IMPROVING POWER SYSTEM OPERATING CAPACITY THROUGH WIDE-AREA SYNCHRONOUS PHASE ANGLE MEASUREMENT

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INTRODUCTION

The earliest days of electrical generation, distribution, and transmission presented a problem that persists today. The system must survive changing conditions of power demand, faults, equipment failures, and other unforeseen conditions while continuing to serve as many people as possible. This requires either armies of operators or automatic systems to detect changes and adapt appropriately. Regardless of the technology, the individuals or devices in control follow a process of evaluating input information, making decisions, and effecting changes in system configuration and operation.

Early electric power control systems consisted of operators in bowler hats standing in front of large knife switches, looking at meters. If the current on a circuit went too high, the operator opened the knife switch and fanned the arc out with his hat. In the next generation of power control systems, electromechanical devices replaced human operators and provided automated protection. Presently, engineers design systems that utilize powerful microprocessor-based equipment capable of more sophisticated protection and automated control.

While automatic control and protection devices for power systems have advanced dramatically in the past 20 years, power system operating state is still determined using an analytical method called state estimation. While the results of analytical methods are often suitable for automatic control, optimized control is obtained when systems operate in a “closed loop” or feedback process, as shown in Figure 1.

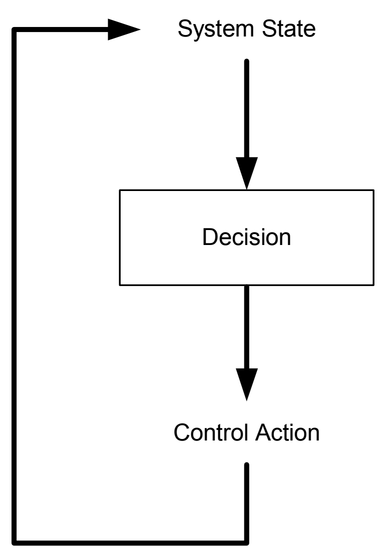

Figure 1 Automatic Control Process

In the case of synchronous phasor or synchrophasor measurement, we can begin to replace computational solutions with measurements, improving response time and accuracy, and offering an opportunity to use this information to make automated, real-time control decisions.

SYNCHRONOUS PHASOR MEASUREMENT

Synchronous phasor measurement can be obtained using dedicated equipment specifically designed to collect and transmit this information. However, adding a new type of instrumentation to existing systems is expensive and requires a new communications structure to handle the data. Dedicated phasor measurement equipment can cost as much as $24,000 USD per node.

For synchronous phasor measurement to be useful and economical, it must be integrated into existing systems to the greatest extent possible. This means that other devices in the station responsible for collecting metering and measurement data can perform this work. An innovative technique for collecting this data is available and has been discussed in depth [1]. This method allows synchronous phasor measurement to be an inexpensive feature of substation protective relays.

While a complete derivation of the measurement technique is beyond the scope of this paper, a few of the key characteristics of the system (patent pending) are listed below:

- All devices are time synchronized; for example, via GPS time synchronization clocks.
- The time-synchronized devices synchronously sample the power system (i.e., all devices capture present system measurements at the same moment in time within an acceptable accuracy).
- Oversampling and filtering algorithms provide the required measurement data for protection functions within the IED.
- Data are collected, timestamped, and either used locally or transmitted along with timestamps reflecting when the data was collected.
- Synchronous sampling has additional benefits, including enhanced system disturbance data collection.

An illustration of the synchronous sampling of data at different points in the power system is shown in Figure 2.

