Synchrophasor-Based Monitoring, Analysis, and Control

Roy Moxley
Schweitzer Engineering Laboratories, Inc.

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Roy Moxley
Schweitzer Engineering Laboratories, Inc.
USA
roy_moxley@selinc.com

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1 INTRODUCTION

Advancements in the availability and installation of phasor measurement units (PMUs) have progressed faster than the installed base of applications for this new technology. The electric power industry has begun to recognize the potential for new synchronized phasor measurement (synchrophasor) applications but is only beginning to put these into service.

Electric power systems are changing to meet economic, environmental, and political requirements. These changes have many consequences. There is greater transmission of power, with longer separations between generation and load. More distributed and relatively uncontrolled generation, such as wind power, is being installed. All of this is coupled with a greater drive for improved efficiency and reliability of service.

This paper addresses how these changing power system requirements are being matched with the capabilities of widespread PMUs, phasor data concentration systems, and now synchrophasor vector processors. Traditional synchronized phasor measurement systems record system events for later analysis. Recent applications involve real-time display of synchronized values for use by system controllers to improve stability. The latest applications close the control loop by using wide-area measurements to initiate changes to the system state.

In-service application examples are provided using synchrophasors for disturbance recording, control supervision, and direct control. Potential applications for direct stability and efficiency improvements are also presented. These technology advancements will help the electric power industry meet the challenges being faced.

2 PMU CAPABILITY AND LOCATIONS

A phasor measurement unit (PMU) is the basis of any synchrophasor system. Understanding its capabilities and limitations is key to understanding the possibilities of wide-area measurement and control. There are several different aspects of the PMU characteristics that have bearing on possible applications.

2.1 Measured Values

There are more than just voltages and currents available to a PMU, although those are perhaps the most important quantities. Phase and positive-sequence voltages and currents are available in either polar or rectangular quantities. While it is possible to convert polar to rectangular and visa versa, processing is simplified if the application is matched to the format. Which of these data formats, transmitted from the PMU, is determined by the user? For adding phasors from many locations, rectangular is preferred. If angles are to be compared across the system, then polar is easier to manipulate.

In addition to voltages and currents there are other analog quantities available [1]. These include measured and calculated values within the PMU. IEEE standard C37.118 provides for analog values in addition to voltages and currents to be transmitted with the same timestamp as the measured values.

Measured values include:

- Ambient temperature
- Calculated line temperature [2]
- Battery voltage (maximum, minimum, and present value)
- Time error

Binary values available to the PMU may also be transmitted in the synchrophasor message. The traditional values sent include breaker status and disconnect switch position. Other values are available depending on the PMU. For example, if the PMU is a protective relay, transmitted binary values include fault detector status, alarm status, control input status, and protection communications channel status. The state of these binary values is useful to a synchrophasor control system by supervising the validity of measurements and providing a backup signal for use by a control system. For example, a relay's out-of-step detection might not be as fast or sensitive as a synchrophasor-based out-of-step determination, but as a backup system, it becomes a valuable redundant relay protection system.

Modern PMUs have the capability of mathematical manipulation of analog and binary values. For example, in order to calculate A-phase power, we could write the following local logic equation in the PMU:

$$PSV01 = IA*VA*\cos(\text{ang } IA - \text{ang } VA) \tag{1}$$

Of course, power is directly measured within most PMUs but other values created from measured values are also useful. These include values created by combining multiple current inputs by either addition or subtraction. Or, logical combinations of digital and analog values can be created. For example, one specific current value is sent if a particular switch is closed, and a different current value is sent if the switch is open. Alternatively, quadrature values are calculated by combining A-phase current with the sum of B- and C-phase voltages.

3 SYNCHROPHASOR APPLICATIONS

While there are many combinations of applications, the basic groups are broken down into the following categories, for purposes of this paper:

1. Post-event monitoring and analysis
2. SCADA control applications
3. Real-time vector processing

Of course, monitoring can be done through SCADA systems, and, as will be shown, real-time vector processing can be used to send SCADA data or to monitor power system conditions. Limits should not be set on applications because they do not fit neatly into a category.

