Breaker Pole Scatter and Its Effect on Quadrilateral Ground Distance Protection

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This paper was presented at the 68th Annual Conference for Protective Relay Engineers and can be accessed at: http://dx.doi.org/10.1109/CPRE.2015.7102187.

For the complete history of this paper, refer to the next page.

Presented at the
68th Annual Conference for Protective Relay Engineers
College Station, Texas
March 30–April 2, 2015

Originally presented at the
41st Annual Western Protective Relay Conference, October 2014

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***Abstract*—In this paper, the effect of breaker pole scatter on quadrilateral ground distance elements is investigated using a simple two-source power system with two short transmission lines. A case study of an unintended operation of a Zone 1 quadrilateral ground distance element due to the delayed opening of a breaker pole in an actual system is presented. A simple solution based on relay logic is proposed to improve the security of quadrilateral ground distance elements. The effectiveness of the proposed solution is verified by running a real-time test using a Real Time Digital Simulator (RTDS®).**

I. Introduction

Circuit breakers (simply called breakers in this paper) are capable of making and breaking an electric circuit under normal and abnormal conditions, such as short circuits. In power system protection schemes, protective relays detect abnormal power system conditions and breakers isolate a faulted section. When a relay detects a fault, it sends a trip signal to the breaker(s). The trip signal energizes the breaker trip coil, which then mechanically opens the contacts of the breaker poles. The current flowing through a breaker is not interrupted when the breaker contacts begin to separate. The current continues to flow through an electric arc that is developed between the opening contacts. The fault current is typically interrupted at the next zero crossing. However, as the current waveform approaches the zero crossing, the arc becomes unstable. As a result, the current is slightly interrupted before the physical zero crossing. This is known as current chopping [1].

Because of a phase shift between the phase currents, the breaker interrupts currents at different points in time. This is known as breaker pole scatter. Various dielectric media, such as air, oil, vacuum, and sulfur hexafluoride (SF_6) gas, are used as interrupting media in breakers. Vacuum breakers are common in medium-voltage systems, and SF_6 breakers are widely used in high-voltage systems. For most modern high-voltage breakers, the interruption time can be as low as 2 to 3 cycles [2].

In short transmission lines, the fault resistance during line-to-ground faults can be significantly higher than the line impedance. Mho distance elements cannot provide adequate protection on short lines for faults with high resistance. Quadrilateral distance elements are preferred for short transmission line protection because they provide increased resistive coverage over traditional mho elements [3] [4].

This paper describes breaker pole scatter and its effect on quadrilateral ground distance protection. Section II is an overview of the breaker pole scatter phenomenon. Section III reviews mho and quadrilateral ground distance elements and their application to short transmission lines. Section IV presents simulation results that show the effect of breaker pole scatter on quadrilateral ground distance elements. Section V discusses the unintended operation of a quadrilateral ground distance element at a Florida Power & Light Company (FPL) substation due to the pole scatter of a remote breaker. This section also includes a proposed solution and the results from Real Time Digital Simulator (RTDS®) testing that demonstrate the effectiveness of the solution. Finally, Section VI presents our concluding remarks.

II. Breaker Pole Scatter

The fast interruption of fault current is essential for increasing personnel safety, limiting equipment damage, improving power system stability, and enhancing power quality. Fig. 1 shows the time chart of the fault clearing process from the occurrence of the fault to the arc extinction in all three breaker poles. The relay operating time is the time between fault inception and the relay output contact closing to energize the breaker trip coil. For modern digital relays, this time can be less than 1 cycle. The breaker opening time is the time interval from the instant the trip coil energizes to the instant when the breaker contacts have separated in all three poles. The breaker arcing time is the time interval between the instant of the first initiation of an arc and the instant of final arc extinction in all poles. Breakers are rated for interrupting time, which is the time interval between the trip coil energizing and when the arc is extinguished in all poles [5].

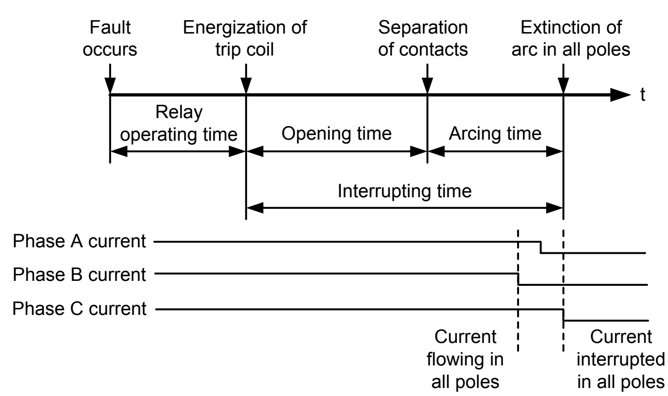

Fig. 1. Fault clearing time includes relay and breaker operating time.

When the breaker arcing contact begins to separate from the fixed contact, an electric arc appears between these contacts. The high current creates a highly ionized metal vapor that sustains the arc by providing a conductive path. Most breakers extinguish the arc by using a combination of the following three basic arc interruption principles [6]:

- Lengthening of the arc.
- Deionization by recombination of ions and free electrons.
- Cooling of the arc.

Usually, the arc is extinguished at the first current zero crossing when the dielectric recovery voltage across the moving contacts is greater than the voltage required for an arc restrike. In three-phase systems, the current zero crossings generally occur at different instants in the three phases. Hence, the breaker poles interrupt the arc at different times following trip coil energization. This phenomenon is known as breaker pole scatter.

