Case Study: Comparative Analysis of Conventional Double Blinder and Rate-of-Change-of-Swing-Center Voltage Methods for Power-Swing Blocking During CFE Major Power-Swing Event

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Abstract—**Phase distance protection schemes are prone to misoperation during power-swing oscillations, contributing to a loss of system stability. For this reason, it is important to have a power-swing detection scheme that allows blocking or tripping at selected points in the system to maintain stability. Traditionally, these schemes have been widely deployed and use impedance-rate-of-change estimation based on concentric zones or blinders that allow measuring the speed of the impedance trajectory during oscillation and making blocking or tripping decisions. However, these schemes have limitations related to the zones' reach and maximum load. Additionally, exhaustive studies are required to cover all possible swing scenarios to determine maximum oscillation speed.**

In this technical paper, we analyze the performance of conventional schemes during a real-world power-swing event that did not block distance elements because of the mentioned limitations. We compare the actual performance with an algorithm based on the principle of rate-of-change-of-swing-center voltage that is not influenced by parameters of the transmission lines or load levels and that does not require user settings, which eases scheme deployment and commissioning on Comisión Federal de Electricidad (CFE) existing relays currently in service. We also compare the actual performance with a newer method of continuous measuring of rate-of-change of impedance.

I. INTRODUCTION

A power swing is a phenomenon that occurs when the voltage phase angle of one or more sources within the same synchronized network varies with respect to another. Larger power swings can occur after a major event or disturbance, such as a fault and subsequent loss of transmission capacity, as in this case study, slow fault clearing time, or loss of load or generation, removing key assets from the system. This alters the electromechanical balance of one or more generators, increasing or decreasing active power output and causing accelerating power and voltage angle changes from their initial equilibrium point. All faults cause power swings, but the system is stable if it is able to absorb energy and reach a new equilibrium point (i.e., transient stability). "Power swings are therefore [common] and unavoidable phenomena that allow the system to find a new power flow pattern and remain stable if conditions allow" [1]. A power swing is unstable when a set of generators slip a pole or one set of generators operates at a different frequency than another set of generators (i.e., loss of synchronism or out-of-step condition) relative to the rest of the system. Characteristics of power swings continue to change as more unconventional low- or no-inertia sources, such as solar or wind turbines, are added to the power system. The behavior of these sources during power system transients and swings is driven by their proprietary control algorithms, creating additional challenges because lower total inertia at some regions leads to faster oscillation and greater uncertainty about simulation results because of the lack of detailed simulation models for some inverter-based plants.

Large power swings can cause undesired operations in protective relays, for phase distance protection mainly, because large changes of power and angle may cause apparent impedance to enter the distance element operation characteristic. An apparent impedance entering protection Zone 1 causes an instantaneous trip. However, the instantaneous protection zones are not the only concern. The activation of further zones used for delay backups or pilot schemes can also cause undesired outages of transmission lines. This can aggravate the system condition, by losing additional lines and transmission capacity, and contribute to a loss of system stability. To mitigate this problem, distance relays have power-swing detection algorithms, which prevent unnecessary outages of transmission lines from the interconnected system, providing time for dedicated control schemes to maintain the transient stability of the system within its margins, such as load- or generation-shedding schemes or segregating the system only at planned locations on transmission links to remove the oscillations. Therefore, it is necessary to detect oscillations and generate a power-swing blocking (PSB) signal for distance elements.

There are two possible scenarios for power swings, as shown in Fig. 1. For a stable power swing, the apparent impedance may enter one or more distance protection zones and then exit through the same quadrant it entered. Blocking is always desirable in this situation, as the system will recover stability.

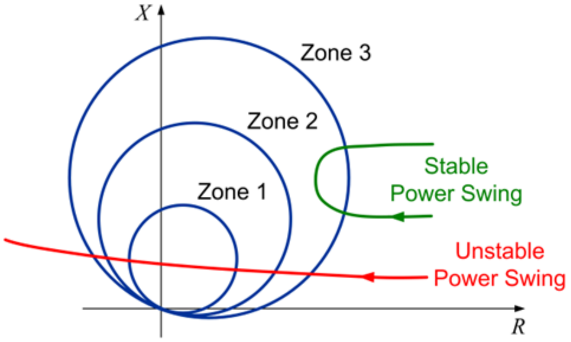

Fig. 1. The impedance trajectory for a stable and an unstable power swing.

For an unstable power swing, the apparent impedance enters the protection zone from one quadrant and then exits through the opposite quadrant, which indicates that part of the system has lost synchronism (that is, there is more than a 180-degree angular difference between systems). It may be desirable to trip some lines and disconnect the systems from one another to avoid major damage. However, deciding where to separate the systems requires careful studies, so out-of-step tripping (OOST) is enabled at these locations. For the remainder of the lines, PSB is required.

In this paper, we present the performance of distance protection schemes during an actual power-swing event on the Mexican power system. During the power swing, the PSB function failed to operate and did not block the required distance elements. The PSB blocking scheme was based on the conventional double blinder scheme to estimate the rate-of-change-of-impedance to detect an out-of-step condition. Then, this event was played back in relays using the principle of rate-of-change of swing center for PSB detection and the performance of both methods are compared. Section II describes the conventional method commonly used in the Mexican power system, and several other utilities, based on the double blinder method. Section III analyzes the field event. Section IV describes the swing-center voltage (SCV) rate-of-change method available on modern relays. Section V is a comparison of the two methods for the same field events. Section VI presents a recent alternative method based on continuous rate-of-change of impedance. This method does not require settings definitions and is suitable for systems with low inertia.

II. PSB METHOD USED DURING THE CASE STUDY EVENTS

Comisión Federal de Electricidad (CFE) applies PSB on protection schemes with distance protection. In this paper, we refer to conventional methods as those based on the double blinder method that employs impedance blinders and timers to estimate the impedance rate of change. These methods are widely deployed because they have been historically implemented by most manufacturers since the days of electromechanical technology.

Despite the simplicity of relay implementation in conventional methods, several aspects need to be considered when adjusting relays correctly because of the different challenges posed by the behavior of the system with an increasing number of low-inertia sources.

The conventional method principle of operation assumes that the positive-sequence impedance enters the first blinder and, subsequently, the second blinder after a certain delay time, which is inversely proportional to the impedance rate of change during oscillation. Therefore, if the measured time difference delay between the impedance entering the outer blinder, or zone, and the impedance entering the inner blinder, or zone, is longer than the set time, a PSB condition is declared. If this time is shorter than the set time, no blocking occurs.

The double blinder method has certain setting requirements. The inner blinder should be set greater than all distance elements that require blocking. The outer blinder should be set smaller than the worst-case load impedance of the transmission line. A security margin is required between the inner blinder and the farthest-reaching (largest) distance element and between the inner and outer blinders, on the order of 20 percent. (See Appendix A). In the event of a fault occurring during a power swing, it is assumed that the apparent impedance of the fault jumps faster than for oscillations within the protection zones, allowing the distance elements to operate to clear the fault. There is only a small delay, according to the time response of the distance measurement filter and the processing cycles of the relay to detect a fault during a power swing, typically on the order of one cycle.

Distance elements should still work in the case of short-circuit faults during oscillation. For unbalanced faults, supervision of negative- or zero-sequence current is typically used to remove the blocking and enable the protection functions to trip. Three-phase faults are more challenging and other techniques (outside the scope of this paper) are used to enable a trip on these conditions, even with lower performance than normal conditions.

Methods based on impedance rate of change and impedance blinders are limited by the time it takes for the impedance path to cross the power-swing detection blinders. Exhaustive transient stability studies are desirable to cover multiple scenarios and contingencies and determine the fastest possible oscillation. Coordination between blinders is complicated in certain cases, such as very long lines with high loads or worst-case scenarios, like out-of-service parallel lines and emergency temporary loading conditions. The margin between the last protection zone and the load impedance may be too narrow and, therefore, the time between activation of outer and inner blinder is too quick for fast oscillations. It may be close to the filtering delay of the apparent distance measurement, so it may not be possible to differentiate the filtering delay from a power swing with enough of a security margin.

