Real-Time Synchrophasor Applications for Wide-Area Protection, Control, and Monitoring

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Real-Time Synchrophasor Applications for Wide-Area Protection, Control, and Monitoring

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***Abstract*—To date, synchronized phasor measurements have been used mainly for power system model validation, post-event analysis, real-time display, and other similar activities. However, synchrophasors have a greater potential than monitoring and visualization. Synchrophasors will increasingly contribute to the reliable and economical operation of power systems as real-time control and protection schemes become broadly used.**

This paper describes several synchrophasor-based protection and control systems. One of these systems uses synchrophasor information for generator shedding. The other system uses synchrophasors for backup transmission line protection for ground faults. In addition, the paper describes a user-programmable, real-time synchrophasor processor and two of its applications: a distributed bus differential protection scheme and a system integrity protection system suitable for two-area power systems.

***Index Terms*—power transmission protection, real-time control, real-time systems, synchrophasor applications, synchrophasors, system integrity protection systems, wide-area protection.**

I. INTRODUCTION

SYNCHRONOUS phasor measurements come from dedicated phasor measurement units (PMUs), and more recently from protective relays and meters, also called phasor measurement and control units (PMCUs) [1]. Originally, the measurements were collected and aligned in phasor data concentrators (PDCs) [2][3], but PDCs cannot truly process the data using algorithms, nor can they directly provide protection, control, and monitoring functions. The synchrophasor vector processor (SVP) [4] is a user-programmable, real-time processor that provides these functions.

Another approach for synchrophasor-based protection, control, and monitoring is to communicate data directly between PMCUs. In addition to measuring power system quantities and transmitting synchrophasor data, new PMCUs can also receive and process synchrophasor data [5]. Adding a communications link between existing PMCUs enables an effective exchange of synchrophasor data. No additional components are required.

This paper describes two synchrophasor-based protection and control systems that communicate data directly between PMCUs. One of these systems uses the synchrophasor angle difference between two power system locations to make generator-shedding decisions [6]. The other system uses synchrophasors for backup transmission line protection for ground faults [7]. This paper also describes the SVP and summarizes two of its applications: a distributed bus differential protection scheme [8] and a system integrity protection system suitable for two-area power systems [8].

II. SYNCHROPHASOR-BASED GENERATION-SHEDDING SCHEME IN MEXICO

Comisión Federal de Electricidad (CFE) implemented an automatic generation-shedding scheme (AGSS) based on relays exchanging real-time synchrophasor information [6]. CFE has specific regional generation and transmission challenges because of large loads at the center of the country and large hydroelectric generation in the Southeast.

During normal conditions, Angostura can generate up to 900 MW, while the total load of Tapachula and the Southern region does not exceed 100 MW (see Fig. 1). The excess power in the region flows from Angostura to Chicoasén and from there to the rest of the system. If the 400 kV transmission link between Chicoasén and Angostura is lost, all areas remain connected through the 115 kV network. During this condition, the Angostura generators may experience angular instability, and the 115 kV network will overload. CFE must shed Angostura generation in order to maintain system stability if the link between Chicoasén and Angostura is lost.

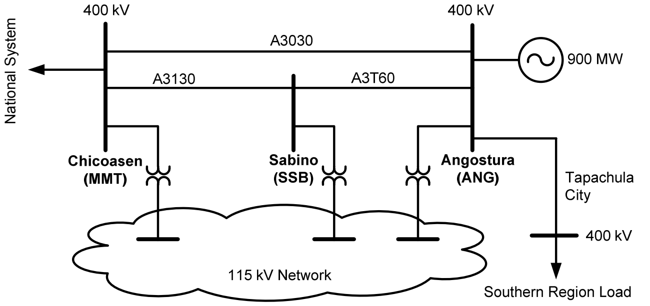

Fig. 1. Chicoasén-Angostura 400 kV transmission link with parallel 115 kV network

CFE implemented a new method to detect a loss of transmission capacity using relays with synchrophasor measurement and control capabilities. In this new AGSS,

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relays exchange synchrophasor data and calculate the angle difference between Angostura and Chicoasén in real time. If an angle difference between Angostura and Chicoasén is greater than a user-defined threshold, the scheme sheds generation according to the logic in Fig. 2.