The breaker pole scatter time can be affected by various factors, such as the breaker operating mechanism, the dielectric strength of the arc interrupters, and external circuit parameters [7]. The breaker operating mechanism provides energy to separate the arcing contacts from the fixed contacts. Because of equipment strain and wear, and the unequal distribution of fault current over the three phases, the breaker pole operating time can change over time. After many years of operation, degradation of the dielectric medium can occur, resulting in varying arcing time. Depending on the power system parameters and the type of short circuit, the fault current may have different dc offset components in the three phases, which cause additional (and different) zero-crossing delays for each phase. Delayed current zero crossing is significant for faults close to a generating station due to the high X/R ratio [8] [9]. The delayed zero crossing of a faulted phase can lead to increased breaker pole scatter time.

Breaker pole scatter monitoring is available in modern digital relays, and therefore it is good practice to use it to detect high breaker pole scatter. Fig. 2a shows the normal interruption of three phase currents. The three poles open in succession with a time separation of 1/6th cycle (i.e., 3.3 milliseconds at 50 Hz or 2.8 milliseconds at 60 Hz). Sometimes a breaker pole does not interrupt current at its first zero crossing. Fig. 2b shows the delayed interruption of the Phase A current by 0.5 cycles, which results in an increased breaker pole scatter time.

High breaker pole scatter with a pole interruption delayed by 0.5 cycles or more can have a negative impact on the recovery voltage and power system protection. Reference [10] describes the negative impact on the recovery voltage after the capacitive charging current of a 550 kV overhead line is interrupted with a breaker pole opening delayed by 0.5 cycles.

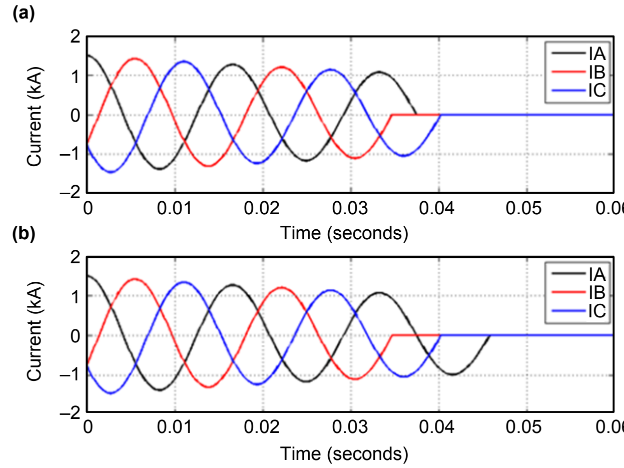

Fig. 2. Breaker currents for normal interruption (a) and currents during high breaker pole scatter (Phase A current interruption delayed by 0.5 cycles) (b).

III. Mho and Quadrilateral Ground Distance Elements

For the FPL system described in this paper, the distance elements include an instantaneous Zone 1 and two time-delayed forward-looking zones, Zone 2 and Zone 4. Zone 3 is used as a reverse-looking zone for directional comparison blocking (DCB) schemes.

Zone 1 provides primary protection for around 80 percent of the line. Zone 2 provides primary protection for the line section not covered by Zone 1 and backs up the remote bus and part of the adjacent lines. The other time-delayed forward-looking zone (Zone 4) provides backup protection for the whole length of the longest adjacent line. Fig. 3 shows the time-distance characteristics of four distance relays in a two-source power system. A fault close to the middle of Line 2 causes Zone 1 operation at both line ends. The relays at Bus Y and Bus Z pick up instantaneously and trip Breaker B3 and Breaker B4 to clear the fault. In the event Breaker B3 fails to trip, Zone 4 of the upstream relay at Bus X will pick up and, after a coordination time delay, trip Breaker B1 to clear the fault.

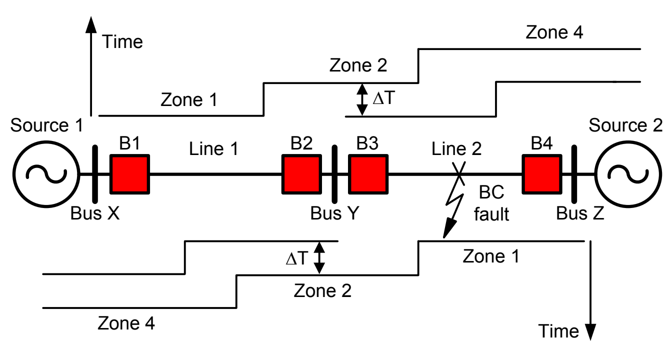

Fig. 3. Zones of distance protection in a two-source power system.

To analyze distance element operation, the apparent impedance and the element operating characteristic are plotted on the impedance or R-X plane. The distance element operates when the apparent impedance enters the operating characteristic. During normal load conditions, the apparent impedance plots close to the real axis of the impedance plane, typically out of the operating characteristic. However, during faults, the apparent impedance moves closer to the line impedance and typically plots inside the operating characteristic.

The two types of distance elements typically available in a digital relay are mho and quadrilateral.

The mho characteristic can be obtained with a single comparator, is inherently directional, and has a well-defined reach [11]. A mho element uses a comparator to test the angle between a line-drop-compensated voltage and a polarizing reference voltage [12]. Fig. 4 shows the operating characteristic of a self-polarized mho element. Mho distance elements are widely used for transmission line phase and ground fault protection.