A highly resistive and/or evolving fault could cause the apparent impedance to move slowly within the PSB detection blinders, causing unwanted blocking and delaying the operation of distance schemes.

“The impedance trajectory during a power swing is not necessarily a horizontal or near-horizontal path (right-to-left or left-to-right [on impedance plane]). The impedance may traverse along complicated paths, such as approaching [almost] vertically and retreating horizontally" [1].

III. ANALYSIS OF REAL EVENT IN MEXICAN POWER SYSTEM

The Mexican transmission grid operated with a high percentage of renewable energy in the North regions, and power transmission was high to the South areas but still below limits for N-2 contingencies between the north and south systems. The sequence of events leading to a power swing began when a wildfire caused phase-to-ground faults in two parallel transmission lines. The transmission lines tripped within one minute of each other at a critical power transmission link between two regions. The trip of the second line led to a power swing because of the loss of transmission capacity. Other transmission links between the north and south were expected to remain in service to keep the system interconnected until system protection or remedial action schemes could act and stabilize the system. However, the distance and pilot schemes of the other two parallel transmission lines, with similar parameters and protection settings, were unable to detect the oscillation and activate their PSB functions. Then distance elements tripped. Fig. 2 shows a simplified view of the North and South areas and location of transmission lines tripped due to wildfire and transmission lines where the PSB scheme failed to detect the power swing. Fig. 3 shows more details of power flows on the link and the substations involved.

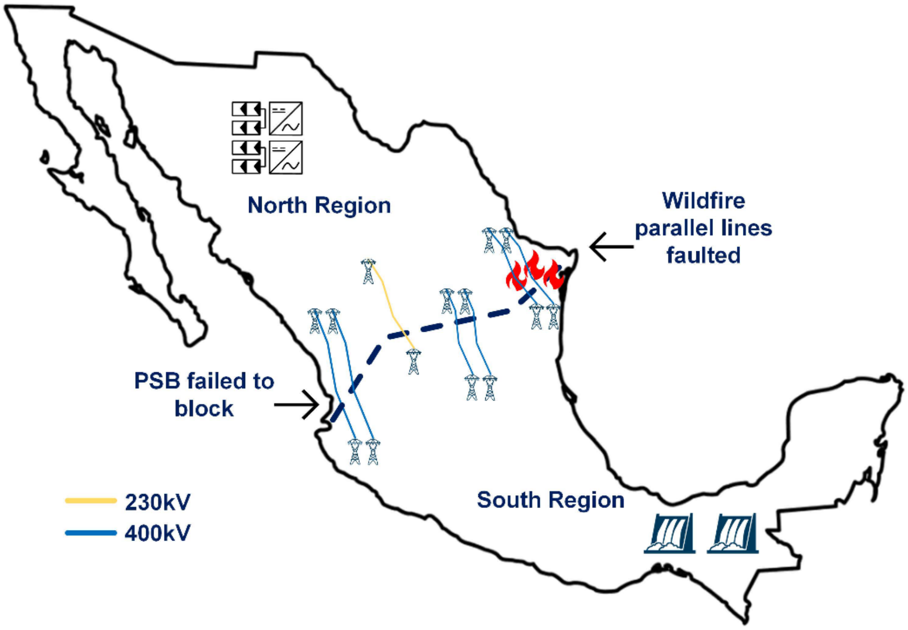

Fig. 2. Location of transmission lines under discussion.

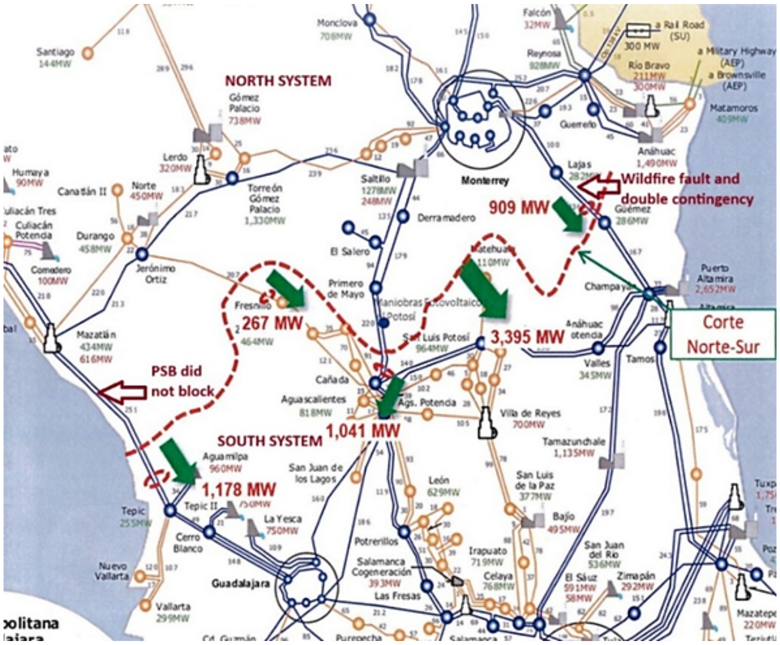

Fig. 3. Mexico's national transmission grid.

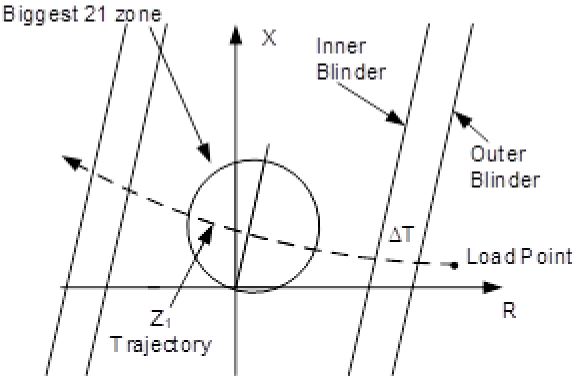

Fig. 4. Double blinder PSB characteristic.