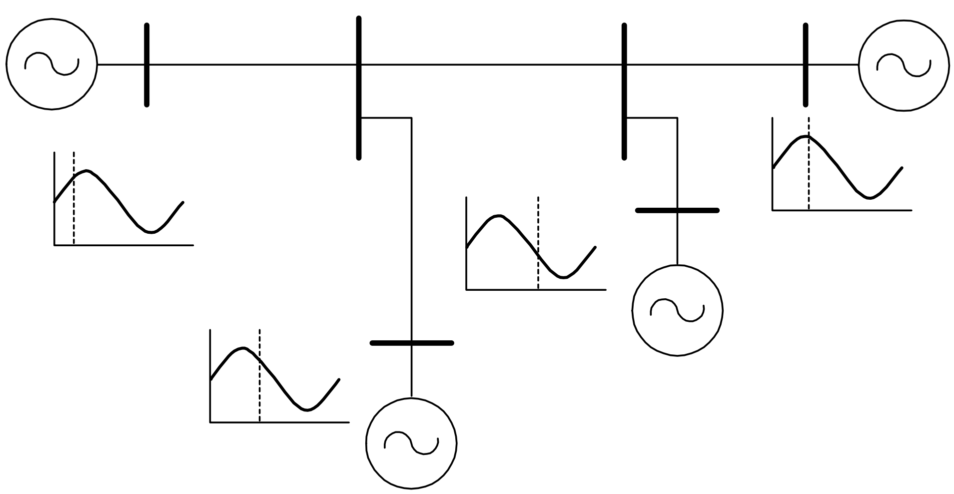

Figure 2 Synchronous Sampling at Different Power System Locations

Synchrophasor Monitoring Systems

Three elements comprise a synchrophasor monitoring system: 1) the central data collection and presentation system, 2) a protocol for transmitting the data, and 3) communications links to carry the data to the central location. Pilot projects to provide synchrophasor monitoring systems have focused on these three areas, but the work of providing a practical system that can be readily adopted by existing utilities as an expansion of their present field monitoring and display systems is not complete.

Central Data Collection and Presentation

Synchrophasor data is presently applied as an experiment to learn how it can assist utilities. As the industry matures in its use and application of these systems, the issue of exactly how the data will be collected and presented becomes very important.

Synchrophasor data comes from many disparate sources throughout the utility. Each individual data collection site is valuable only in the context of other synchrophasor data collected at other points in the system. Figure 3 shows an example for a single transmission line.

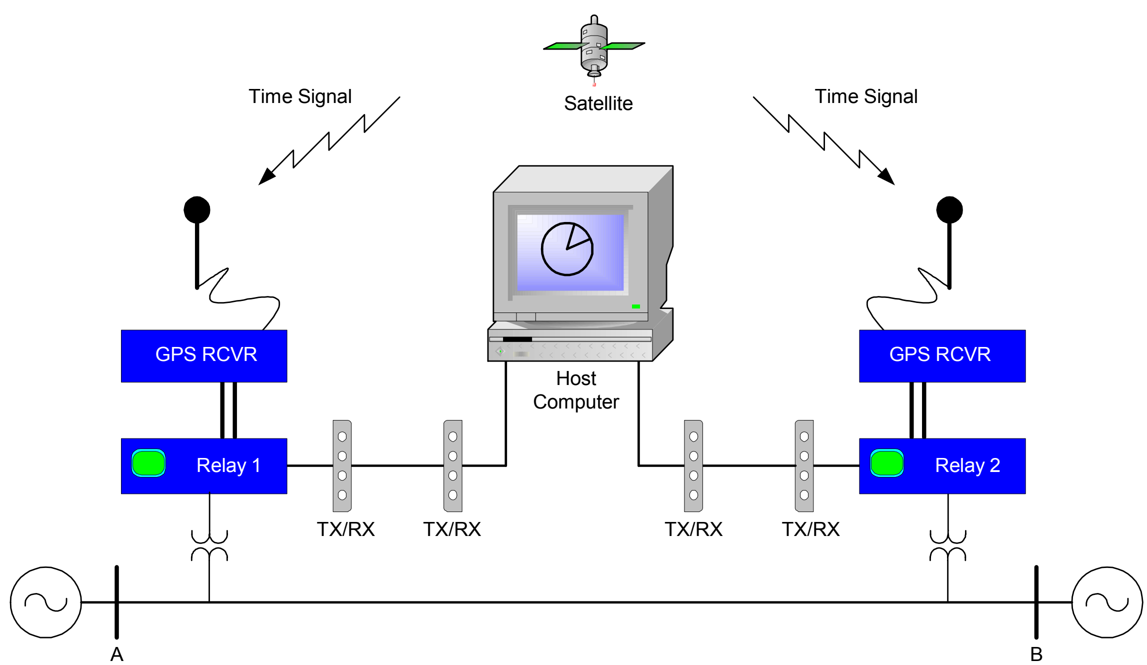

Figure 3 Example Synchrophasor Monitoring System

The example system effectively monitors a single line. However, if you attempt to use a standard PC as the host computer and expand to monitoring many locations across a utility, you will quickly exceed the communications capability of the computer. As you add connections, either the overhead of managing the actual and virtual serial connections or the overhead of the network communications (if using Ethernet connections) soon burdens the computer and produces slow updates and poor data logging performance.