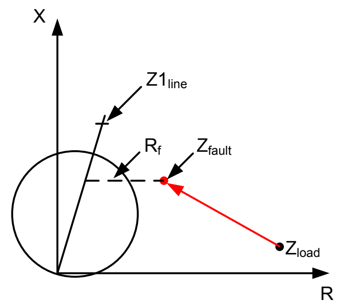

Fig. 4. The mho element does not operate for a fault with fault resistance R_f on a short line.

The majority of faults on transmission lines are ground faults caused by insulator flashover or an object touching the conductor. For insulator flashover scenarios, the fault current flows through the tower structure to ground. The fault resistance of insulator flashover faults is the sum of the arc resistance, the tower footing resistance, and the resistance of the return path through ground. For scenarios where an object is touching the conductor, the fault current distributes to ground through the object. The fault resistance in this case is the sum of the resistances of the object and the ground return path. Typical tower footing resistance ranges from 5 ohms to 100 ohms [4]. The resistance of an object (a tree, for example) can also be very high. Therefore, fault resistance is usually higher for ground faults than for phase faults.

A mho distance element is more affected by fault resistance than a quadrilateral distance element, especially for shorter lines. This condition can push the apparent impedance of a fault on the line outside of the mho circle. However, increasing the size of the circle (longer reach) to accommodate these high-resistance faults is not acceptable for Zone 1 and creates the potential for tripping on load or for faults on other lines. Fig. 4 shows a fault with fault resistance R_f. In this case, the mho element does not operate because the apparent impedance falls outside the operating characteristic.

The quadrilateral characteristic typically provides good fault resistance coverage in short transmission lines because the resistive reach can be set independently from the reactance reach. Fig. 5 shows that a fault not detected by the mho ground distance element would be detected by the quadrilateral ground distance element.

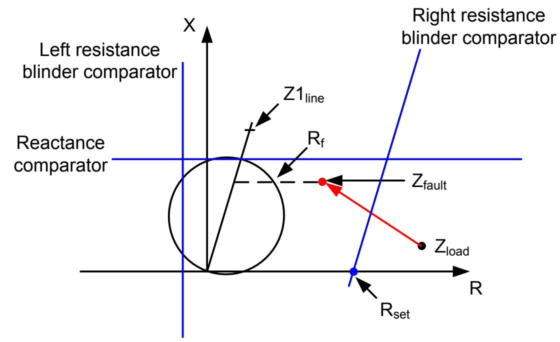

Fig. 5. A quadrilateral ground distance element provides better fault resistance coverage than a mho ground distance element.

The quadrilateral characteristic is created with the following four comparators [13]:

- A reactance comparator.
- A directional comparator (not shown in Fig. 5).
- A left resistance blinder comparator.
- A right resistance blinder comparator.

A reactance comparator uses a digital product comparator to test the angle between the line-drop-compensated voltage and polarizing current [12], as shown in (1).

$$S = \operatorname{Im}\left[dV \bullet I_p^{*} \right] \quad (1)$$

where:

I_p = the polarizing current (this is typically 3I0 or 3I2).

Equation (2) is used to calculate the line-drop-compensated voltage.

$$dV = \left(m \bullet Z \bullet I - V \right) \quad (2)$$

where:

V = the measured voltage.

m = the reach setting of the protection zone.

Z = the positive-sequence line impedance.

$I = I_{phase} + k0 \bullet 3I0$ (the phase current plus the residual current compensated by k0) [12].

$k0 = \dfrac{(Z0 - Z1)}{3 \bullet Z1}$.

Z0 = the zero-sequence line impedance.

Z1 = the positive-sequence line impedance.

The reactance comparator operates when S > 0.

$$0 < \text{Im}\left[dV \bullet I_p^*\right]$$
$$0 < \text{Im}\left[\left(m \bullet Z \bullet I - V\right) \bullet I_p^*\right]$$
$$0 < \text{Im}\left(m \bullet Z \bullet I \bullet I_p^*\right) - \text{Im}\left(V \bullet I_p^*\right) \quad (3)$$
$$\text{Im}\left(V \bullet I_p^*\right) < \text{Im}\left(m \bullet Z \bullet I \bullet I_p^*\right)$$
$$\frac{\text{Im}\left(V \bullet I_p^*\right)}{\text{Im}\left(Z \bullet I \bullet I_p^*\right)} < m$$

Substitute I with $I_{phase} + k0 \bullet 3I0$.

$$\frac{\text{Im}\left(V \bullet I_p^*\right)}{\text{Im}\left(Z \bullet \left(I_{phase} + k0 \bullet 3I0\right) \bullet I_p^*\right)} < m \quad (4)$$

The left-hand side of (4) is the reactance calculation. If the reactance calculation is less than the reach setting *m*, the reactance comparator picks up.

Quadrilateral ground distance elements are preferred for ground fault protection of short transmission lines and for ground fault protection of lines of any length because of their good fault resistance coverage. However, quadrilateral ground distance elements are affected by load flow, which creates a tilt in the apparent impedance [13].

IV. Breaker Pole Scatter and Quadrilateral Ground Distance Elements

In order to study the effect of breaker pole scatter on quadrilateral ground distance elements, a two-source power system with two short lines (shown in Fig. 6a) is modeled using an RTDS. Using this model, the security of the Line 1 Zone 1 distance elements under the breaker pole scatter of the Line 2 breakers (with a fault on Line 2) is studied.