3.1 Monitor/Analysis

For decades, synchrophasors have been used to view system-wide events. As more PMUs were added to the power system, the event analysis capability improved. For example, in Figure 1 [3], we see how synchrophasors give a simple, graphical view of how a generator trip impacted phase angles at different parts of the Western United States power system.

Here we see synchronized phase angle measurements showing the effects of a generator trip in May of 2001, at different points in the Western Electricity Coordinating Council (WECC) region of the United States. In this case, the trip was in the northwest area, which is closest to the PMU located at Coulee. Colstrip is located to the east of Coulee, Malin (the reference in Figure 1) is south of Coulee, and Vincent is further south. Synchronized measurements clearly show the impact of automatic generation control that was initiated approximately 250 seconds after the generator trip.

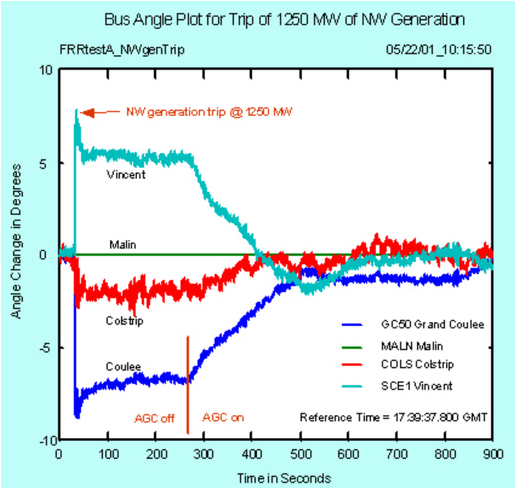

Figure 1: NW Generation Trip

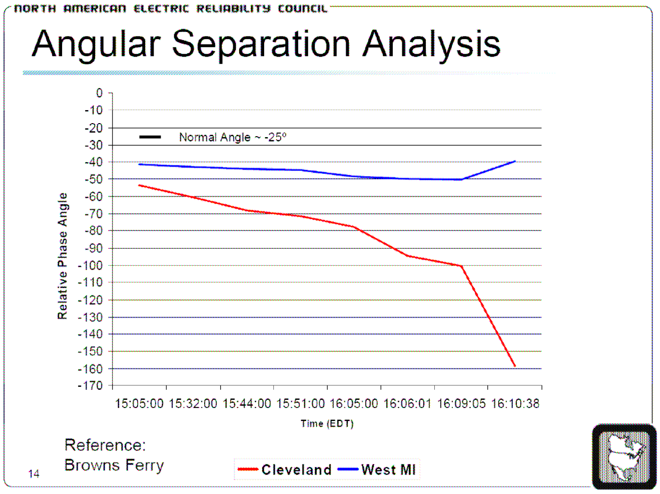

Figure 2: Angular Separation of Ohio With Western Michigan

A major event in the Eastern United States has been the drive behind recent synchrophasor-based initiatives. In this case, it took months of analysis and piecing together event reports to create the type of data shown in Figure 1. In Figure 2 we see the result of modeling and event analysis of the August 2003 blackout in the Northeastern United States.

This chart, provided by the North American Electric Reliability Corporation (NERC), shows what was not available to operators in the Cleveland area on August 14, 2003. Using the Browns Ferry Nuclear Plant bus, in the state of Tennessee, as the reference for the Eastern grid, we see the system was in a severely stressed condition for hours.

At time 15:00 the angle between Cleveland and Browns Ferry was at more than double its normal value, and the angle between Cleveland and Western Michigan, normally close to constant, was increasing minute by minute. Had operators been able to see this information in real time they would have had a single, actionable quantity that would have made the seriousness of the situation clear.

Because of the perceived value of synchrophasor measurements, the United States Department of Energy has promoted the installation of PMUs and the collection of synchrophasor data. Following a blackout in the state of Florida, NERC issued a press release [4], a portion of which is quoted below:

> *Rick Sergel, President & CEO of the North American Electric Reliability Corporation, made a statement yesterday in reference to February 26th's category four system disturbance in South Florida. The event involved the loss of approximately a dozen generating units, 26 transmission lines, and the loss of more than 4,000 MW of load.*
>
> *"While we can't predict the timetable of analysis, information collected by new monitoring technologies, called 'synchro-phasors,' will enable our teams to analyze yesterday's outages more quickly than in the past. This new technology is like the 'MRI' of bulk power systems, giving operators and analysts more granulated data and helping them to dissect and piece together the events that occurred step by step, microsecond by microsecond."*

In this case, the electric provider for the area had PMU data from a protective relay on the nuclear plant outgoing line (as well as at several other locations) that tripped very early in the blackout. Several other relay/PMUs also provided event data. These relay-based PMUs provide an improvement over prior technologies to assist analysis in a number of ways.

