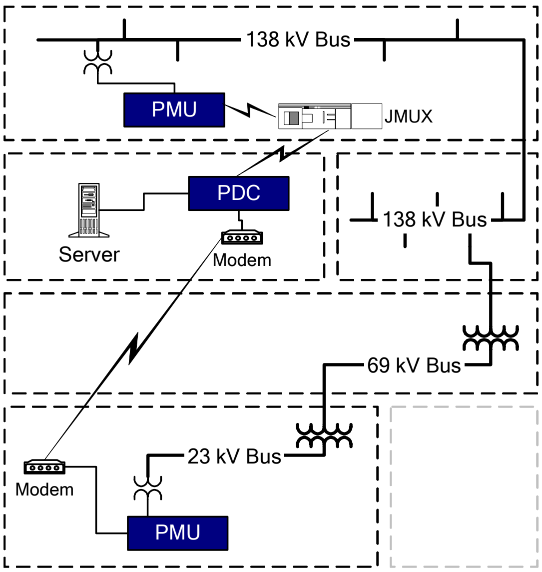

Fig. 7. Synchrophasor System: 138 kV at East Garden City, Phasor Data Concentrator at Hicksville Headquarters, 23 kV at Buell Substation

Fig. 8. Relay Providing Phasor Measurements

Even though one of the PMCU systems was communicating over a phone line and one PMCU was communicating over a multiplexer, both of the PMCU cabinets included an identical system of clock, relay/PMCU, test plug, and modem. The modem was not necessary at East Garden City station, but in order to keep both units the same and to make them more portable if it was determined that a different location was needed, we included the modem at both sites.

While this system is more complex than the simple two-bus system in Fig. 3, if you consider the 138 kV substation to be at the source and the 23 kV system to be in front of the load, it can be argued that, in effect, this is similar to the simple system.

III. Communications

From East Garden City station, there was an existing communications network via an in-house SONET ring with a multiplexer at each end. A low-speed data card was added at each location for the synchrophasor system. This inexpensive addition was adequate because the relay acting as a PMU efficiently passed the phasor measurements using a maximum 57.6 k baud rate. A picture of the back of the multiplexer at the Hicksville headquarters is in Fig. 9.

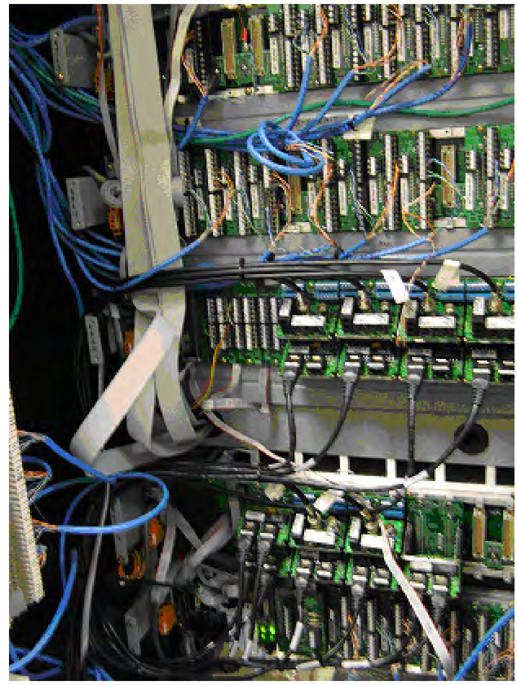

Fig. 9. Multiplexer Wiring at Hicksville

Fig. 9 illustrates the care that must be taken when wiring to existing multiplexer circuits. As it turned out, there was a reversal of the communication wires from the relay and the phasor data concentrator to the multiplexer. This was not a particularly difficult problem to troubleshoot and overcome, but if the sites had been more remote, it would have been a more time-consuming problem.

The communication with Buell station was slightly more complicated because broadband communications were not available. A station phone line with a modem was used for the initial installation, with a dedicated leased line added later. The phone line had a nominal capacity of 38.4 kbps. However, we found it to be more reliable at a lower rate. With only a single voltage signal being transmitted, even with the additional overhead of IEEE PC37.118 protocol, this lower baud rate had plenty of capacity for 20 synchronized phasor measurement messages per second. Cost was a major factor in using a standard phone line at Buell. The performance of the phone line has been very good, with less than one dropped connection per month of service so far.

IV. Data Collection and Server

Data from the two stations were brought into the main computer room at the LIPA control center. For the initial installation, the phasor data concentrator was housed in a small cabinet with a phone modem and cabling.

Fig. 10. Phasor Data Concentrator Cabinet in Temporary Location

The keyboard and screen are not required while the system is performing data collection. They are essential for setup and troubleshooting. The telephone on top of the cabinet is very useful for talking to a technician at the other end of whichever communications circuit is being initialized.

The hardened computer shown in Fig. 10 concentrates the data packets from the two relays, then it sends the data to a server system with archiving capability.

Fig. 11. Data Server and Archiver

The data server provides the display software and secure archiving of the synchrophasor data. With only two PMCU locations and only the voltage being recorded, the data requirements are not extensive [1]. The hardware was chosen to support data storage requirements as they grow with time. The server has dual drives for data storage, with "hot swap" capability to avoid loss of data. The program running on the server provides visualization of data as well as storage.