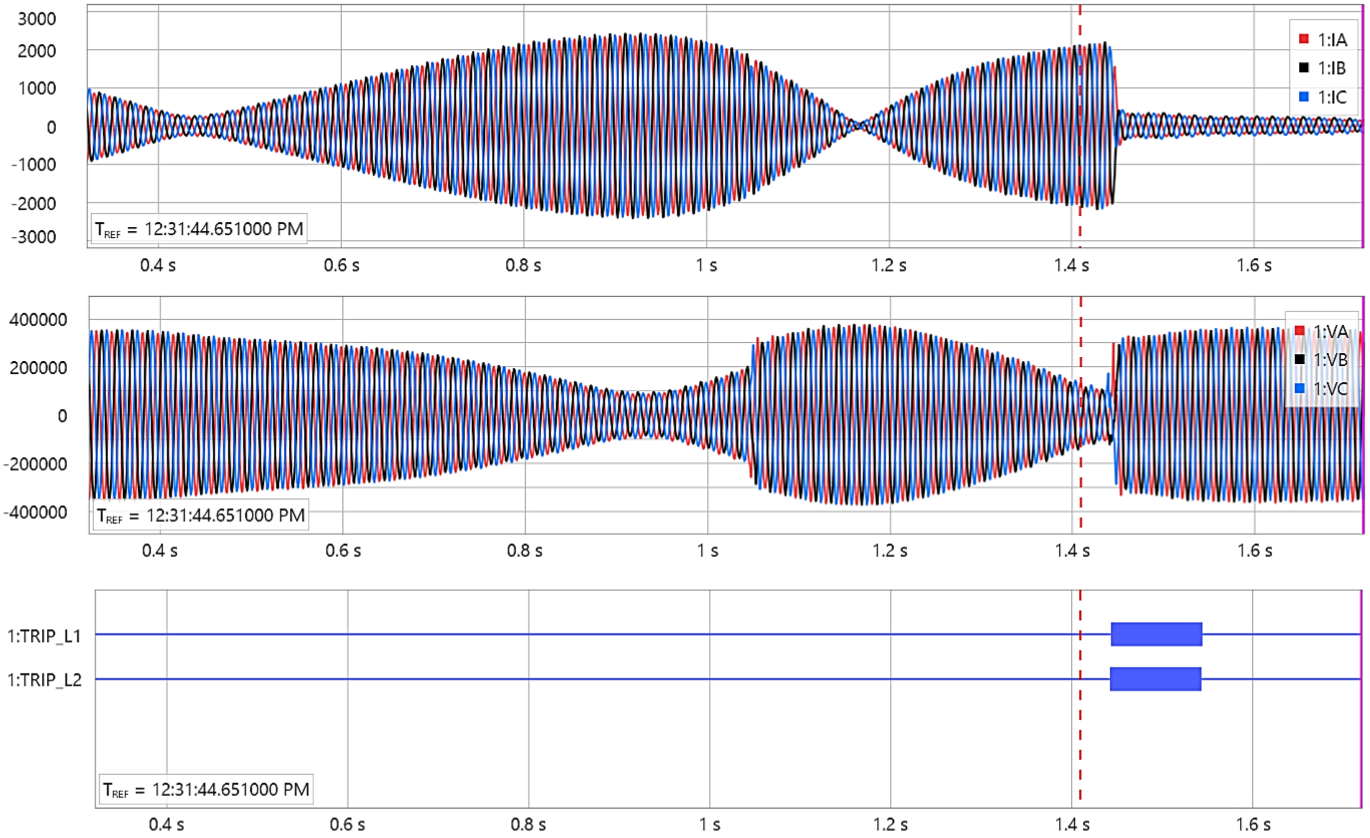

Fig. 5. Power swing recorded by DFR at one of the parallel lines being analyzed.

The impedance double blinder-based PSB (see Fig. 4) function was active in all four relays of both lines. This power-swing event oscillography, shown in Fig. 5, was recorded by protective relays and dedicated digital fault recorder (DFR) devices, which allow the forensic analysis of the event. The geographic location of the transmission lines from which events were obtained is shown in Fig. 3.

A. *Analyzing Protection Settings*

The first step in this analysis is to review the protective relay settings. In the relays installed on these transmission lines, it is possible to select which distance zones will be blocked by the PSB elements. Double blinder settings are the positive and negative values for reactance and resistance to construct the two-zone characteristics. "Power swings cause a significant change in the apparent resistance; therefore, the swing impedance typically enters the power-swing characteristic via the left-hand or right-hand resistive blinders" [2]. When using a conventional double blinder method, the top and bottom settings shown in Table I are not critical as long as the distance zones are encompassed by the blinders.

Table I shows that three blocking elements are configured, corresponding to the blocking of Zones 1, 2, and 4 of the distance elements shown in Table II. This is quite common, since the goal is to block the instantaneous trip zones and the zones that generate time backup and pilot protection signals. It is important to notice the resistive reach of the blinders, where there is a margin of only 0.87 secondary ohms between the inner and outer blinder (as shown in Fig. 6) and the oscillation detection time is half a cycle (8.3 milliseconds at 60 Hz). This means that for the algorithm to be able to detect oscillation, it must cross the outer and inner blinders in a time of no less than 0.5 cycles. For any case where the oscillation speed is faster than these settings, the blocking elements will not be activated, and Zones 1, 2, and 4 will operate as configured in protection settings.

TABLE I
PSB SETTINGS

Setting	Value	Description
OOSB1	Y	Block Zone 1
OOSB2	Y	Block Zone 2
OOSB4	Y	Block Zone 4
OSBD	0.5 Cycles	PSB delay
X1T6	13.48*	Inner reactance—top
X1B6	–13.48*	Inner reactance—bottom
R1R6	7.31*	Inner resistance—right
R1L6	–7.31*	Inner resistance—left
X1T7	14.35	Outer reactance—top
X1B7	–14.35*	Outer reactance—bottom
R1R7	8.18*	Outer resistance—right
R1L7	–8.18*	Outer resistance—left

*Settings in secondary ohms

TABLE II
DISTANCE ZONE SETTINGS

Setting	Value	Description
Z1P	8.91*	Instantaneous trip
Z2P	13.36*	Pilot signal
Z3P	11.14*	Reverse blocking for pilot scheme
Z4P	13.29*	Time-delayed trip

*Settings in secondary ohms

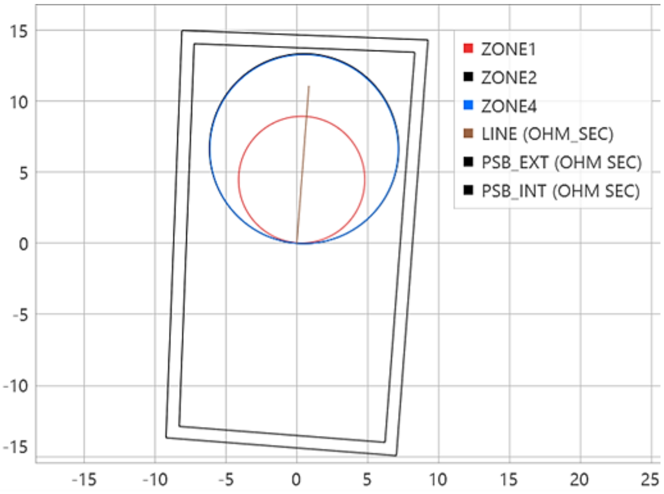

Fig. 6. Protection distance and PSB zones for this event.

The timer settings indicate that rapid oscillation was expected; however, in this case it was even faster than expected, partly due to the high penetration of solar energy in northern Mexico. An alternative to improve the performance of the PSB detection when the double blinder method is used is to review the PSB zones' reach, but this is not feasible because increasing the reach of the outer blinder would overlap with the load impedance of the line under high load conditions. Maximum load for emergency conditions is 1,350 MVA for this line, when parallel lines are out of service and considering the thermal limit with two conductors per phase, at 400 kV voltage level.

The recommended procedure to set PSB zones and an OSBD timer is explained in Appendix A, with a load angle of 45 degrees and some margin. Using this procedure, minimum Zload = 14.06 secondary ohms and R7 = 8.23 secondary ohms. The configured setting of the outer blinder of the PSB in the relay during this event is 8.18 secondary ohms.

B. *Analyzing Oscillography Records*

The record obtained from DFR shows that this event is a power-swing phenomenon, where the relays trip during the second oscillation (see Fig. 5). Fig. 5 also shows that the second oscillation cycle was faster than the first one and that the current is at maximum level when voltage is at its minimum because the measuring point is close to the electrical center of the oscillation and the system was approaching unstable conditions. For relay behavior, the analysis is based primarily on the events recorded by the protective relays instead of DFR records. This offers the advantage of working with the filtered signals used in the protection algorithms, in addition to having the status of the internal protection elements and logic enabled in the schemes.

Fig. 7 shows the oscillography of one of the relays used in further analysis and illustrates the simultaneous activation of the distance protection Zones 1, 2, and 4. Fig. 8 shows behavior at the remote-end terminal of the same line where the distance protection zones are not activated; the impedance trajectory does not cross the distance protection zones.