First, the PMUs provide data to record local power swings, voltage sags, and other system information to determine the root cause of the disturbance spread. (In this case there is no question of the initiating event, switching into a line reactor fault with local protection disabled. The question being investigated is what caused the outage to spread.)

Second, because the relays providing the PMU data are time synchronized, the event reports are likewise time synchronized to the microsecond. The precise timing makes it possible to see the exact spread of the voltage drops across the area and determine how all the relays operated. This improves checking of settings and coordination of protection.

Third, remote PMUs, some more than a thousand miles away, saw the power fluctuations caused by the loss of generation. The PMU data are used to check damping ratios of various oscillatory modes of the system. This provides a check of overall system stability.

3.2 SCADA Control Applications

Because of the accuracy and data streaming capability of synchrophasors, they are ideal for direct, SCADA-based control. Input of PMU data into EMS systems is not included in this paper, but other control applications have been growing and are discussed. These applications can be loosely grouped into two categories, low speed and high speed.

3.2.1 Low-Speed SCADA-Based Control

Power system control using synchrophasor data transmitted to a central control center can improve system operation and stability. While some synchrophasor applications depend on wide bandwidth and high-speed communications from the PMU to a control area, this is not a necessity. All that is required is that the data be transmitted faster than system changes related to the condition being controlled. Traditional SCADA control receives data from scans ranging on the order of one to ten seconds. Communications processors, used for engineering access or transmitting traditional SCADA data, can send combined synchrophasor data to a control center.

In one case in the Central United States, an electric utility has a relatively long North-South line from one end of their network to the other. The northern terminus of the line is at a station with a ring bus configuration. Other lines from the station connect through a strong adjoining network to the remote end of this North-South line (Figure 3).

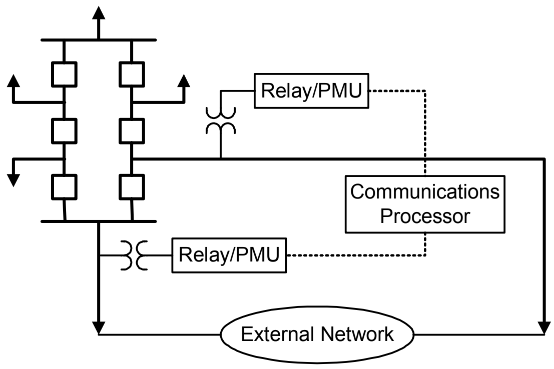

Figure 3: Line Connection Through an External Network

The problem with this configuration was that closing the North-South line could result in an overload on the line, depending on the angle across the system. The northern station was configured with a ring bus, similar to that shown in Figure 3, so there was no relay with voltage transformers connected across a tie point to measure the closing angle.

The solution to this problem was to use the communications processor, already connected to the relays for engineering access, to collect synchrophasor data and send the operators this information. Based on the processing requirements for measuring the angle and bandwidth available to send the information, the measurement is transmitted every 20 seconds. In this case, as with many applications, this update frequency is more than sufficient to meet system needs. The angle only varies with load across the large external network, which does not vary rapidly. The synchrophasor solution, checking the angle prior to closing, is far superior to closing the line and seeing if an overload occurred. Because the system needed no additional equipment, other than what was already there, it was also less expensive than the traditional alternative of adding voltage transformer connections between relays to all connection points between incoming lines. Because it could not be assured which breakers would “complete” the ring, this approach requires many wires and control switches.

Another synchrophasor-based control system was “discovered” during implementation of a blackstart test performed by the Salt River Project in the Western United States [5]. The connection of the isolated area to the Western grid was made at a point about 100 km from the control center. The system diagram for the blackstart test is shown in Figure 4.