An alternative architecture (described in the IEEE standard) uses data concentrator devices throughout the utility that collect and summarize data and forward it to the central monitoring location. While this architecture addresses the communications processing burden issues, it adds other issues, such as where data will be logged and how it will be forwarded, and ultimately, where the concentration nodes will be located.

Both of the architectures (with and without field data concentration) collect data and display it on a system that is separate from other utility control and monitoring systems, including SCADA. This means that the implementation will add another monitor and computer to the central control station, increasing the workload on the operations staff. It also means that other utility information (like circuit breaker status) will not be directly integrated into this system. While the payoffs of this additional workload are worth the increased control capabilities discussed later in *Applications*, the system will not be widely accepted until it integrates well with existing utility data collection, presentation, and control systems.

Even with an increased operation workload, the system and data collected is very useful and will continue to be deployed by utilities to improve control. For example, a utility with a particularly critical transmission link may find that installing a separate system to monitor this path is well worth the investment and effort of maintaining a separate system.

Long-term development of this and other new approaches to data collection within the utility will probably lead to significant development of the concept of utility SCADA. It is no longer adequate to install SCADA systems that only collect traditional SCADA real time measurement and status information. Synchrophasor measurements, logged data reports, and other new and innovative data sources in the field demand that utilities include substations in a larger enterprise-wide approach to data collection, storage, and integration.

Communications Protocol

The IEEE standard 1344 proposes a message format for transmitting data to a monitoring location. Other data transmission formats have also been developed for this data. While widespread implementation of this system does not require a single, interoperable protocol for all devices, it is likely that the market will demand one. A single standard protocol would allow collection of this data from dedicated phase measurement units (PMUs) as well as meters, protective relays, and other smart IEDs that perform measurements.

The required data collection or sampling rate observed by the monitoring system (via periodically transmitted data from the field) varies significantly. While some systems allow for data to be transmitted as quickly as 30 or more times per second, the intended application of the data will determine what data rates are actually necessary, allowing utilities to carefully allocate expenditures on communications links and bandwidth.

Delays in the communications paths are also an issue for certain types of control if the data transmission format requires that all data arrive at the monitoring location in a synchronized fashion. Digital communications networks and links are very fast and can provide this performance, but often at a very high cost. The development of data transmission and control algorithms that are unaffected by slight variations in channel delay and that can tolerate different delays from different system locations will help greatly. For example, data transmitted with timestamps can be resolved into coherent system data in the central monitoring system. However, the total delay between data collection and the resolution of the data into an input to a control system determines the responsiveness and stability of the control system. Therefore, the overall system must be designed to have adequate performance for the intended control algorithm.

Many emerging (e.g., IEC 61850) and well-established systems (i.e., DNP and IEC 60870-101) for transmitting utility field measurement and status data are available, but none has presently integrated a messaging type for synchrophasor data. As the demand for this data develops and the systems that display and utilize this data develop, additional work in these standards may prove helpful.

Communications Systems

Today there are many ways to provide communications paths to move data from field measurement points to central data collection points. Leased line, power line carrier, and other methods used for traditional SCADA and protection communications lack the bandwidth or information carrying capacity to be useful for this application. The most popular designs for new installations include digital point-to-point and digital communications networks (including microwave).

As mentioned previously, the data update rates and data transmission requirements for the control system determine the bandwidth or data carrying capacity of the links from field measurement points to the data concentration or control center locations. By carefully considering the control algorithms and data protocols to be used, utilities can minimize the bandwidth requirements and reduce the expense and difficulty of deploying synchrophasor measurement and monitoring systems.

Digital Point-to-Point Communications

There are several forms for digital communications; fiber-optic cable and wireless are two of the most popular. In this paper, we use the term "point-to-point" to denote that the communication travels across a medium provided on a point-to-point basis from one location to another. It is important to note that logical point-to-point connections can operate across networks and this is discussed in the following section, *Digital Communications Networks*.