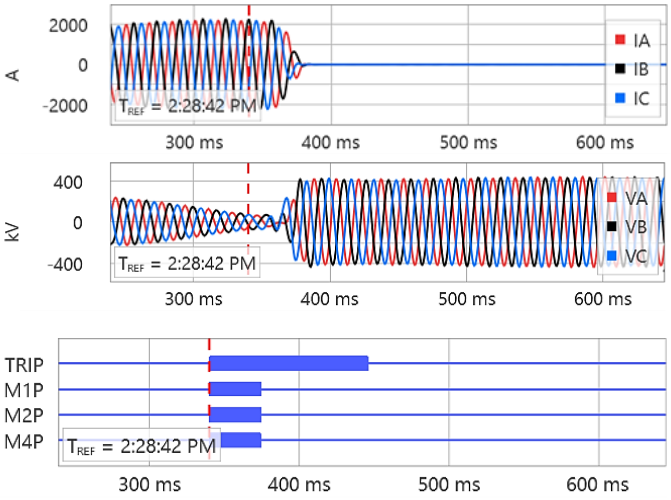

Fig. 7. An event recorded by a protective relay showing distance protection activation, trip, and no activation of PSB.

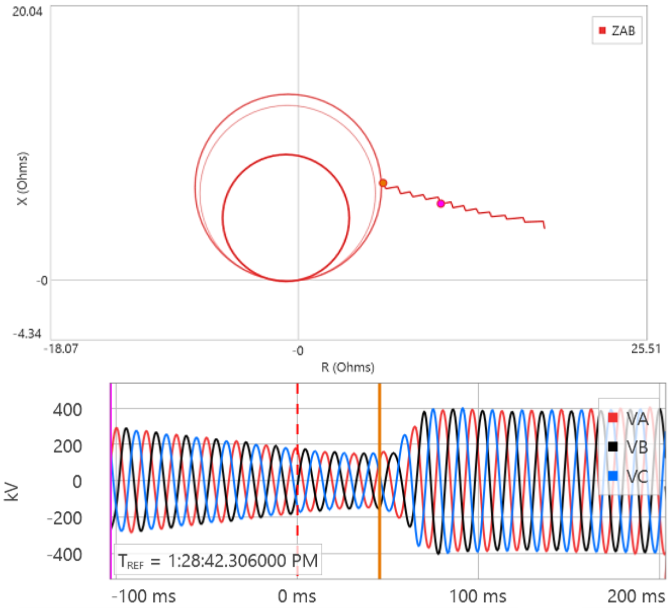

Fig. 8. An event recorded from the remote end to the relay of Fig. 6.

The relay record was used to model the positive-sequence impedance measured by the relay and compare it to the distance protection zones and PSB blinders, as shown in Fig. 9 and Fig. 10. This allows us to determine the time elapsed since the impedance crossed the outer and inner blinder and compare it to the OSBD setting. The impedance travel time between the blinders of the PSB was 4.3 milliseconds, below the half-cycle timer setting that corresponds to an estimated rate-of-change of 3.37 ohms per cycle. This is why the PSB did not operate for this event.

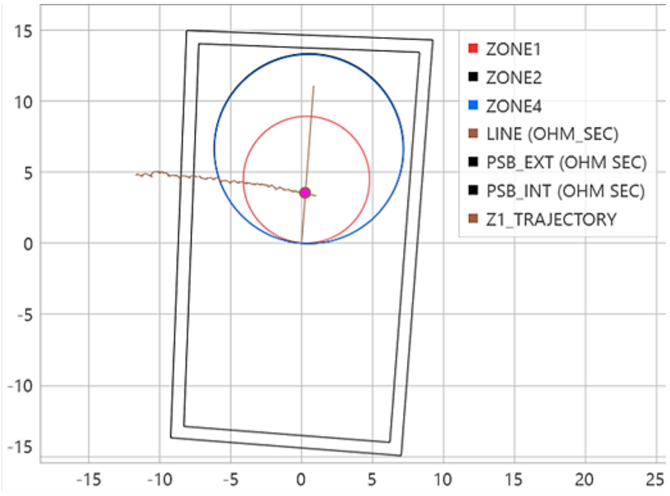

Fig. 9. Impedance trajectory crossing PSB zones faster than the OSBD setting.

This first part of the analysis demonstrates one of the previously mentioned weaknesses of the double blinder impedance-based methods: the coordination between protection and PSB zones. For cases like this, with long and heavily loaded lines, it becomes very difficult to set the correct resistive reach to detect power swings, even when typical criteria are followed.

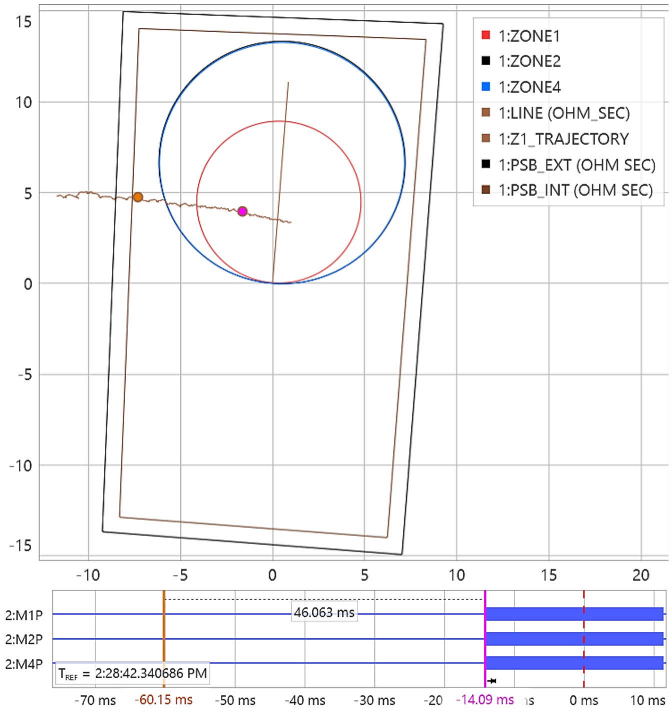

Fig. 10. Operation of distance zones.

From the digital signals of the event record, we can determine that 46 milliseconds after the impedance crosses the inner PSB zone, all the forward phase distance protection zones operate (Zone 1, Zone 2, and Zone 4) causing the transmission lines to trip, as shown in Fig. 10.

Distance Zones 1, 2, and 4 are activated simultaneously because they are supervised by the same phase directional element that uses the positive-sequence impedance angle and declares forward direction from –30 degrees to 120 degrees.

In this case, although the PBS scheme was configured to block the distance element zones in the event of an oscillation with such characteristics, it was an unusually rapid oscillation when the system was reaching unstable conditions. The tripping of the transmission lines due to the operation of the distance units contributed to segregating the network and preventing a greater number of generators from losing synchronism, which could aggravate the widespread consequences of the event. The main concern with the lack of blocking for this event was that the lines that tripped may not be the optimal locations.

System conditions have changed since these schemes were originally commissioned. Currently, a growing number of nonconventional generation sources, such as photovoltaic and wind, connect to the system through inverters. These types of sources change the nature of the system by being low or no inertia and remaining synchronized through their own control algorithms, instead of the mechanical inertia of traditional synchronous generators. This not only poses a challenge for oscillation detection methods but also for the transient stability studies necessary for modeling PSB and tripping schemes. The nonconventional sources present in the grid when this event occurred contributed to relays with settings calculated some years ago exhibiting unexpected performance under the conditions of a power system with new behavior.

IV. THE SCV METHOD: AN EASILY DEPLOYABLE ALTERNATIVE

The proposed SCV rate-of-change method has zero settings and is independent of network parameters. It is based on monitoring the rate-of-change of line SCV and "does not require any stability studies or user settings for the proper blocking of relay elements that are prone to operate during stable or unstable power swings. The method is applicable to long, heavily loaded transmission lines that pose great problems in the application of PSB elements based on traditional [double blinder] methods" [3]. This is an easily deployable solution for the utility, as a large proportion of the already installed base of transmission line relays have this function available or may be updated with it.

"SCV is defined as the voltage at the location of a two-source equivalent system where the voltage value is zero when the angles between the two sources are 180 degrees apart" [3]. Fig. 11 shows the phasor diagram of a general two-source system with the SCV shown as the phasor from origin o to the point o′.