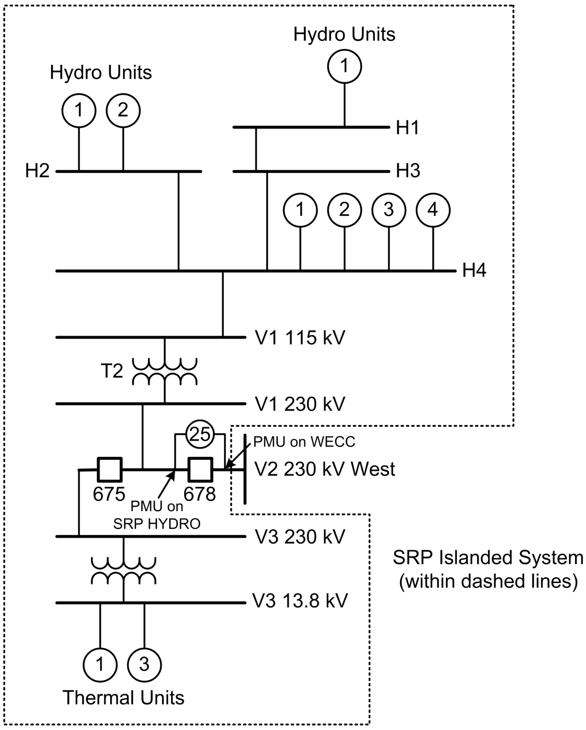

Figure 4: Blackstart Connection

The problem that presented itself during the test was that the automatic synchronizing relay, shown as device 25 in Figure 4, was not functioning. The operators needed to synchronize two systems, not connected at another point, without risking damage to either breakers or generators.

In this case, it was the nature of the available high-speed, wide-bandwidth data path that made synchrophasors perfect for the application. Operators were able to see the angle across the tie point, along with the slip frequency, with a total delay of less than 200 ms. This was 25 times faster than traditional SCADA and provided confidence that the breaker could be closed without damaging equipment. The moment of synchronism, as seen by the operators, is shown in Figure 5. For this application, the PMUs transmitted data over an Ethernet connection to a central data concentrator and visualization system.

While the blackstart example, and the ring bus example were to solve specific problems, because the solution was very low, or no, cost, they can be applied throughout the power system.

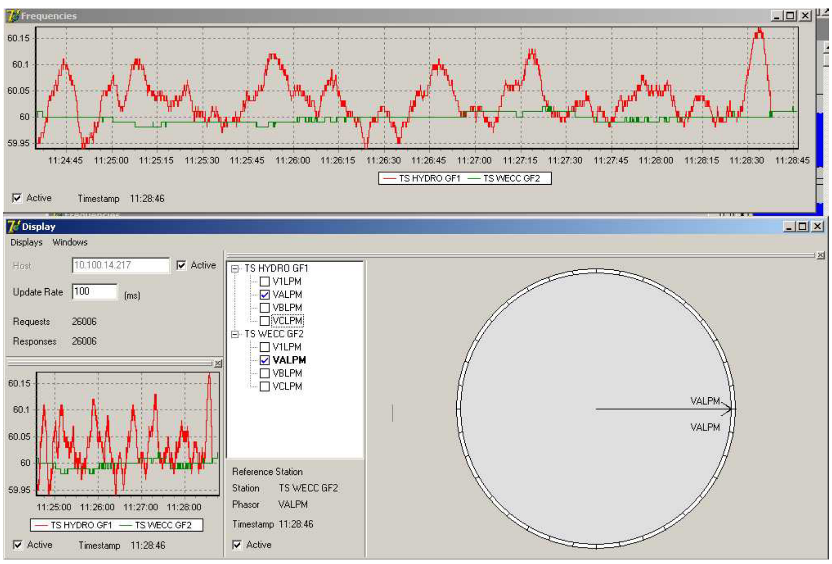

Figure 5: Synchronizing Point Based on Received Synchrophasor Data

3.2.2 High-Speed SCADA-Based Control

There are applications for synchrophasors within SCADA systems, but they require data acquisition speeds far faster than can be delivered by traditional SCADA or any system using human controllers. One of these was a Static Var Control (SVC) installed at Southern California Edison (SCE) in the Western United States [6].