Fiber-optic systems require that fiber-optic cable be connected between the field location and the central monitoring location. This fiber-optic cable provides the communications path with fairly simple transceivers at distances up to 80 km. The digital signaling methods provide communications paths from 9600 to 64000 bits per second. High-speed links accommodate communications for more demanding applications, including line current differential.

You can also utilize wireless systems, including microwave or spread-spectrum radios, for point-to-point communications. These technologies can be helpful where it is impractical to add or purchase a dedicated connection. Spread spectrum radios also operate in an unlicensed band in many areas of the world, which greatly decreases design and deployment costs.

Because utilities are typically deploying communications networks and because adding new point-to-point connections from the field to the control center or data concentration site can be expensive, long-term deployment of these systems will probably utilize virtual connections across digital networks.

Digital Communications Networks

Digital communications networks provide point-to-point data transfer similar to point-to-point connections, but perform that transfer across a shared network. Messages are routed from one point to another, forming a virtual circuit or link. The advantage from a communications perspective is that communications networks are much more efficient than point-to-point networks because you can significantly increase the utilization of the connections that combine to make the network. For example, a single fiber-optic pair is capable of data rates much higher than the 56000 bps required by many applications.

The logical operation of a digital network is shown in Figure 4. Switches, multiplexers, or other network management devices are access points to virtual circuits that provide point-to-point data flow. The physical construction of the network is a large number of point-to-point connections that each carry many logical connections. In large networks and networks that are interconnected, the actual data path can be very complex when compared to the virtual circuit across the network. There may also be multiple data paths that can supply the same virtual circuit operation.

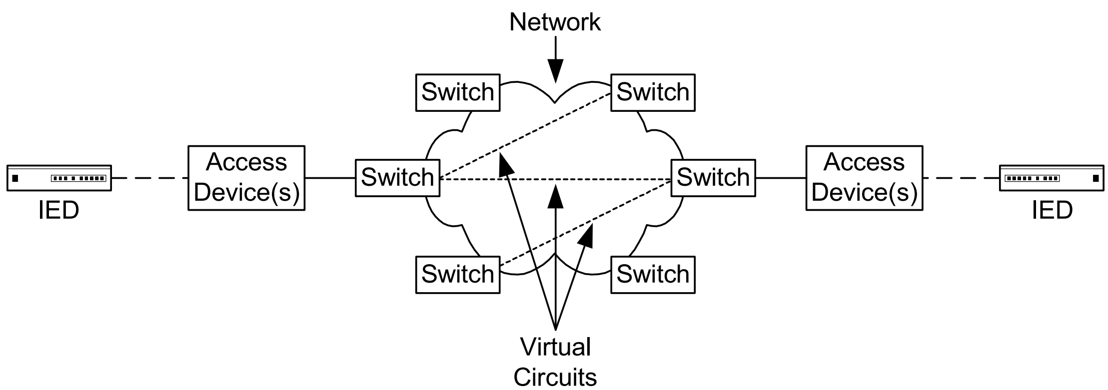

Figure 4 Virtual Circuit on a Digital Communications Network

Unless you install a separate point-to-point medium, communications between two locations will probably travel (at least for some distance) across a shared network. Many utilities have installed fiber-optic cables between substations and are now using that system as a digital network rather than a series of point-to-point connections. Digital communications networks have also replaced the backbone communications used by telephone companies. This means that calls and communications using analog telephone equipment are converted to digital, travel across the network, and are converted back to analog.

One advantage of operating over a digital communications network is that the digital network has multiple paths available to create virtual circuits and can automatically reroute traffic around failed sections of the network. Therefore, if the system is properly installed and maintained, there may be a higher likelihood that it is functional when you need it.

One drawback to this system is that paths can be rerouted at will by the network. This means that systems must be tolerant of changes and shifts in data transmission time. Proper design of the communications protocols and control algorithms that use this data should produce systems tolerant of operation over digital communications networks.

APPLICATIONS

Applications that benefit from synchrophasor data extend across the spectrum of power systems, from the smallest distributed generator system to large bulk power systems. As this information becomes less expensive and easier to obtain, we expect that new and creative uses will also develop.