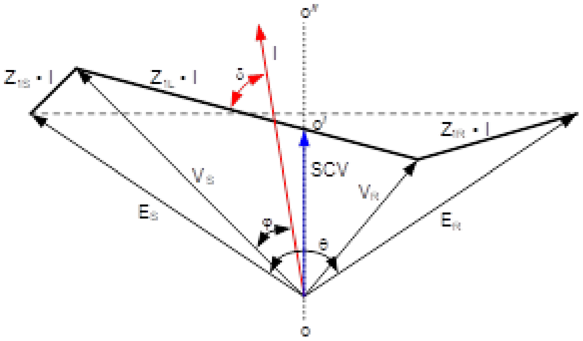

Fig. 11. Phasor diagram of a two-source system.

The magnitude of the SCV is related directly to the angle between sources and is bounded by a lower limit of zero and upper limit of one per unit, unlike other electrical quantities influenced by a variety of system parameters, such as impedance, power, or current. It is independent of system parameters like line and source impedances.

It may seem necessary to measure the voltage in both sources to implement this method in protective relays; however, it is possible to estimate the magnitude of the SCV with only local measurements. A good approximation is to use the local voltage and current by applying (1):

$$SCV \approx |Vs| \bullet \cos\phi \qquad (1)$$

Where |Vs| is the magnitude of the locally measured voltage and ϕ is the angular difference between Vs and the local measured current. The resultant phasor |Vs| • cosϕ is the projection of the voltage on the current axis and is close to the value of the SCV, as illustrated in Fig. 12. This estimate will differ slightly from the system SCV, but it is still appropriate for tracking a power swing and is a very close approximation of the SCV rate of change. Therefore, we will refer to the phasor |Vs| • cosϕ as SCV from now on.

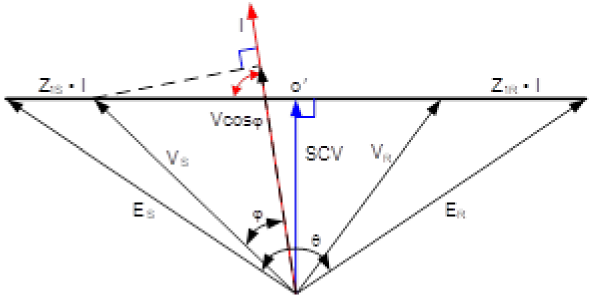

Fig. 12. Phasor |Vs| • cosϕ is a projection of local voltage onto local current.

There are also two important differences to point out between the SCV of the system and the local estimate of the SCV.

1. When there is no load flowing on a transmission line, the current from a line terminal is basically the line-charging current that leads the local terminal voltage by about 90 degrees. In this case, the local estimate of the SCV is close to zero and does not represent the true system SCV [3].
2. The local estimate of the SCV has a sign change in its value when the difference angle of two equivalent sources goes through zero degrees. This sign change results from the reversal of the line current. That is, φ changes 180 degrees when δ goes through the 0-degree point. The system SCV does not have this discontinuity [3].

The implementation of this principle in protective relays is based on the positive-sequence SCV and consists of three functions for the detection of power swings, which are an SCV slope detector, a swing signature detector, and a dependable PSB detector. The basic logic is shown in Fig. 13. The slope detector monitors the absolute value of the rate-of-change of the SCV, the magnitude of SCV1, and the output of a discontinuity detector and generates a PSB output when it detects a significant change in the derivative of the SCV that occurs during a power swing. According to "Zero-Setting Power-Swing Blocking Protection,"

> The swing signature detector logic stores the absolute value of the first order derivative, dSCV1, continuously in a buffer memory over an interval of a few cycles. The maximum value of this buffer memory is then established as $dSCV1_{MAX}$. [If a real fault is detected] this slope maximum value $dSCV1_{MAX}$ will be very high because discontinuity has occurred in the SCV1 waveform. A number of the older samples are then compared to this maximum value….
>
> The dependable PSB (DPSB) function will assert the PSB signal in situations where neither the slope detector nor the swing signature detector can detect a power swing fast enough. This will happen particularly after a lasting external fault has been cleared and the network embarks into a power-swing situation. The [DPSB] function issues a temporary PSB signal

> and, after some delay, the slope detector detects any power swing in the network. Therefore, the purpose of the dependable power-swing detector is to supply a temporary DPSB signal that will assert the PSB bit to compensate for the pickup delay of the slope detector.
>
> An example of this type of situation might occur after a [slow-clearing] fault right behind or at the remote end of a transmission line on a marginally stable network. …[I]f a close reverse or forward fault clears with a significant delay, there is a possibility that the network has entered a power swing. [In this case], the Z1 trajectory at the relay may cross [into the] Zone 2 or Zone 1 phase-mho [characteristic] right after the fault clears, [but before the slope detector has detected the power swing. In this case,] the phase mho elements of the relay [may] issue a trip signal as a result of the power swing and not because of a real fault. [3]

To overcome this problem, the dependable power-swing detector asserts the DPSB signal to block the distance elements until the slope detector has had time to detect a power swing [3].

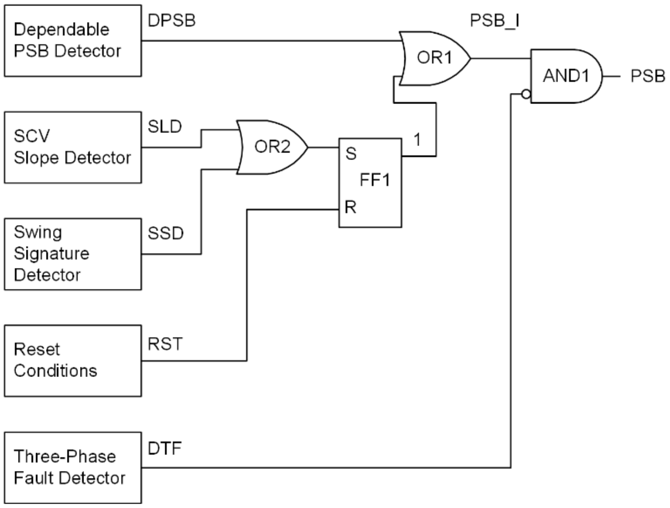

Fig. 13. Basic SCV PSB logic.

To increase security and reduce the sensitivity of the scheme, it is complemented with a start zone that supervises the slope detector, a polygon that covers all the protection zones (see Fig. 14) and detects impedance trajectories that could cross the protection zones. Its reach is not really a critical issue and does not require user settings; it adjusts automatically, taking into account the protection zones and OOST zones, if activated.

This case study is focused on the performance of the PSB functions, so we will only mention that the SCV-based oscillation detection method also has OOST implementations and fault detection mechanisms during power swings, which release the protection elements to operate, if necessary.

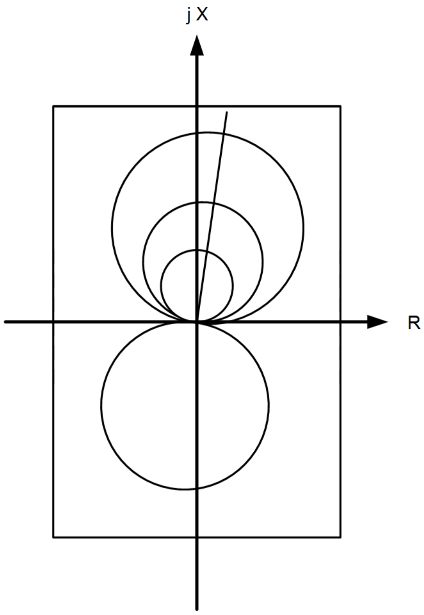

Fig. 14. The PSB starter zone.

V. COMPARISON: PERFORMANCE OF THE SCV RATE OF CHANGE FOR THE POWER-SWING EVENT

The conventional method originally implemented did not detect the power swing for this event, as mentioned in Section III.

The utility was interested in comparing the performance of the conventional method versus the SCV rate-of-change method for this specific event.