Table I lists the system parameters in primary units. These parameters are from an actual FPL system, which is described in the next section. Both lines are very short and have strong sources at both ends. The Breaker B1 and Breaker B4 relays are connected to receive input signals from the RTDS and to trip the breakers in a closed-loop test system. Each line is protected using mho phase, mho ground, and quadrilateral ground distance elements. Zone 1 reach is set to 80 percent of the line length, and Zone 2 reach is set to 125 percent. The quadrilateral ground distance element resistive reach is set to cover a fault resistance of 24 ohms for Line 1 and 20 ohms for Line 2.

Table I
Two-Source Power System Model System Parameters

System Parameter	Line 1	Line 2	Source 1	Source 2
Z1MAG (ohms)	5.34	4.45	4.36	7.05
Z1ANG (degrees)	80	80	84.71	83.93
Z0MAG (ohms)	14.4	13.95	6.49	11.77
Z0ANG (degrees)	75	76	79.53	80.83
Length (miles)	7.8	6.51	NA	NA

A BC fault at 36 percent of Line 2 from the Bus Z end is applied, and two test cases are simulated. In the first case, all breakers interrupted the fault current at the first zero crossing. In the second case, one pole of Breaker B4 interrupted current at the second zero crossing, which delayed current interruption by 0.5 cycles.

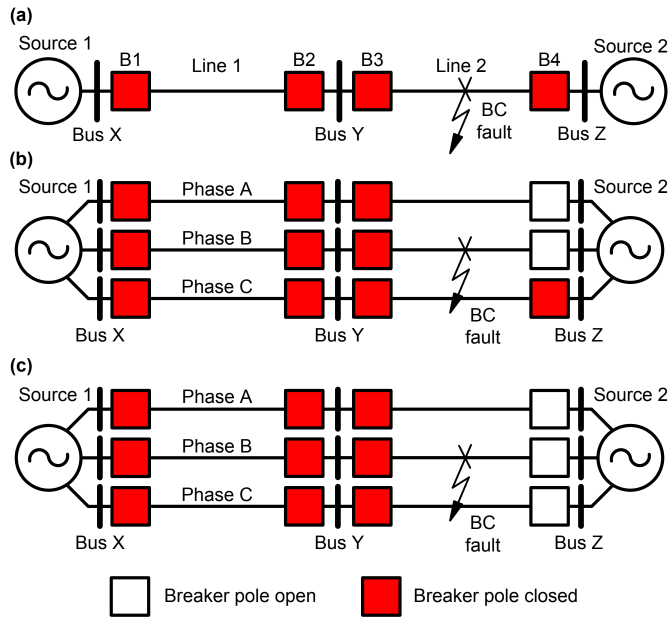

Fig. 6. Two-source power system model has two short transmission lines (a), BC fault on Line 2 is followed by normal current interruption in Poles A and B of Breaker B4 at Bus Z (b), and Breaker B4 Pole C interrupts current with a 0.5-cycle delay following interruption of Poles A and B (c).

A. Normal Fault Current Interruption

All breakers in the system were modeled such that each pole interrupts current at the first zero crossing. When a BC fault is applied on Line 2, the relays at Bus Z detect the fault as a Zone 1 line-to-line fault and trip the line. Fig. 7a shows the three phase currents measured by Breaker B4, and Fig. 7b shows the zero-sequence current magnitude. For this BC fault, breaker Poles B and C interrupt the current at the same instant. Because this is a line-to-line fault, no zero-sequence current flows through the lines.

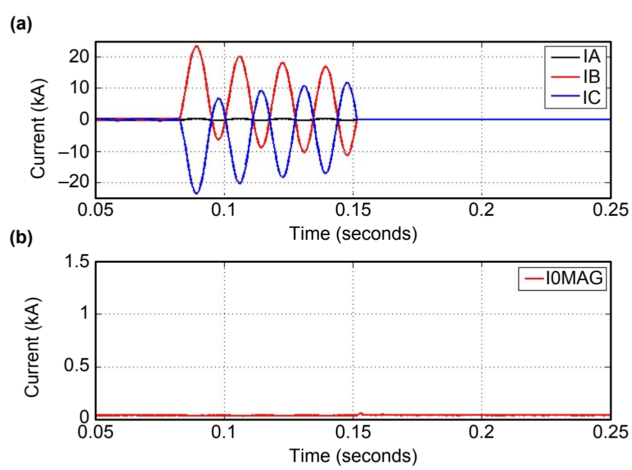

Fig. 7. Breaker B4 currents for a BC fault on Line 2 with normal fault current interruption (a) and zero-sequence current magnitude (b).

B. Fault Current Interruption With High Breaker Pole Scatter

When a BC fault is applied on Line 2 as before, the fault is cleared at Bus Z by normal current interruption in Poles A and B of Breaker B4, followed by a current interruption delayed by 0.5 cycles in Pole C, as shown in Fig. 6b and Fig. 6c, respectively. Each breaker pole interrupts at a current zero crossing.

Fig. 8a shows the three phase currents measured by Breaker B4. Because of the delayed current interruption of Pole C, the Phase C fault current flows for an extra 0.5 cycles. During the last 0.5 cycles of the fault, Breaker B4 Pole C current flows to the ground and returns from Pole B of Breaker B1. As a result, positive-, negative-, and zero-sequence currents flow during the 0.5 cycles. Fig. 8b shows the zero-sequence current magnitude measured by the relay at Bus Z.