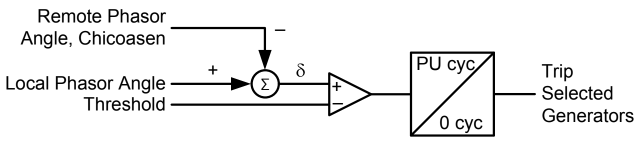

Fig. 2. Angle-based AGSS logic at Angostura

CFE determined that a double-line outage produces an angle difference of 14 degrees, resulting in instability. A single-line fault causes an angle difference of less than 7 degrees and does not cause instability. Based on these results, CFE chose an angle difference of 10 degrees as the detection threshold for double-line outages.

CFE placed relays with synchrophasor measurement and control capabilities at Angostura and Chicoasén to measure the local 400 kV bus voltage. The relay at Angostura receives remote bus voltage from the relay at Chicoasén. The relay at Angostura time-aligns the synchronized local and remote phasor data, calculates the angle difference, compares it to the angle-difference setting, and issues a generator trip if the calculated angle difference exceeds the phase-angle-difference threshold.

III. TRANSMISSION LINE BACKUP PROTECTION USING SYNCHROPHASORS

Relays that combine time-synchronized measurements and programmable logic control capabilities can use synchrophasor measurements from both ends of a two-terminal transmission line to provide backup protection [7] (see Fig. 3).

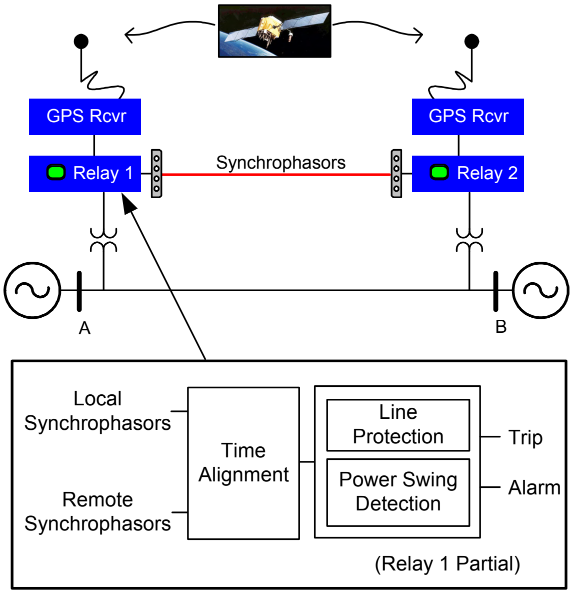

Fig. 3. Relays exchange synchrophasors for backup line protection in a two-terminal application

Line protection relays calculate synchrophasors at specific rates (e.g., 60 times per second). Communications channels make local and remote time-stamped currents available to the relays at each end of the line. These relays time-align local and remote currents on a per-phase basis, calculate sequence components, and make this information available to faulted-phase identification (FPI) logic and protection elements, such as negative-sequence (87LQ) and zero-sequence (87LG) current differential elements. The FPI logic makes these synchrophasor-based elements suitable for single-pole tripping (SPT) applications.

In the present implementation, the synchrophasor-based backup protection elements detect faults with fault resistance (R_F) greater than 300 ohms within 160 milliseconds. This R_F coverage is similar to that of negative-sequence voltage-polarized directional elements (67Q).

A. Negative-Sequence Current Differential Element

The negative-sequence current differential element (87LQ) characteristic uses operating (I_{2OP}) and restraint (I_{2RT}) quantities [7] according to (1) and (2).

$$I_{2OP} = \left| \overline{I_{2L}} + \overline{I_{2R}} \right| \tag{1}$$

$$I_{2RT} = \left| \overline{I_{2L}} - \overline{I_{2R}} \right| \tag{2}$$

where:

$\overline{I_{2L}}$ is the local negative-sequence current phasor.

$\overline{I_{2R}}$ is the remote negative-sequence current phasor.

The element operates when the following conditions are met:

$$I_{2OP} > 87\_Slope \cdot I_{2RT} \tag{3}$$

$$I_{2OP} > 0.1 \cdot I_{NOM} \tag{4}$$

where:

87_Slope is the slope of the 87LQ element characteristic.