We used the oscillography records of the protective relays and a test set and played back the COMTRADE event files into relays of the same characteristics in two scenarios:

A. Events Played Back Using the Original Settings As in the Real Event

This validated the nonactivation of PSB during the real event. It also allowed monitoring of all the relay elements related to power-swing detection that were not stored in the original relays due to the event report configuration.

As seen in Fig. 15, the signals replayed into the relay in the laboratory environment are the same as those recorded by the relay during the real event, demonstrating that the test was performed correctly and the relay behavior is as expected.

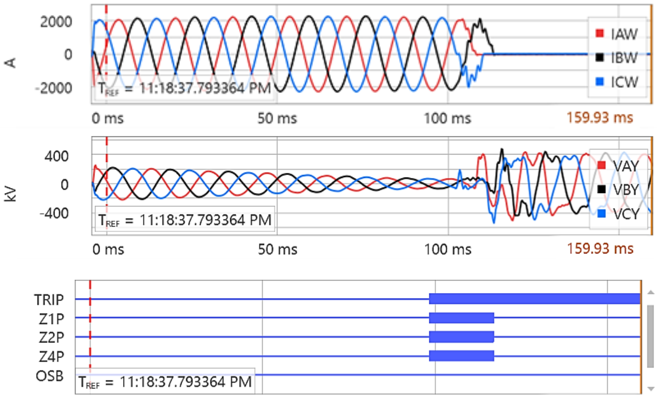

Fig. 15. Event played back with the same settings as the real event.

B. Events Played Back and Relay Configured With the SCV Rate-of-Change Method

The relay configuration was changed from the conventional to the SCV method by changing only one setting related to method selection. Then the COMTRADE event file was played back into the relay in the laboratory and the elements related to the PSB function were monitored.

When the event was played back with SCV enabled, the PSB signal was issued 31.5 milliseconds before the activation of the distance protection elements in the original relay, as we can see in Fig. 16. The distance zones used for pilot schemes and the instantaneous trip zone were successfully blocked by the PSB signal.

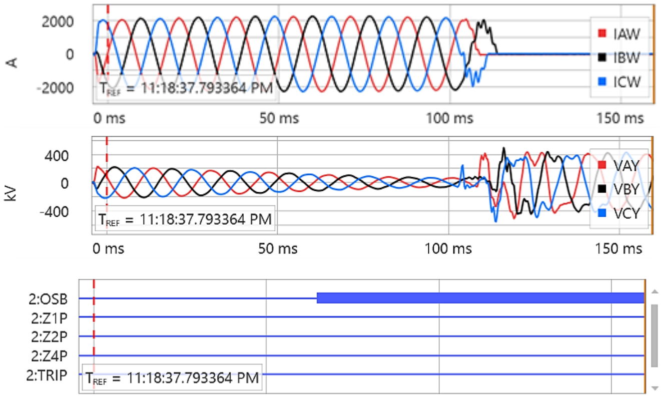

Fig. 16. Event played back with the SCV method.

The testing routine consisted of multiple repetitions where 100 percent of the tests resulted in the detection of the power swing and successful activation of the PSB. We verified that only by enabling the PSB function can the scheme detect oscillation without the need to perform a transient stability study or use network data. As Fig. 16 shows, the performance of the scheme is satisfactory for the speed of the oscillation experienced in this event.

By measuring the time that it takes for the impedance to cross the outer and inner PSB detection zones in the original event, we can estimate the rate-of-change of impedance as seen by protective relays. See Table III.

TABLE III
ESTIMATED IMPEDANCE RATE-OF-CHANGE OF FIELD EVENTS

Relay event	**Δt (ms)**	**Rate of change (Ω/cycle)**
Relay under analysis	4.3	3.3
Remote-end relay	5.6	2.58

The results of all the test repetitions were consistent and according to expectations. A summary is shown in Table IV.

TABLE IV
SUMMARY OF RESULTS OF LABORATORY TEST ROUTINES

Played back event	**PSB method used**	**PSB activation**	**Distance zones activation**
1	Conventional	No	Yes
1	SCV	Yes	No
2	Conventional	No	Yes
2	SCV	Yes	No

For the selected points in the system where it is necessary to block and keep links connected, according to the utility network studies and simulations, the rate-of-change of SCV is the most convenient alternative.

We can conclude that for this event, considering oscillation speed and coordination of PSB detection blinders for a long, heavily loaded line, an impedance-based method is very difficult to set and is not suitable in this case.

The utility has been aware of different rate-of-change methods available in modern relays for a while; however, due to different manufacturer implementations, they did not have a standard way to develop algorithm approval or test and standardize relay settings methodology. On the other hand, conventional method approval and relay settings using the double blinder method was standardized and tested several years ago, and it was working well until this event.

The utility has developed an oscillation real-time simulation and a relay hardware-in-the-loop testing environment to test and approve PSB schemes for line distance relays with or without settings. It is in the process of standardizing regular settings procedures to include this method. The main drivers of this addition are the simplicity of the rate-of-change method, faster oscillation conditions, and uncertainty of the behavior of the oscillations with a higher penetration of renewable energies based on inverters.

VI. CONTINUOUS MEASURING OF RATE-OF-CHANGE OF IMPEDANCE: A NEWER ALTERNATIVE

Another power-swing detection method is now available for protective relays based on a continuous measurement of the rate-of-change of impedance, unlike conventional methods that only make a raw measurement of the impedance rate of change. It continuously measures dZ/dt (the apparent impedance derivative), so coordination with detection blinders and protection zones is not necessary [4]. The logic works on a per-loop basis, allowing the healthy loops to block and faulted loops to operate during a power swing. The logic does not require user settings, since a factory constant is used as the swing rate threshold, and it includes a module to remove blocking for faults during a power swing. OOST logic for unstable swings is available.

The following section describes the key components of the PSB logic. This section is taken directly from [4].

A. *Impedance-Rate-of-Change Measurement*

Fig. 17 illustrates a trajectory of an impedance that traverses the impedance plane from right to left during a power swing. The dots represent complex impedance values: *k* is the index of the newest impedance value while *k*–1 is the index of the previous value. The logic processes the input data at a rate of once a millisecond. [4]

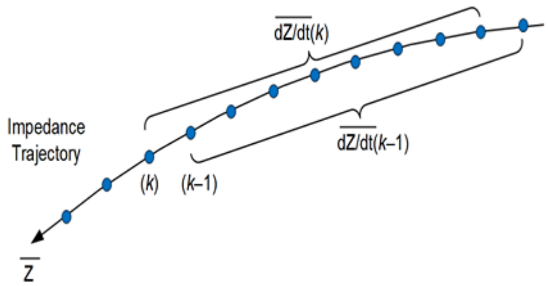

Fig. 17. Impedance-rate-of-change measurement [4].

The logic calculates … dZ/dt as a complex value. This complex value provides information about both the rate and direction of the impedance change. The magnitude of the dZ/dt signal tells the logic how fast the impedance is traversing. The angle of the dZ/dt signal tells the logic the angle (direction on the impedance plane) of the impedance trajectory. [4]

B. *Impedance-Rate-of-Change Consistency Logic*

Implementation includes the impedance-rate-of-change consistency logic illustrated in Fig. 18. When deciding if the change in impedance at the *k*th processing interval is consistent with a power swing, the logic uses the 5 ms-old change in apparent impedance (*k*–5 ms) as a reference. The new value of the change in impedance (the value at sample *k*) must point in approximately the same direction as the 5 ms-old change (sample *k*–5 ms); the logic allows a trajectory angle difference within ±20 degrees. Also, the new value must not be too different in magnitude from the old value. [4]

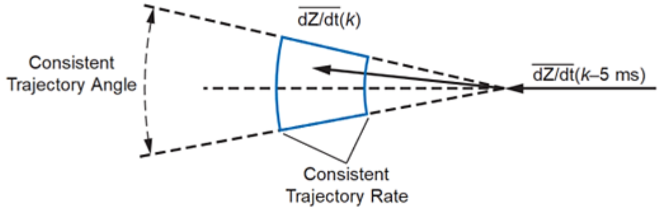

Fig. 18. Consistency trajectory of impedance [1].