Distributed Generation

With the spread of small generators throughout the power system, the possibility of accidental and undetected islanding increases. When part of the system is islanded, it becomes isolated from the overall grid with sufficient local generation to meet local load without a complete collapse. Because a total collapse of the islanded portion does not immediately occur, the islanded condition can persist and lead to equipment damage and human injury.

Islanded systems can suffer damage, as well as damage connected equipment, such as motors. Limited available short circuit fault current from the islanded system can cause a loss of coordination of fuses or protective relays. Faults can persist because current flow below calculated fault levels can still cause damage to transformers, switches, or even conductors, as well as the generator. Extended voltage sags can damage motor windings through heating.

Injury to system operating personnel or bystanders can come from a number of causes, including confusion over the system state. Line repair crew may assume a circuit is dead because it is disconnected from the normal source. A feeder that is sectionalized from its substation or an open recloser could have live feed from the islanded load side. A downed wire may have insufficient current to initiate a protective operation, while having sufficient voltage to harm a person upon accidental contact.

Low cost synchrophasor measurement equipment, such as that available in a meter or other device, can provide an islanding detection system not based on a sudden shift in vectors or frequency. While these traditional detection systems may work under some conditions, they can have settings difficulties in operating for islanding under any possible load and generation conditions. For example, systems based on frequency can be particularly difficult to set properly if the system is fairly weak or has a fairly low amount of reserve power delivery capacity compared to the peak load.

Synchrophasors, on the other hand, provide a remote operator with real time, positive means of detection for system separations. Synchronous phasor measurements sent from a remote point on the system can be compared with other measurements in the system. The voltages, currents, and phase angles available in the synchrophasor data from each measurement point provide vector shift and rate of change of frequency used in other islanding detection systems for those locations. However, the combination and comparison of the data yields a much more positive and secure means of detecting islanding problems. For example, a display of synchrophasor information between two systems will quickly show if the voltage phasors and current phasors between two points are related, as shown in Figure 5.