I_{NOM} is the relay rated current.

The relay aligns the local and remote phasors according to their time stamps. Therefore, one advantage of using time-stamped phasors is that channel asymmetry does not affect the element operating and restraint quantities. The 87LG element operates similarly to 87LQ but uses zero-sequence quantities.

B. Faulted Phase Identification

The synchrophasor-based protection element includes FPI logic that uses the total zero-sequence and total negative-sequence fault currents [7][9]. The total currents are the sum of the local and remote currents. To identify the faulted phase, the FPI logic calculates the angle difference between the total sequence fault currents and compares the relative magnitudes of the total phase-to-phase currents (I_{AB_T}, I_{BC_T}, and I_{CA_T}) with the maximum phase-to-phase current. The relay uses the output of the FPI logic for tripping the faulted phase in SPT applications.

C. Protection Element Performance

Fig. 5 illustrates the R_F coverage of the 87LQ and 67Q elements for phase-to-ground faults at different fault locations along the transmission line of the system in Fig. 4 [7]. We used an RTDS to model this system. If the element sensitivity thresholds are set to $0.1I_{NOM}$, the 87LQ R_F coverage matches the intersection of the local and remote 67Q coverage. However, in a permissive overreaching transfer trip (POTT) scheme with forward and reverse elements, the scheme must coordinate forward and reverse 67Q element sensitivities. The 87LQ element is not subject to this requirement, so it can be set more sensitively than 67Q elements. Fig. 5 shows the additional R_F coverage of 87LQ with $0.05I_{NOM}$ sensitivity.

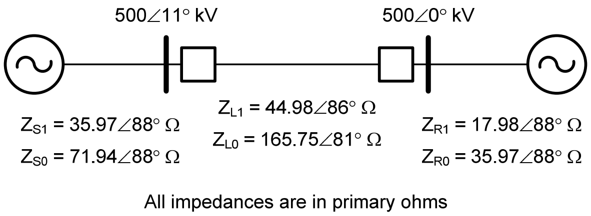

Fig. 4. Power system parameters and operating conditions to analyze R_F coverage capabilities of the 87LQ and 67Q elements

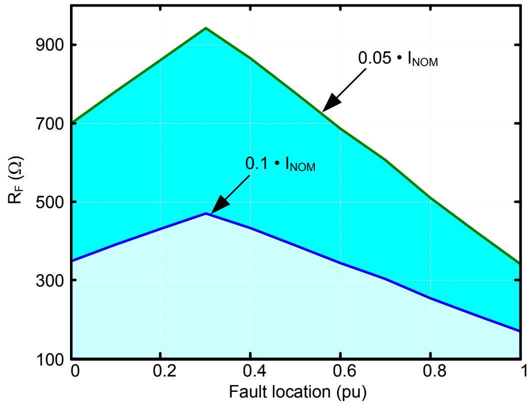

Fig. 5. The 87LQ and 67Q elements have the same R_F coverage for phase-to-ground faults when set to $0.1I_{NOM}$ sensitivity; however, setting the 87LQ element to $0.05I_{NOM}$ improves the R_F coverage

The operating time of the differential element depends on the synchrophasor message rate, the synchrophasor filtering process, and element sensitivity. In this application, the relays exchange synchrophasors at 20 messages per second and the filtering system attenuates harmonics according to the IEEE Standard C37.118 [10]. We set the sensitivity to $0.1I_{NOM}$ and 87_Slope = 0.2. The relays exchange I_A, I_B, and I_C synchronized phasors along with their corresponding synchronized time stamps through the use of peer-to-peer relay communications at 38400 bps. A faster message rate and faster filtering process reduce element operating time.

IV. THE SYNCHROPHASOR VECTOR PROCESSOR

The SVP purpose is to collect and time-align synchronous phasor measurements (SPMs), collect logical inputs, perform vector and scalar calculations, perform control operations/algorithms on the data, issue command/signals, and share and report data [4]. The SVP is a computer rated for utility applications, with specialized I/O and processing capabilities. The SVP preserves microsecond timing and efficiently performs high-speed vector and matrix mathematics.