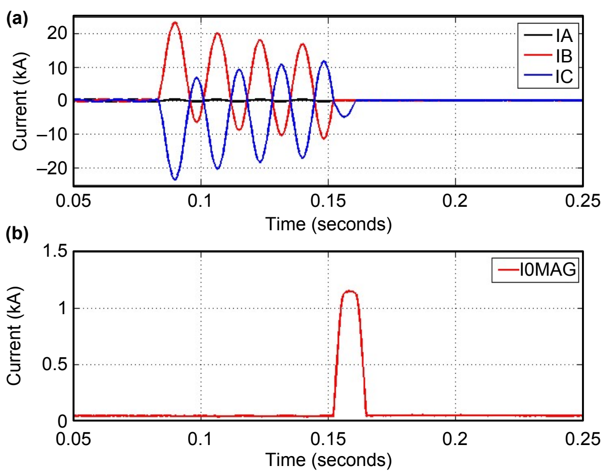

Fig. 8. Breaker B4 currents for a BC fault on Line 2 and current interruption delayed 0.5 cycles in Pole C (a) and zero-sequence current magnitude (b).

Fig. 9a shows the three phase currents flowing through Breaker B1 during the sequence of events previously described. To demonstrate the effect of the high breaker pole scatter of Breaker B4 on the relay at Bus X, it is assumed that Breaker B3 remains closed during the event. This assumption is valid for Zone 2 faults on Line 2 from the Bus Y end and also for an interruption time of Breaker B3 that is greater than that of Breaker B4 by 1 cycle or more.

During the first few cycles of the BC fault on Line 2, current flows on all three phases of Breaker B1 and no zero-sequence current flows from Source 1 to the fault. When Breaker B4 Poles A and B open, Breaker B1 Phase B fault current increases, Phase C fault current decreases, and Phase A current becomes zero (see Fig. 9a). Also, Phase B voltage at Bus X decreases, and Phase C voltage increases (not shown in the figure). During this 0.5-cycle window, zero-sequence current flows from Source 1 to the fault (see Fig. 9b). Once Breaker B4 Pole C interrupts, the power system becomes a radial system with the BC fault fed from Source 1. The zero-sequence current disappears, and equal Phase B and Phase C currents flow from Source 1 until Breaker B1 or Breaker B3 clears the fault.

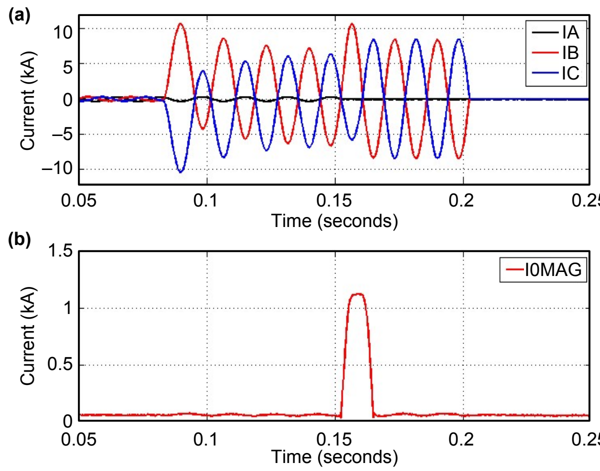

Fig. 9. Breaker B1 currents for a BC fault on Line 2 and Breaker B4 Pole C opening delayed by 0.5 cycles (a) and zero-sequence current magnitude (b).

Fig. 10a and Fig. 10b show the Zone 1 quadrilateral BG reactance and resistance calculations, respectively, for the relay at Breaker B1. During the fault condition, both reactance and resistance calculations are below the Zone 1 reactance and resistance reach settings. When zero-sequence current flows through the breaker, the negative-sequence current lags the zero-sequence current by 90 to 150 degrees. The fault identification logic declares the fault as a BG fault and asserts the FSB word bit, as shown in Fig. 10c [14]. The relay issues an instantaneous trip signal to Breaker B1 once it detects the fault in Zone 1. The delayed current interruption of Breaker B4 Pole C by 0.5 cycles results in an unintended operation of the quadrilateral ground distance element at Bus X.

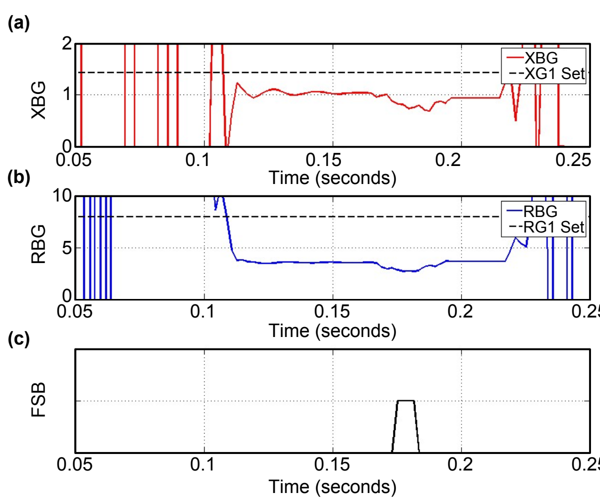

Fig. 10. Zone 1 quadrilateral BG reactance calculation for a BC fault on Line 2 with Breaker B4 Pole C opening delayed by 0.5 cycles (a), Zone 1 quadrilateral BG resistance calculation (b), and assertion of Phase B fault identification bit during high breaker pole scatter (c).