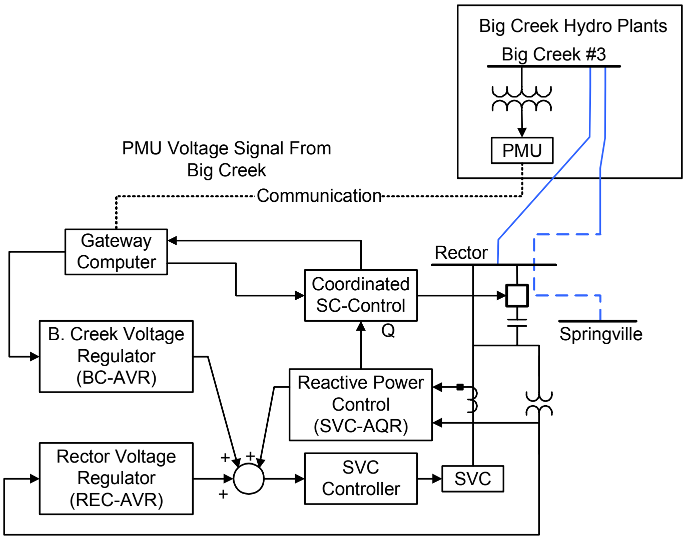

Figure 6: PMU Voltage Control Signal to SVC

In this system, signals from a PMU provide remote voltage measurement to the SVC control. Details as to why these were necessary and the system performance can be found in [6]. The key to the project success was that the synchrophasor voltage measurement would be provided in real time to the SVC in a format that its control could use. The system diagram in Figure 6 shows how this was accomplished. The PMU signal was sent using IEEE C37.118 format to a rugged computer that converted this into a DNP3 protocol that could be "understood" by the SVC control.

As a single input, the SVC, in this case, used synchronized phasor measurements as contents within the SCADA protocol. The needs to have the signal arrive at very high speed, be accurate, and stream continuously were met very well by transporting the synchrophasor-based data via the SCADA protocol. Also, fewer changes were required to migrate these recently available data into mature and existing applications. The success of the system is shown in Figure 7. The SVC greatly improved the area voltage following a fault, while not causing an overvoltage at the generation station.

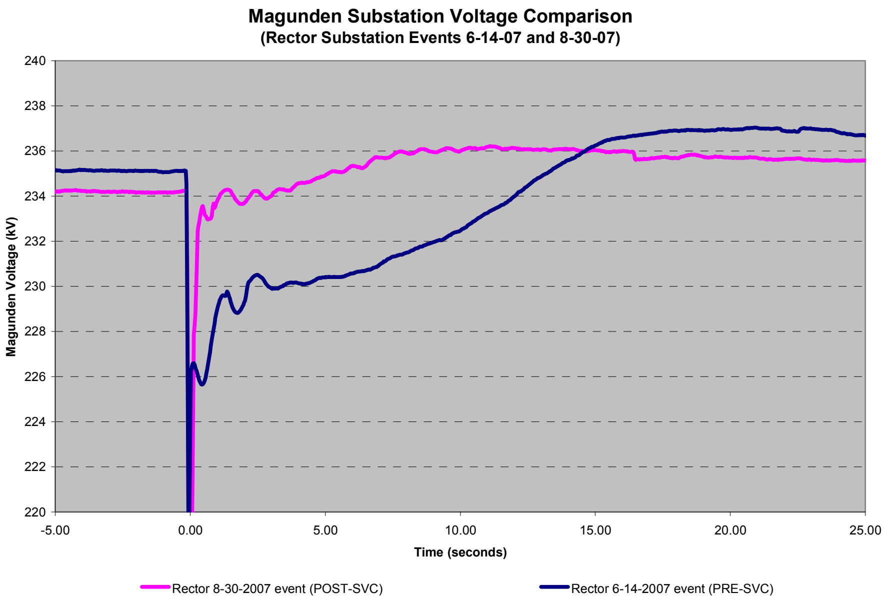

Figure 7: Success of SVC Control Using Synchrophasor Voltage Input

The same gateway that converts the synchrophasor protocol into DNP format for the SVC control can convert to other common protocols, such as Modbus®, IEC 60870-103, and others.

While the present control uses only one quantity, future modifications could include additional inputs from remote PMUs to improve stability throughout the area.