To ensure that the fastest received SPM can be processed before the next one is received, the SVP must be capable of completing its control loop processing at least every cycle.

A simple task for an SVP might be collecting SPMs from two ends of a transmission line, comparing the voltage angles, and issuing a warning to an operator if a threshold has been exceeded. A more complicated example might be distributed SVPs performing localized state measurement and forwarding results to a higher level, to build the entire state vector, in real time, and without the nonlinear and time-consuming steps of state estimation.

Fig. 6 shows the components of a real-time synchrophasor control system. It consists of:

- *Microsecond-Accurate Clock, Like a GPS Clock.* Because time is the reference point for a synchrophasor system, it is important to use a high-quality clock.
- Phasor Measurement and Control Units. PMCUs may be dedicated devices, as well as relays or meters and other equipment that provide the synchronous measurements. The most common synchrophasor format is IEEE C37.118. The PMCU must time-align its measured quantities to the common time reference. For a synchrophasor control system to perform control, the PMCU must be capable of receiving control commands, or separate control devices must be added. IEEE C37.118 does not specifically accommodate control commands. Therefore, the PMCU must be capable of control via some other protocol like DNP3, IEC 61850, SEL MIRRORED BITS® communications, or SEL Fast Message.
- Communications Channels. Specific applications dictate the communications requirements. These range from one message a minute to one per cycle. For some applications, serial communications at 9600 bps will work. For high-speed applications where large amounts of synchrophasor data are transmitted, an Ethernet or similar communications channel may be required.

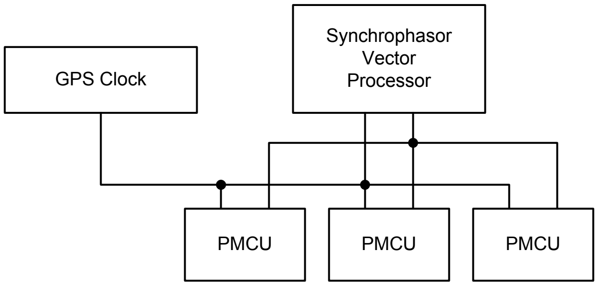

Fig. 6. Real-time synchrophasor control system

A. Distributed Bus Differential Protection

This section describes a backup bus differential protection scheme (BDPS) that uses synchrophasors and is suitable for as many as 64 terminals [8]. This scheme consists of one SVP and relays with synchrophasor measurement and control capabilities that measure the currents of all the bus terminals and send trip commands to the terminal breakers, as Fig. 7 illustrates. The scheme uses the topology processor available within the SVP to adapt the differential element to different bus configurations and operating conditions.

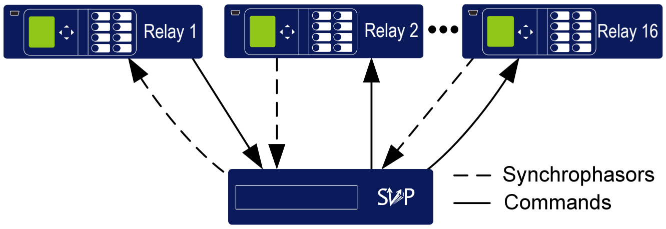

Fig. 7. Distributed BDPS for as many as 64 terminals uses relays at terminal locations and one SVP

The SVP connects to 16 relays with synchrophasor measurement and control capabilities. Each relay can monitor as many as four terminals. The BDPS performs the following tasks:

- Processes the bus topology information to determine the appropriate protection zones.
- Detects bus faults using current phasors and protection zone information.
- Transmits trip signals to the appropriate relays to clear the bus fault.

1) Protection Zone Selection

The BDPS uses the topology processor (TP) and current processor (CP) built into the substation state and topology processor (SSTP) module to determine the protection zones, as Fig. 8 illustrates. The topology processor generates lists of branches within each protection zone. The SSTP requires the bus topology information, the status of breakers and disconnects, the current transformer polarities, and the terminal current measurements.