In Fig. 10, XBG is the Zone 1 quadrilateral BG reactance calculation, XG1 Set is the Zone 1 quadrilateral ground reactance reach setting, RBG is the Zone 1 quadrilateral BG resistance calculation, RG1 Set is the Zone 1 quadrilateral ground reach setting, and FSB is the Phase B fault identification bit.

V. Case Study of the Unintended Operation of a Quadrilateral Ground Distance Element

Fig. 11 shows a simplified one-line diagram of a section of the FPL system, which includes 230 kV and 138 kV sections, involved in the unintended operation. Only substations, transmission lines, tap points (marked as *T*), and breakers relevant to this paper are included in the figure. Substation PL and Substation RI have breaker-and-a-half bus arrangements. All the breakers are SF_6-type breakers. Substation PL, Substation LA, and Substation RI are connected to each other with very short transmission lines. The line lengths for Line 1, Line 2, and Line 3 are 6.51, 7.9, and 14.4 miles, respectively. Phase mho, ground mho, and quadrilateral ground distance elements are used to protect these lines. Also, a DCB scheme over a power line carrier is used for communications-assisted tripping. The line impedances for Line 1 and Line 2 are 4.45 ohms and 5.34 ohms, respectively. Zone 1 and Zone 2 reach are set to 0.8 per unit (pu) and 1.25 pu of line impedance for Line 1. A resistive reach of 24 ohms is set for the quadrilateral ground distance element. Zone 1 and Zone 2 reach are set to 0.8 pu and 1.35 pu of line impedance for Line 2. The resistive reach is set to 20 ohms for Line 2.

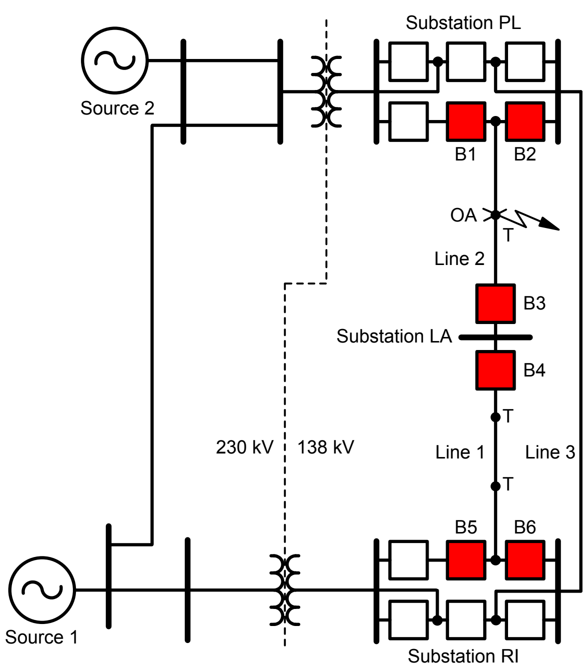

Fig. 11. Simplified one-line diagram of a section of the FPL power system.

A. Analysis of FPL Unintended Operation

In May 2012, a circuit switcher connected to a capacitor bank at the OA tap point (shown on Line 2 in Fig. 11) failed to interrupt the Phase B current, which resulted in an arc once the blades of the switch opened. The arc persisted for some time and eventually made contact with Phase C on the line side, resulting in a BC fault at the OA tap point. The relays at both ends of Line 2 correctly identified the fault as a Zone 1 BC fault and tripped the line. During current interruption by Breaker B2, interruption of breaker Pole C was delayed by 0.5 cycles following the interruption of breaker Pole B. This high breaker pole scatter effect generated enough zero-sequence current for the Zone 1 quadrilateral ground distance element to pick up at Substation RI. A BC fault at the OA tap point with the high breaker pole scatter of Breaker B2 appeared as a Zone 1 BG fault for the relay at Substation RI. This led to the unintended tripping of Breaker B5 and Breaker B6. Fig. 12 through Fig. 16 show the three phase currents from all five breakers.

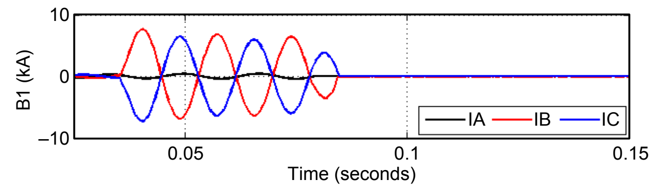

Fig. 12. Breaker B1 currents following a BC fault at the OA tap point.

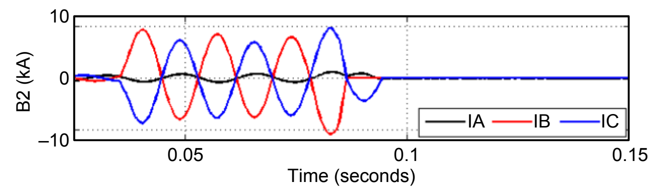

Fig. 13. Breaker B2 currents with Pole A and Pole C interruption delayed by 0.5 cycles.

Fig. 14 shows the Breaker B3 currents after passing through the cosine filter. All other breaker currents shown in Fig. 12 through Fig. 16 are raw waveforms. Filtered current waveforms are plotted because a raw event file was not available from Substation LA. Because of cosine filter delay, 4-cycle raw fault current appears as 5-cycle filtered current.

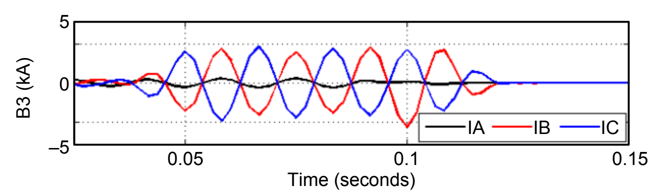

Fig. 14. Breaker B3 currents (filtered).