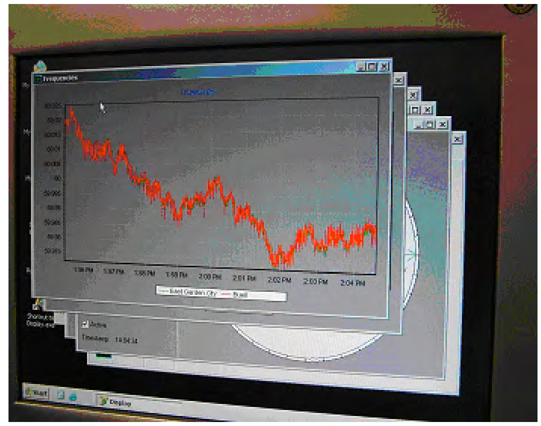

Fig. 12. Screen Capture of Frequency Trending With Vector Display Screens in Additional "Windows"

The server provides the ability to "deliver" the visualization screens to several different users. At this point, the data are for analysis. State estimation can be a great potential application for LIPA, provided sufficient PMU sources are introduced.

V. Concerns and Lessons Learned

From the experience of installing the synchrophasor equipment, we have successfully addressed a number of minor concerns and gained valuable knowledge of how to avoid these startup issues. It has been important for all parties to work together to assure that measurement needs are being met. This is particularly challenging with an R&D demonstration project, as we try to leverage cost and performance measurement criteria.

The most difficult and time-consuming part of the process was setting up the communications. This demonstrated the importance of working early with the various communications groups and those who do the actual installation. Double-checking of communication wiring connections prevented signal losses. Instead of connecting wires to the various cabinets, even in advance, it would have been faster to install plugs and internal wires. This could have reduced faulty connections. We adjusted communications baud rates to meet the capabilities of the actual lines, but this did not reduce the message rate.

Once the phasor data concentrator received the data and sent them to the server, the issue of security needed to be resolved. Because we used a "dialup" line to receive data from one of the PMCUs, we could not connect the server to the corporate network. The phasor data concentrator has the capability of sending data through a firewall, but details of the firewall configuration still needed to be determined in order to distribute the data in real time to multiple users, one of the goals of the project.

Because the phasor data concentrator is in a secure location, in the utility's computer operations center, physical access to the equipment is time consuming. This problem is compounded by the firewall concern referenced above. Currently, in the early stages of the project, someone needs to physically access the equipment to make a change, view a trend screen, or reference data. Once network access is available, updates and data collection could be made from any location on the utility network.

VI. Conclusions

1. Synchrophasor information is readily available and straightforward to acquire. A small system can be installed without large capital or engineering outlays. Future growth can occur in an incremental fashion as needs are identified.
2. Accommodation of different types of communications should be built into a synchrophasor system from the ground up. Because the optimal locations for synchrophasor data might not be where broadband is available, it is important to be able to connect to and from multiple types of communications media.
3. All the "stakeholders" in the project should be involved early in the design process. This will provide for early issue resolution of problems like communications and system security.
4. The needs of multiple users should be addressed in either system design or in flexibility for future changes. Database formats, training, and viewing options can be determined at an early stage to provide for the best efficiency.
5. In order to add analytical capability to the system, a way needs to be developed to bring in SCADA inputs of the system topology so that system impedance is known at the same time voltage angles are measured.

VII. References

[1] R. Moxley, "Synchrophasors in the Real World," Schweitzer Engineering Laboratories, Inc. Available: http://www.selinc.com/techpprs.htm

[2] Y. Gong, N. Schulz, and A. Guzmán, "Synchrophasor-Based Real-Time Voltage Stability Index," *Proceedings of the 32nd Annual Western Protective Relay Conference*, October 2005.

VIII. Biographies

Nayana Niglye is a lead engineer at KeySpan, serving the Long Island Power Authority. She holds her MSEE from Polytechnic University (2002) and Bachelor of Electrical Engineering from Walchand College of Engineering, India (1995). Presently, her functionalities include power system planning functions. Before joining KeySpan, she served as a deputy manager in Reliance Industries, India, responsible for substation automation and control. She has developed several power system automation algorithms, which is her area of interest.

Frederick S. Peritore holds a Bachelor of Engineering degree from Stony Brook University and an MBA from Long Island University, with honors. He has many years of gas and electric utility experience in distribution design, reliability, and meter engineering. He has managed internal audit and quality assurance functions encompassing major construction, system performance, and power generation and has been the recipient of several performance awards in his company and in the industry. In his current position, he is a program manager in the electric research and development organization of KeySpan, serving the Long Island Power Authority.

Richard D. Soper is an engineer at KeySpan, serving the Long Island Power Authority.

Chris Anderson has an A.A.S in Electronics Engineering Technology from I.T.T Technical Institute, and he is currently working on his B.S. in Electrical Engineering through Kennedy Western University. He joined SEL in July 1999. In the first three years at SEL, he worked in product development for transmission protection products. Since 2002, he has been an associate product engineer supporting transmission protection in Research and Development.

Roy Moxley has a B.S. in Electrical Engineering from the University of Colorado. He joined Schweitzer Engineering Laboratories in 2000 as market manager for transmission system products. He is now a senior product manager. Before joining SEL, he was with General Electric Company as a relay application engineer, transmission and distribution (T&D) field application engineer, and T&D account manager. He is a registered professional engineer in the State of Pennsylvania.

Armando Guzmán (M '95, SM '01) received his BSEE with honors from Guadalajara Autonomous University (UAG), Mexico, in 1979. He received a diploma in fiber-optics engineering from Monterrey Institute of Technology and Advanced Studies (ITESM), Mexico, in 1990, and his MSEE from University of Idaho, USA, in 2002. He served as regional supervisor of the Protection Department in the Western Transmission Region of the Federal Electricity Commission (the electrical utility company of Mexico) in Guadalajara, Mexico for 13 years. He lectured at UAG in power system protection. Since 1993, he has been with Schweitzer Engineering Laboratories in Pullman, Washington, where he is presently research engineering manager. He holds several patents in power system protection and metering. He is a senior member of IEEE and has authored and coauthored several technical papers.

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