4 REAL-TIME VECTOR PROCESSING

While some of the in-service applications shown in this paper approach real-time speeds, there is clearly a need for a system to retrieve, time align, process, and provide a control output based on synchrophasor data. One available device to perform these functions is referred to as a Synchrophasor Vector Processor or SVP. A function diagram of the SVP is shown in Figure 8.

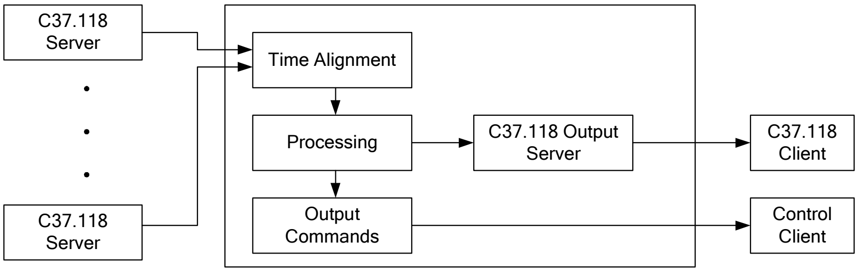

Figure 8: SVP Inputs, Outputs, and Functions

In order to perform control functions at "relay" speeds, the SVP must have a control throughput of faster than 20 ms. This fast operating speed provides for a number of control opportunities [7].

Some of these applications are the automated version of the manual actions previously described, such as automatic synchronizing, phase angle-based close permission, and Flexible AC Transmission (FACTS) device control.

Additional control functions are also enabled by the wide-area inputs available to the SVP. For example, area loop power flows can be detected and minimized by using PMUs at different parts of the power system to provide inputs to an SVP connected to control transformer tap positions, as shown in Figure 9.

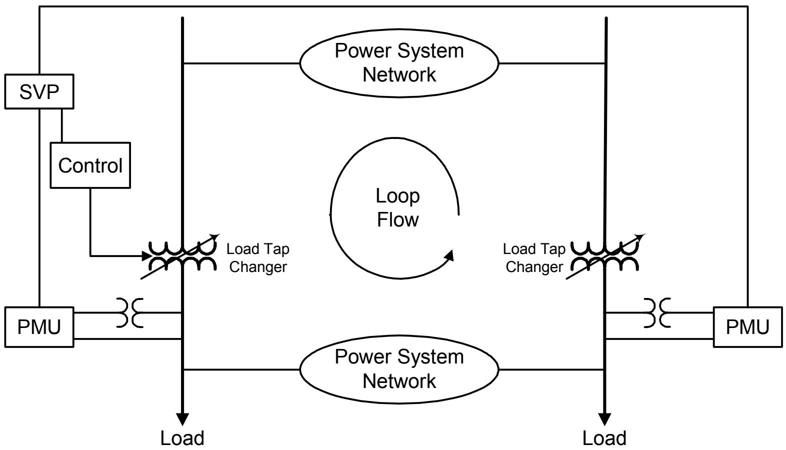

Figure 9: Loop Flow Detection and Minimization With SVP

Because there are changing loads, in addition to the loop flow, this is not as simple as if the two transformers are next to each other in a substation. The advantage of this system is that the PMU has access to both load and tap positions and can send these data to the SVP in real time. A tap change of Transformer 1 that produces an increase in Transformer 2 loading would be detected at the time it occurred. The SVP can measure the load change at both transformers to determine if loop flow is occurring. Active control of the load tap changer can be taken to minimize loop flow.

5 CONCLUSIONS

1. For monitoring purposes, it is advantageous to have PMUs at all critical locations. Time synchronized event records have been proven valuable in wide-area disturbances. Long-term disturbance recording using synchronized phasor measurements is improving power system analysis and operations.
2. Low-speed and high-speed SCADA-based control is practical without the need for additional equipment. Conversion of standard synchrophasor protocol to one used by EMS or automated control systems is available and proven.
3. Real-time control makes possible new applications to improve efficiency and system stability. The limit to the new control's function is only what will be considered by the power system engineer.

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7 BIOGRAPHY

Roy Moxley has a BS in Electrical Engineering from the University of Colorado. He joined Schweitzer Engineering Laboratories, Inc. in 2000 and serves as a senior product manager. Prior to 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 and has authored numerous technical papers presented at U.S. and international relay and automation conferences.

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