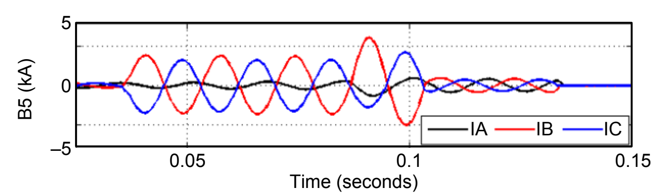

Fig. 15. Breaker B5 currents showing an increase in Phase B and a decrease in Phase C currents during delayed pole interruption of Breaker B2.

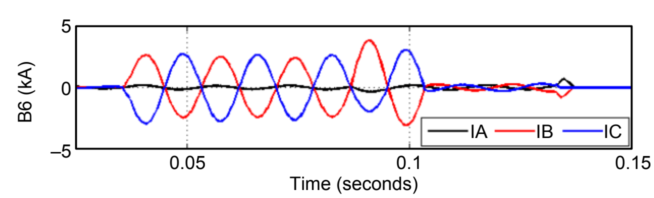

Fig. 16. Breaker B6 currents have similar behavior to Breaker B5 currents.

Fig. 17 depicts the magnitudes of the zero-sequence currents flowing through the breakers during the event.

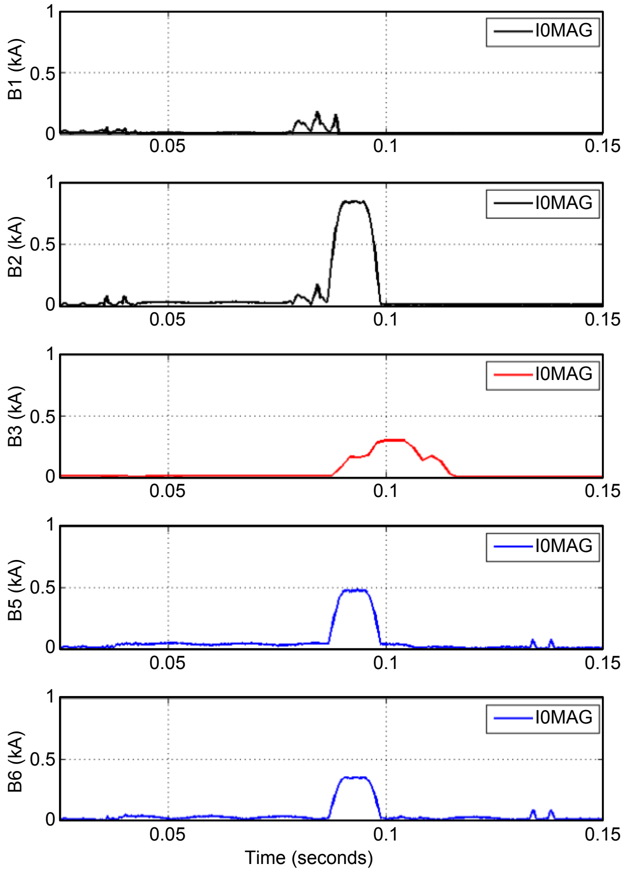

Fig. 17. Zero-sequence current magnitude flows through all five breakers during the event that caused an unintended protection operation.

The sequence of events for this unintended operation was as follows:

1. A BC fault occurred at the OA tap point when an arc from circuit switcher Pole B reached Pole C during capacitor bank opening.
2. The relays at Substation PL and Substation LA identified the fault as a Zone 1 BC fault and issued trip signals to their breakers. This fault was outside the protection zone of the relay at Substation RI. Therefore, no action was taken.
3. Three cycles after fault inception, Breaker B1 opened all three breaker poles. However, Breaker B2 only interrupted Pole B current.
4. With Poles A and C of Breaker B2 still closed, Phase B current increased and Phase C current decreased in Breaker B3 and Breaker B5. Zero-sequence current was detected in all breakers involved (as shown in Fig. 17). With the Zone 1 quadrilateral BG reactance and resistance calculations below the set reach and with the assertion of the Phase B fault identification bit, the Zone 1 quadrilateral ground distance element of the relay at Substation RI asserted and then issued a trip signal to Breaker B5 and Breaker B6.
5. At 3.5 cycles, Poles A and C of Breaker B2 interrupted. With Breaker B1 and Breaker B2 open, the zero-sequence current no longer flowed.
6. At 4 cycles, Breaker B3 at Substation LA opened. With the current interruption by Breaker B3, both ends of Line 2 were open and the fault was cleared.
7. For the next 2 cycles, Breaker B5 and Breaker B6 supplied loads at Substation LA and load taps along Line 1 before both breakers opened.

Fig. 18 shows the operation of protection elements at all three substations for the event described previously. Because protection elements operate on filtered quantities, the operation of each element is delayed because of filtering.