The impedance rate of change must be within that small region in the next processing interval for the PSB logic to consider the impedance trajectory consistent with a power swing. [4]

1) *Impedance Supervisory Zones*

PSB uses two supervisory zones, and OOST logic uses one supervisory zone.

- Power-swing impedance supervisory zone (Z_{PSB}): This zone is used to supervise the PSB logic, as shown in Fig. 19. This zone encompasses all distance protection zones that are enabled and configured to be blocked by the PSB logic. The logic does not declare a power swing until the impedance enters the Z_{PSB} zone. This reduces spurious PSB assertion during load changes. [4] [Reference [5] describes how the logic determines the size of Z_{PSB}.]

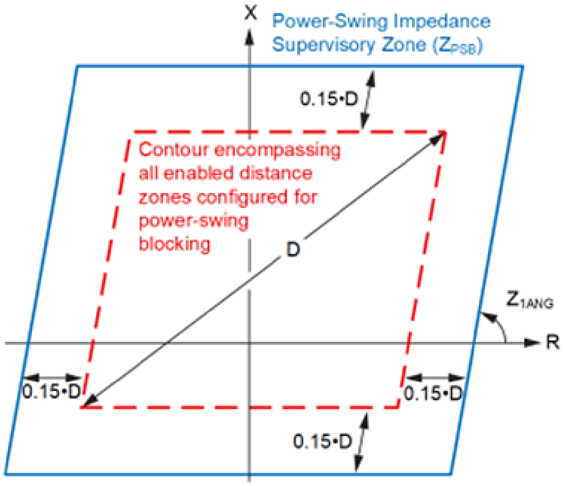

Fig. 19. PSB supervisory zone.

- Power-swing fault detection zone (Z_{FLT}), shown in Fig. 20: This is a narrow quadrilateral zone placed close to the line impedance and used to reset the PSB signal when the impedance enters that zone and stays there, i.e., when it ceases to traverse the impedance plane. [4]

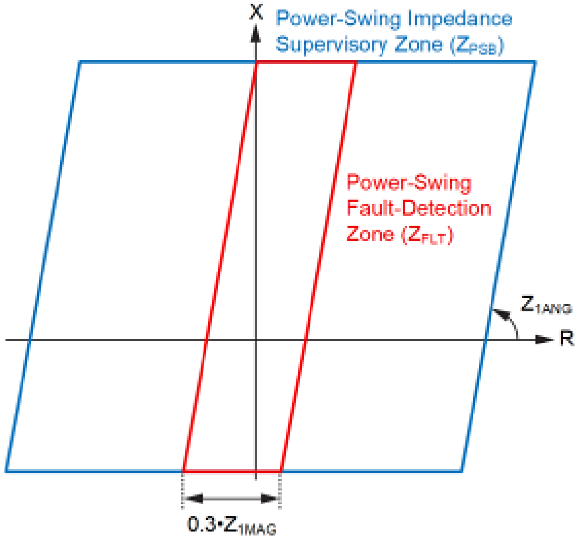

Fig. 20. Fault during power-swing detection zone.

The longest event we have, obtained from the DFR, was reproduced on a modern relay that features logic for continuously measuring the rate-of-change of impedance (see Fig. 21). The plot in black depicts the Z1 trajectory during the event.

When the PSB function is activated for Zones 1, 2, and 4, the new logic detects the power swing and activates the PSB function; the protection zones do not generate a trip signal.

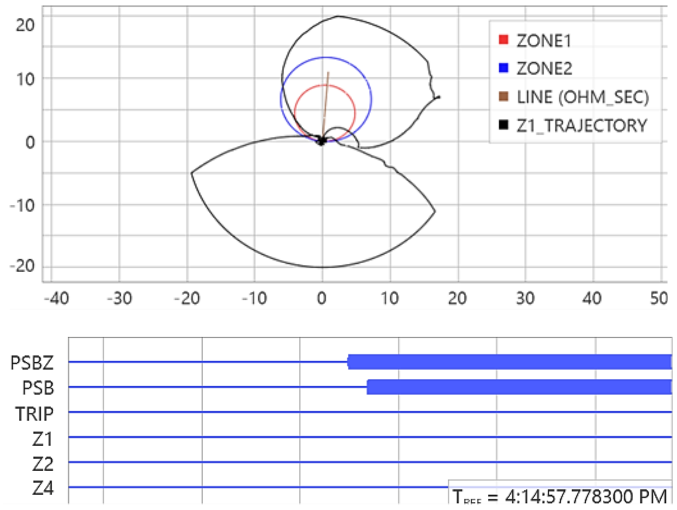

Fig. 21. DFR event played back in relay with continuous rate-of-change of impedance and PSB enabled.

The test is then repeated with the PSB function disabled (see Fig. 22), and the distance elements operate when the impedance crosses the protection zones.

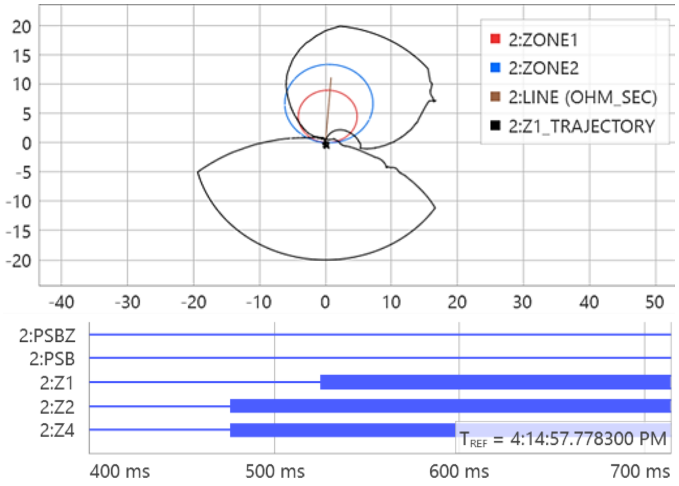

Fig. 22. DFR event played back in relay with continuous rate-of-change of impedance and PSB disabled.

VII. CONCLUSION

Conventional power-swing detection methods, based on double blinder impedance zones, have been the main methods used by utility companies for a long time and are generally well known. In some cases, power-swing relays are applied based on historical data, i.e., where the system has previously had a power-swing condition that resulted in an undesired operation. [2]. The inertial behavior of the system is also well known. However, power-swing phenomena do not occur frequently in interconnected power systems, so protection engineers do not often have the opportunity to analyze the behavior of these schemes in the face of a real event. Therefore, settings are based on criteria and studies that may not address all possible scenarios. In a real event, the weaknesses of the double blinder method mentioned in previous sections led the scheme to perform differently than expected. In addition, power systems are constantly changing, and the number of low-inertia sources whose behavior is controlled by their own control algorithms is increasing, which modifies the system response and the conditions under which power swings occur.

In this paper, we present the performance of conventional PSB schemes under a real-world event in the utility grid, where the scheme was unable to detect the power oscillation phenomenon as expected. We present two alternative methods that do not depend on transmission line and system parameters, such as impedances or load levels, which resolve the difficulty of coordinating impedance zones.

The first method, based on the rate-of-change of SCV, is easily deployable, since a large part of the installed base of utility line protection relays have this built-in function, requiring only that the conventional method is deactivated and the SCV-based method is activated. The second alternative is the continuous measurement of the rate-of-change of impedance, which requires the addition of recently developed relays to the utility's protection schemes that have this function available and bring other benefits, such as line monitoring, MHz event reports, etc.