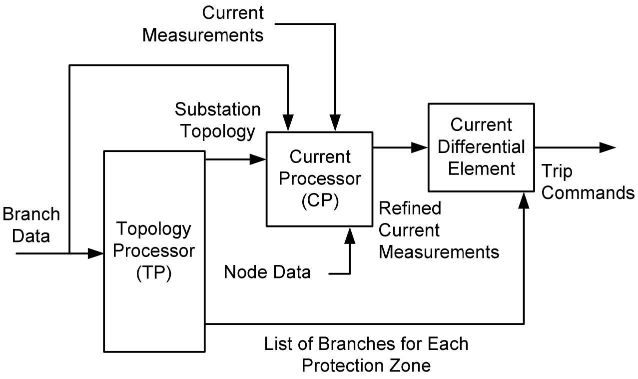

Fig. 8. The distributed bus protection scheme uses the topology and current processors to determine the bus protection zones

2) Current Differential Element

The current differential element, shown in Fig. 9, uses the refined currents from the CP and the list of branches for each protection zone to detect bus faults. The SVP accommodates as many as 300 differential elements. Using the current phasors $\overline{I}_{01},\ldots,\overline{I}_{64}$, the differential element calculates the restraint quantity I_{RT} and the operating quantity I_{OP} according to (5) and (6). The differential element characteristic consists of two slopes: SLP1 and SLP2. SLP1 is effective for internal faults, and SLP2 is effective for external faults. This slope adaptability adds security to the filtered differential element during external fault conditions. The function that generates the differential element characteristic has two output bits. The first bit, FDIF, indicates that I_{OP} is greater than $I_{RT} \bullet \text{SLPn}$. The second bit, 87O, indicates that I_{OP} is greater than the differential element threshold O87P. Assertion of these two bits indicates that the operating point is in the tripping region of the differential element characteristic.

$$I_{RT} = \left|\overline{I}_{01}\right| + \left|\overline{I}_{02}\right| + \cdots + \left|\overline{I}_{64}\right| \tag{5}$$

$$I_{OP} = \left|\overline{I}_{01} + \overline{I}_{02} + \cdots + \overline{I}_{64}\right| \tag{6}$$

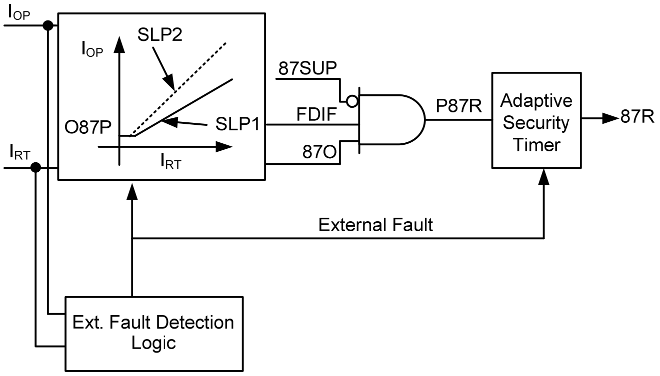

Fig. 9. Current differential element characteristic, external fault detection logic, and 87R output logic

B. Detecting Power Swings to Prevent System Disturbances

The SVP [4] and relays can simplify and improve system integrity protection schemes (SIPS) that use synchrophasors [11]. This section describes a SIPS that detects power swings and out-of-step conditions and activates remedial actions to prevent power system instability [8]. The SIPS consists of two relays with synchrophasor measurement and control capabilities and one SVP. The relays also include programmable logic capabilities to program outputs and perform remedial actions. This SIPS is suitable for two-area power systems.

1) System Integrity Protection Schemes for Two-Area Power Systems

In a two-area power system, the electrical center is the point that corresponds to half of the total impedance between the two sources. The electrical center of the system can be at a transmission line or at any other part of the system. The proposed SIPS requires that the system electrical center must be between the relays that acquire the synchrophasor measurements. Reference [7] describes a SIPS for out-of-step tripping (OOST) that processes 20 synchrophasor messages per second. Fig. 10 shows an alternative to the SIPS presented in [7] that uses the SVP to collect synchrophasor data from two relays at 60 messages per second [8]. In this approach, the SVP runs the SIPS OOST element and sends remedial action commands to the relays that acquire the synchrophasor measurements.