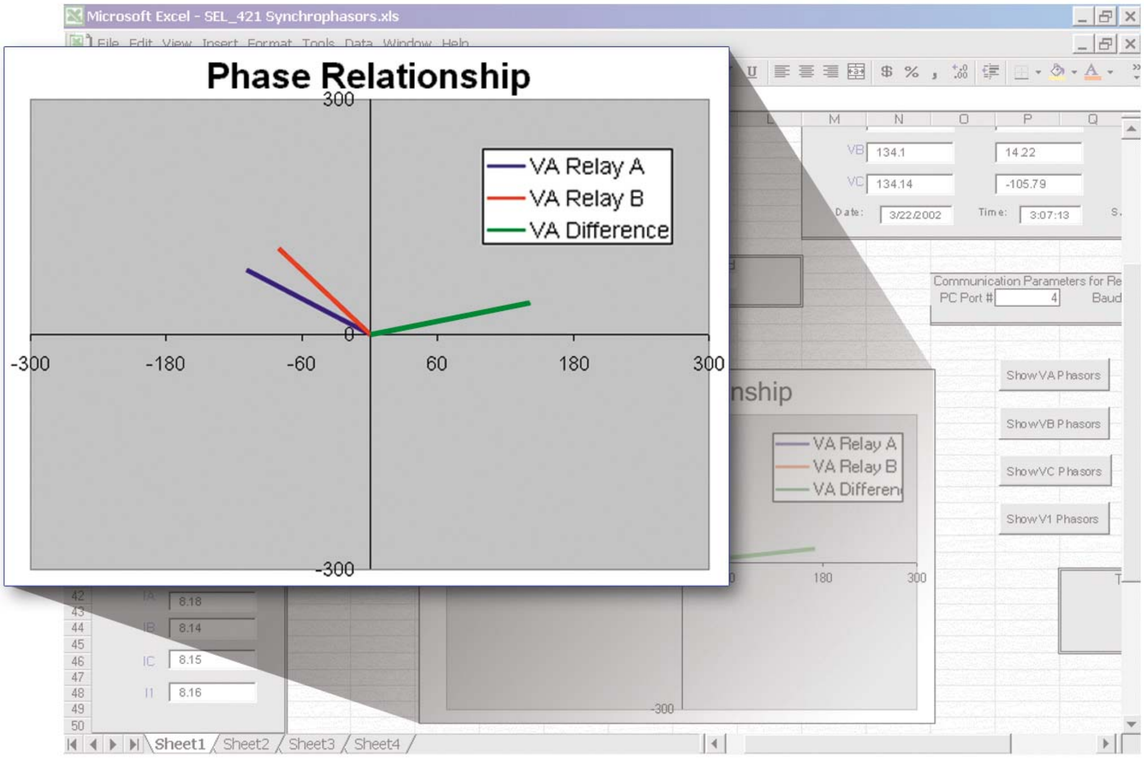

Figure 5 Synchrophasor Data Display Example

Weak Transmission Systems

Figure 6 is an actual system that could benefit greatly from collecting, monitoring, and basing control decisions on synchrophasor information. The local large generators are each 45 Megawatt hydro units. Local load has a maximum of 80 Mw with 40 Mw of additional generation consisting of a number of small generators, including hydroelectric, diesel, and combustion turbine units.

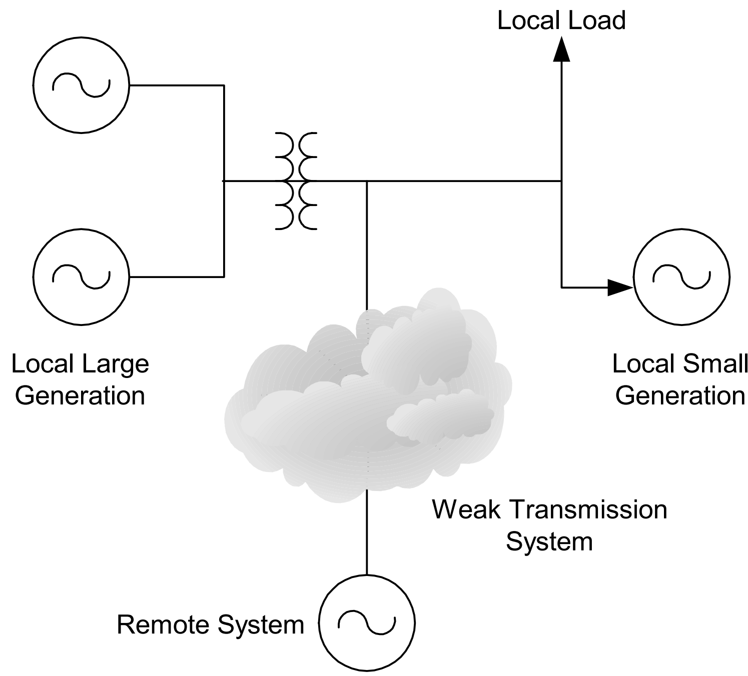

Figure 6 Power System With Weak Transmission System

A weak transmission system carries the excess power from the large generation to the remote system; stability problems occur when portions of the transmission system trip under fault conditions. With local load insufficient to absorb the additional energy from the large generators, depending on output and connected generation, the system moves into an undamped oscillation condition. Power swings of as much as 300 Mw can flow between the large generators. The resulting fluctuations cause the small generation units to trip off, and the local system loses all power.

Variations in the transmission paths between the local and remote system and differences in the amount of local load and generation can create many possible operating conditions; it has been difficult to predict when the loss of portions of the transmission system will trigger an unstable power swing.

Using synchrophasor data from each end of the transmission system, you can measure (instead of estimate) the power angle between these points. Operators or an automatic system can use this information to determine a stability margin for the operating system and take steps to improve stability. Figure 7 illustrates how the angles help in determining stability.