In both cases, the advantages are impressive, since neither requires user settings nor system studies (studies are required only to define the system points to be blocked and tripped). As presented in previous sections, their performance during the CFE oscillation event would have been successful.

The implementation of these alternative methods is simple and feasible. The deployment of SCV requires no investment at most points in the network, and has been successfully tested with events under real-world conditions in a modern power system.

VIII. APPENDIX A: CALCULATION OF PSB BLINDER SETTINGS

A. *Resistance Blinders*

Set inner Zone 6 (X1T6, R1R6, X1B6, and R1L6) to encompass the outermost zone of phase distance protection that you have selected for PSB.

Zone 2 is the outermost characteristic for this particular example. Include safety margin (20 percent for this example).

$$R1R6 = 1.2\frac{Z2P}{2 \bullet \sin(Z1ANG)} \tag{2}$$

where:

Z2P is the Zone 2 mho phase distance element reach.
Z1ANG is the impedance line angle.

Set Zone 7 outer resistance blinders according to maximum load. In other words, set the Zone 7 outer right-hand resistance blinder just inside the corresponding minimum export load impedance locus (maximum load locus).

Determine the minimum load impedance that the relay measures:

$$ZLmin = VLn/ILmax \tag{3}$$

Assuming the maximum load angle as ± 45 degrees and a safety factor of 90 percent, we calculate R1R7 as follows:

$$R1R7 = 0.9 \bullet ZLmin \bullet \cos[45° + (90° - Z1ANG)] \tag{4}$$

B. Reactance Lines

Zone 6 inner reactance lines, X1T6 and X1B6, should completely encompass the outermost zone of phase distance protection that you want to block from tripping during a power swing. Include a safety margin (20 percent).

$$X1T6 = 1.2 \bullet Z2P \tag{5}$$

The distance between Zone 6 and Zone 7's top reactance lines should equal the distance between Zone 6 and Zone 7's right-hand resistance blinders.

$$X1T7 = X1T6 + (R1R7 - R1R6) \tag{6}$$

The time delay to detect power-swing condition OSBD is derived from the impedance trajectory shown in Fig. 23.

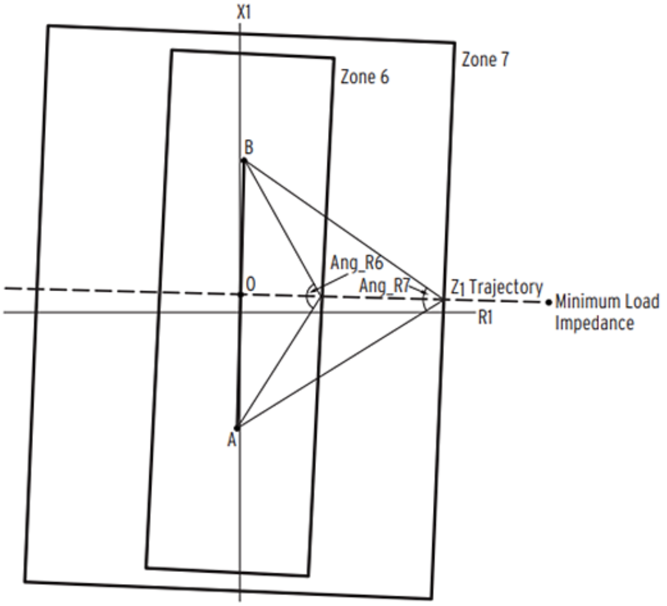

Fig. 23. Swing trajectory to determine the OSBD setting.

Line section AB is the transfer impedance, ZT. The horizontal dashed line represents the trajectory of the power swing perpendicular to line section AB. The trajectory passes through the midpoint of line section AB.

$$ZT = Z1S + Z1L1 + Z1R \tag{7}$$

where:

ZT is the transfer impedance.
Z1S is the positive-sequence source impedance.
Z1L1 is the positive-sequence impedance for Line 1.
Z1R is the positive-sequence remote impedance.

$$Ang_{R6} = 2 \bullet \mathrm{atan}[\frac{\frac{|ZT|}{2}}{R1R6}] \tag{8}$$

$$Ang_{R7} = 2 \bullet \mathrm{atan}[\frac{\frac{|ZT|}{2}}{R1R7}] \tag{9}$$

$$OSBD = \frac{(Ang_{R6} - Ang_{R7}) \bullet fnom}{\frac{360}{cycle} \bullet fslip}\ cycles \tag{10}$$

Select the closest setting available in protective relay.

IX. APPENDIX B: SCV LOCAL ESTIMATE

The relation between the SCV and the phase angle difference, δ, of two source-voltage phasors can be simplified to the following:

$$SCV1 = E1 \bullet \cos\left(\frac{\delta}{2}\right)$$

E1 is the positive-sequence source magnitude equal to ES that is assumed to be also equal to ER. We use SCV1 to represent the fact that we shall use the positive-sequence swing-center voltage in the power-swing detection.

The absolute value of the SCV is at its maximum when the angle between the two sources is zero, and this value is at its minimum (or zero) when the angle is 180 degrees. This property has been exploited so one can detect a power swing by looking at the rate-of-change-of the SCV. The time derivative of SCV1 then becomes the following:

$$\frac{d(SCV1)}{dt} = -\frac{E1}{2}\sin\left(\frac{\delta}{2}\right) d\delta/dt$$

This equation provides the relation between the rate-of-change-of the SCV and the two-machine system slip frequency, dδ/dt [3].

X. APPENDIX C

To determine the size of the power-swing impedance monitoring zone, the logic inspects the configuration of the distance zones enabled and configured for PSB. Fig. 24 illustrates an impedance contour encompassing all distance zones enabled and configured for PSB.

> The encompassing contour has a quadrilateral shape with symmetrical left and right blinders. The logic calculates the size of the contour by using settings of the distance zones, the positive-sequence line impedance magnitude and angle (Z1MAG, Z1ANG), and the basic rules of geometry. The logic establishes the ZPSB power-swing impedance supervisory zone by adding a 15 percent margin around the encompassing contour.
>
> The ZPSB power-swing impedance supervisory zone does not need to be set by the user and it does not need to be coordinated with the load and fault impedance areas. [4]

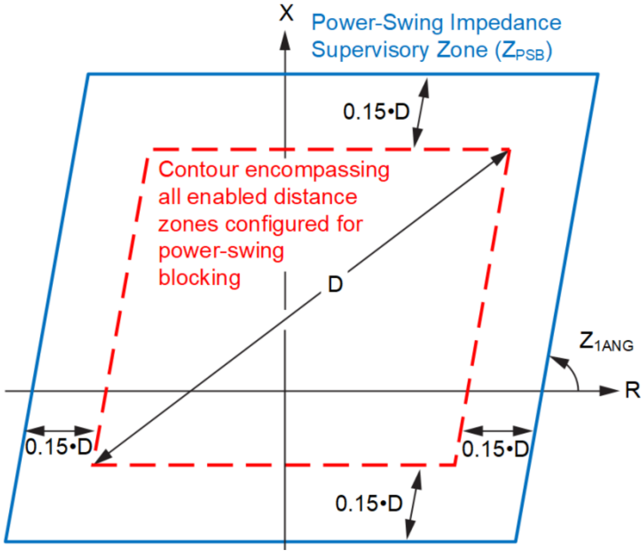

Fig. 24. Power-swing impedance supervisory zone.

XI. REFERENCES

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XII. BIOGRAPHIES

Carlos Vizcaino Núñez received his BS in mechanical and electrical engineering from the University of Colima, Manzanillo, Mexico, in 2002, and an MS in electrical engineering from the Center for Research and Advanced Studies (CINVESTAV) of the National Polytechnic Institute, Guadalajara, Mexico, in 2004. From 2005 to 2010, he was a field application and commissioning engineer for Comisión Federal de Electricidad (CFE). He is presently the manager of the Protection department in the western region for CFE. His research interests include power system protection and electromagnetic transients modeling and simulation.

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