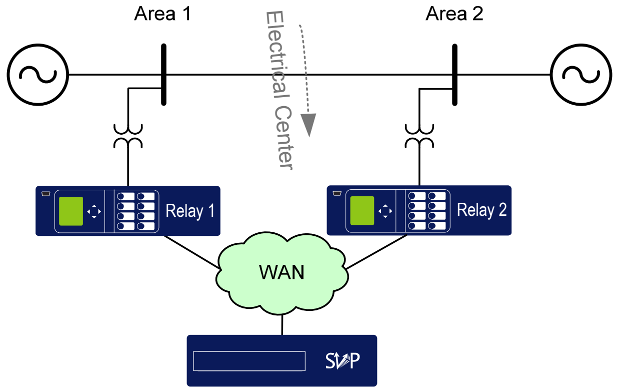

Fig. 10. SIPS suitable for two-area power systems that uses two relays and one SVP for power swing detection

2) *Out-of-Step Tripping Element*

The OOST element that [8] describes uses the positive-sequence voltage synchrophasors that relays acquire at two power system buses to calculate angle difference between these voltages δ_k according to (7). The change of δ_k with respect to time defines the slip frequency S_k, given by (8), and the change of slip frequency with respect to time defines the acceleration A_k between the two areas, given by (9).

$$\delta_k = \text{Arg}\left[V_{1k}^{\text{Relay1}}\right] - \text{Arg}\left[V_{1k}^{\text{Relay2}}\right] \tag{7}$$

$$S_k = \frac{(\delta_k - \delta_{k-1})}{360(t_k - t_{k-1})} \tag{8}$$

$$A_k = \frac{S_k - S_{k-1}}{t_k - t_{k-1}} \tag{9}$$

where:

$\text{Arg}\left[V_{1k}^{\text{Relay1}}\right]$	is the positive-sequence voltage angle measured by Relay 1 at the *k* processing instant.
$\text{Arg}\left[V_{1k}^{\text{Relay2}}\right]$	is the positive-sequence voltage angle measured by Relay 2 at the *k* processing instant.
S_k	is the slip frequency at the *k* processing instant.
A_k	is the angle acceleration at the *k* processing instant.
$t_k - t_{k-1}$	is the relay processing interval.

Fig. 11 shows the characteristic of the OOST element [8] that defines the region of power system stable operation. The OOST element uses the slip frequency and acceleration that the SVP calculates to identify the unstable operating conditions. When the operating point is outside the stable region for 150 ms, the OOST element asserts to indicate this unacceptable operating condition.

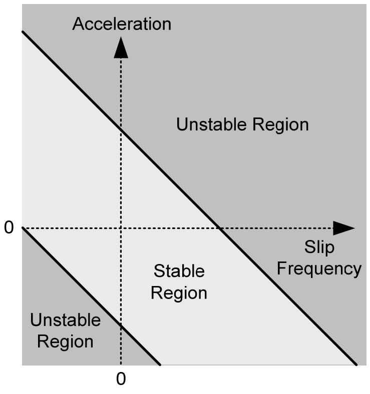

Fig. 11. The OOST element uses slip frequency and acceleration information to identify unstable operating conditions

3) *Implementation of the Out-of-Step Tripping Scheme*

We use the SVP to implement the OOST SIPS. In this scheme, the relays send system voltage phasors to the SVP. The SVP uses the run-time system (RTS) to run the logic and algorithms of the OOST element in real time. After time alignment, the positive-sequence voltage phasors that the relays acquire are available to the RTS. The OOST scheme, shown in Fig. 12, includes the following function blocks:

- PMCU01: Relay at Area 1
- PMCU02: Relay at Area 2
- Diff: Angle difference calculation
- Slip_Calc: Slip frequency calculation
- Acc_Calc: Acceleration calculation
- Out_of_Step_Trip: OOST algorithm and logic
- TRIP: Command to send the remedial action