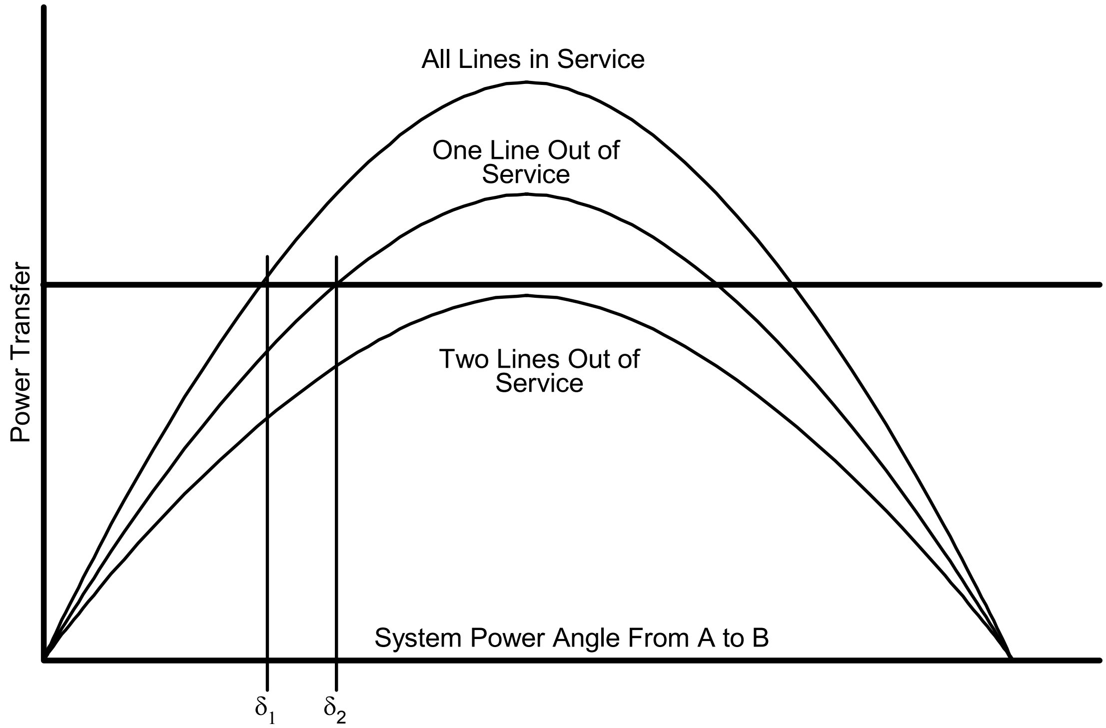

Figure 7 Power System Power Transfer Curves

When the transmission system switches from three lines in service to two lines in service, the system power angle must change from δ_1 to δ_2. Because this shift in angle involves the relative movement of large generator shafts, it cannot occur instantaneously. The time it takes for the shift to take place adds rotational energy to the generator shafts of one end of the system, what we call the local end in Figure 6. For the system to be stable, the available area above the power transfer line with two lines in service must be greater than the area below the power transfer line between δ1 to δ2.

For the utility in the example, the initial operating angle helps determine if stability would be maintained upon loss of a portion of the weak transmission system. If there is not a sufficient margin for stability, they could choose to operate with a lower load angle, exporting less power. Or automatic protection algorithms could coordinate the tripping of generation at the same time as a line trip. Either of these actions improves stability while allowing maximum use of available recourses.

Bulk Power System

The application of synchrophasors on a bulk power system is similar to that of the weak transmission system discussed above. The difference is the complexity of the state measurement problem due to the number of system connections and interactions between different portions of the system.

In large bulk power systems, the natural choice to alleviate problems is to develop more transmission capability. However, the cost of transmission lines for bulk power transport is typically estimated at $1M USD per mile. In order to provide maximum robustness and maximum effect on stability, the lines should follow different paths than existing lines; however, the cost and the difficulty of obtaining right of way for new lines limit new transmission construction. Because of the expense and administrative difficulties faced by utilities, many bulk transmission systems are operating at or near their stability limits.

The western area of the United States (shown in Figure 8) is an example of the limitations the lack of new lines can present. On a very large scale, this is similar to the case of the weak transmission system above. The Los Angeles basin is deficient in generation due to load concentration, air quality regulations restricting operation and building of local power plants, and the availability of lower cost power from outside sources. These outside sources include hydro power from the Northwest US and Western Canada, as well as nuclear and coal plants to the East in Arizona and New Mexico. As with the weak transmission system, interactions and the number of possible operating configurations preclude operation based on pre-determined scenarios and modeling.

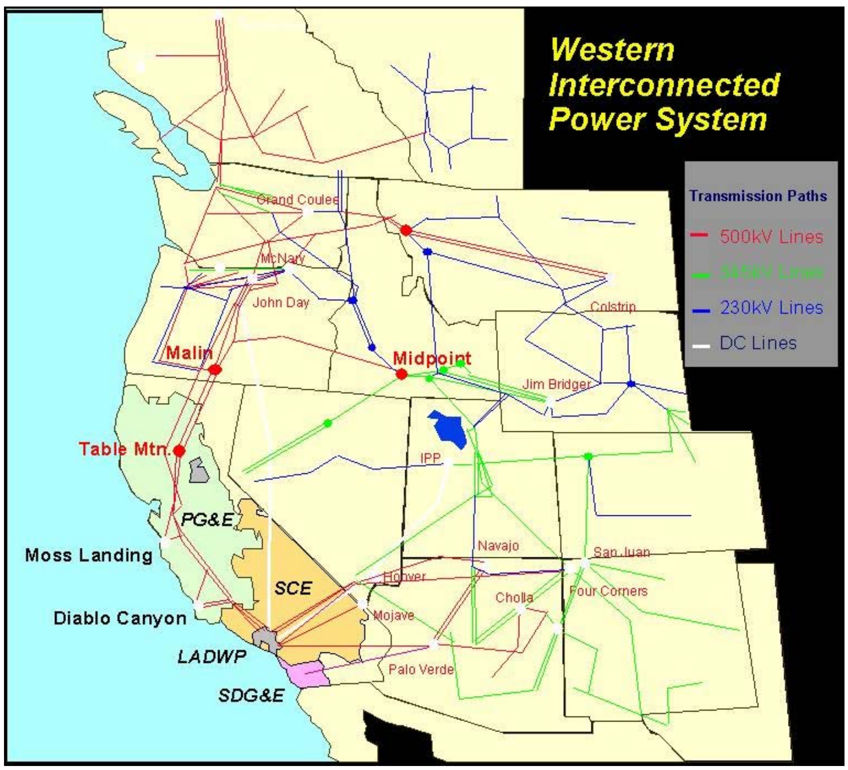

Figure 8 Western Interconnected Power System

For example, the 500KV lines shown in Figure 8 that connect Southern California with Northern California and the rest of the Northwest United States can have a drastic effect on overall system operation. If these lines are not in service, then power imports from Arizona and New Mexico must be severely curtailed. This requirement has led to the use of a remedial action scheme to send a transfer trip across Southern California.

Because of a lack of information on actual system state, the transfer trip scheme must operate regardless of system conditions or the actual stability margin of the remaining system and may result in further measures to curtail load by disconnecting customers. Extensive research is ongoing to establish a measurement system, using synchrophasors data from across the Western Interconnected Power System to establish a stability preservation system based on actual voltage angle measurements rather than pre-established switching systems. The approach to solving this power delivery problem is to increase the collection of the proper information and to use it to support real time control and operation decisions, closing the loop show in Figure 1.

CONCLUSIONS

Several important conclusions about enhancing power system operation with synchrophasor measurements are listed below:

1. Synchrophasor data collection offers new opportunities to control and operate systems based on measured information rather than mathematical models or other open loop methods.
2. Systems for synchrophasor data collection, display, and logging that are presently outside of existing SCADA and other data collection systems must be integrated into overall utility data collection systems in order to reduce implementation cost and present information to operators that is well integrated.
3. Digital networks provide sufficient bandwidth and reliability to transfer the increased amount of data required for synchrophasor monitoring.
4. Synchrophasor measurement and collection can greatly improve the detection of islanding in systems with a large number of distributed generation resources.
5. Operators can replace guesswork or vast numbers of operating scenarios with measurements that help them understand stability margins for operating systems.
6. Large transmission systems with complex interactions benefit from online monitoring and measurement rather than models that do not adequately predict system intricacies.

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BIOGRAPHIES

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. Prior to that 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.

Darold Woodward has a B.S. in Electrical Engineering from Washington State University. He is a member of the Instrument Society of America (ISA). He joined Schweitzer Engineering Laboratories in 1998 in the position of System Integration Engineer. Before joining SEL, he participated in design and commissioning projects for electrical, automation, and instrumentation systems in water, wastewater, and hydroelectric facilities. He is a registered Professional Engineer in the State of Washington.

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