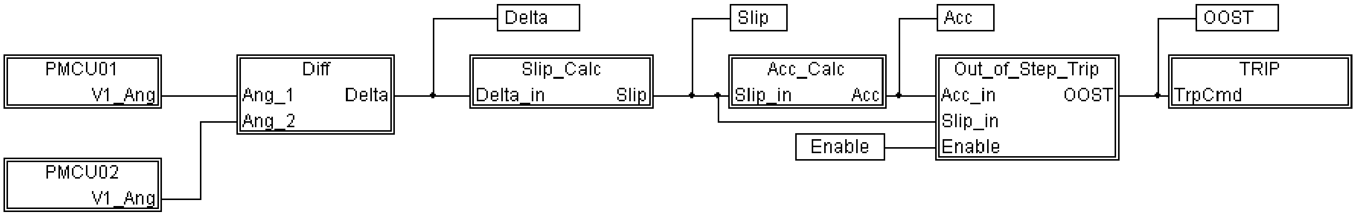

Fig. 12. Implementation of the OOST scheme using the SVP

V. CONCLUSIONS

Now that synchronous phasor measurement data are broadly available from protective relays and meters, it is time to put them to work to improve our power systems. The SVP makes real-time applications practical.

The angle difference between synchrophasors measured at two power system locations can be used to make generator-shedding decisions.

Synchrophasor-based protection complements primary distance protection schemes, provides backup protection, and does not require voltage information. The latter capability allows the relay to protect the line during loss-of-potential conditions.

Synchrophasor-based negative-sequence current differential elements, together with total current FPI, detect high-resistance faults. Communications channel asymmetry does not affect the operating and restraint quantities of the current differential element.

The OOST element does not require power system network parameter and topology information to calculate angle difference, slip frequency, and acceleration between two system areas. Time-aligned current and voltage measurements acquired at different power system locations improve the performance of power swing detection algorithms.

The SVP can perform calculations on synchrophasor data for virtually any application involving vector mathematics. SVP applications described in this paper include a distributed bus differential protection scheme and a system integrity protection system suitable for two-area power systems.

VI. ACKNOWLEDGMENT

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VIII. BIOGRAPHIES

Dr. Edmund O. Schweitzer, III is recognized as a pioneer in digital protection and holds the grade of Fellow of the IEEE, a title bestowed on less than one percent of IEEE members. In 2002, he was elected a member of the National Academy of Engineering. Dr. Schweitzer received his BSEE and MSEE from Purdue University, and his PhD from Washington State University. He served on the electrical engineering faculties of Ohio University and Washington State University, and in 1982 he founded Schweitzer Engineering Laboratories, Inc. (SEL) to develop and manufacture digital protective relays and related products and services. Today, SEL is an employee-owned company, which serves the electric power industry worldwide, and is certified to the international quality standard ISO-9001.

Armando Guzmán received his BSEE with honors from Guadalajara Autonomous University (UAG), Mexico, in 1979. In 1990, he received a diploma in fiber-optics engineering from Monterrey Institute of Technology and Advanced Studies (ITESM), Mexico, and his MSEE from University of Idaho, USA, in 2002. For 13 years, 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. He is presently research engineering manager at Schweitzer Engineering Laboratories, Inc. He holds several patents in power system protection and metering. He is an IEEE Senior Member and has authored and coauthored several technical papers.

Dr. Héctor J. Altuve received his BSEE in 1969 from the Central University of Las Villas, Santa Clara, Cuba, and his PhD in 1981 from Kiev Polytechnic Institute, Kiev, Ukraine. From 1969 until 1993, Dr. Altuve served on the faculty of the Electrical Engineering School at the Central University of Las Villas. In January 2001, Dr. Altuve joined Schweitzer Engineering Laboratories, Inc., where he is currently a Distinguished Engineer and Director of Technology for Latin America. He has authored and coauthored more than 100 technical papers and holds three patents. His main research interests are in power system protection, control, and monitoring. Dr. Altuve is an IEEE Senior Member and a PES Distinguished Lecturer.

Demetrios A. Tziouvaras received his BSEE from the University of New Mexico and MSEE from Santa Clara University. He is an IEEE Senior Member, a member of the Power System Relaying Committee (PSRC), and CIGRE. He was with Pacific Gas and Electric Co. where he held various protection engineering positions including principal protection engineer for 18 years. In 1998, he joined Schweitzer Engineering Laboratories, Inc., where he currently holds the position of senior research engineer. He holds four patents and has authored and coauthored more than 50 technical papers. He served as the convener of CIGRE working group B5.15 on “Modern Distance Protection Functions and Applications” and is a member of several IEEE PSRC and CIGRE working groups.

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