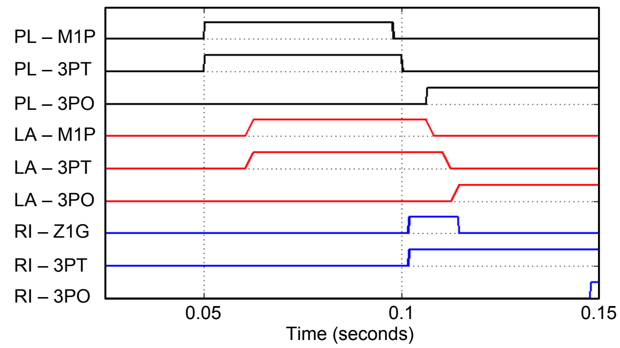

Fig. 18. Operation of protection elements at Substation PL, Substation LA, and Substation RI (M1P is the mho phase Zone 1 element, Z1G is the quadrilateral ground Zone 1 element, 3PT is three-pole trip, and 3PO is three-pole open).

Fig. 19a and Fig. 19b show the Zone 1 quadrilateral BG reactance and resistance calculations for the relay at Substation RI during the event. Because of zero-sequence current flow caused by breaker pole scatter, the fault identification logic declares the fault as a BG fault and asserts the FSB word bit, as shown in Fig. 19c. As a result, the Zone 1 quadrilateral ground distance element asserts and the relay issues a breaker trip signal.

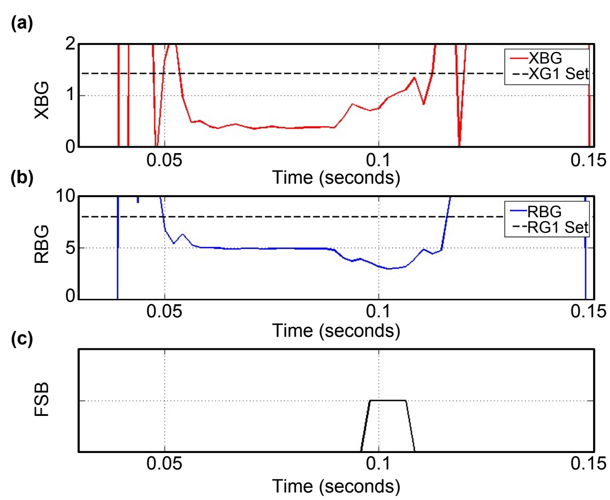

Fig. 19. Zone 1 quadrilateral BG reactance calculation (a), resistance calculation (b), and Phase B fault identification bit (c) during the FPL event that caused an unintended protection operation.

B. Proposed Solution and Test Results

Because of the delayed interruption of one of the breaker poles, a line-to-line fault on the adjacent line can appear as a Zone 1 line-to-ground fault. Because Zone 1 distance elements are used for instantaneous tripping, this condition can result in an unintended operation. The proposed solution is to monitor for faults on adjacent lines and delay the operation of Zone 1 distance elements if a fault moves from the overreaching backup zone to Zone 1. This is a very simple solution and can be implemented using the logic programming abilities of modern relays.

Fig. 20 shows the proposed logic. *MhoPhase4P* is the Zone 4 phase mho element, *MhoGnd4P* is the Zone 4 ground mho element, *QuadGnd1P* is the Zone 1 quadrilateral ground distance element, *MhoGnd1P* is the Zone 1 ground mho element, and *MhoPhase1P* is the Zone 1 phase mho element.

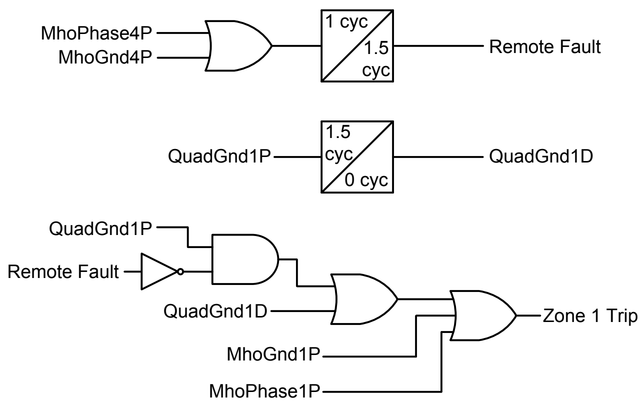

Fig. 20. The proposed logic delays operation of the Zone 1 quadrilateral ground distance element for external faults and avoids unintended operations during high breaker pole scatter conditions.

The Zone 4 phase and ground mho elements are set to detect any fault on the adjacent line and beyond. If any Zone 4 element picks up for one cycle or more, the relay determines that a remote fault has occurred. If the fault moves into the Zone 1 quadrilateral ground distance element region, the remote fault logic blocks Zone 1 trip for 1.5 cycles. During the 1.5-cycle blocking period, any transient caused by breaker pole scatter dies out. The proposed logic does not block Zone 1 trip for any fault that starts within Zone 1 reach. However, for evolving external-to-internal faults, the fault clearance is delayed if the internal fault is inside the Zone 1 quadrilateral ground distance element region.

To test the proposed logic shown in Fig. 20, it was programmed in the Zone 1 trip equation of the Substation RI quadrilateral ground distance elements. Zone 4 phase and ground distance element reach was set to cover the whole length of Line 2. Two methods were used for testing the proposed logic. The first method consisted of replaying the COMTRADE file captured during the actual FPL unintended operation event and injecting the current and voltage signals into a relay programmed with the new logic. The second method consisted of modeling the section of the FPL system shown in Fig. 11 in an RTDS and injecting the signals resulting from different faults into a relay programmed with the new logic. Various internal and external faults with high breaker pole scatter were simulated to verify the relay security and speed.

Fig. 21 shows the relay event report for the COMTRADE file playback test. The proposed logic successfully blocked the Zone 1 trip and prevented the operation during the high breaker pole scatter condition in the remote breaker.

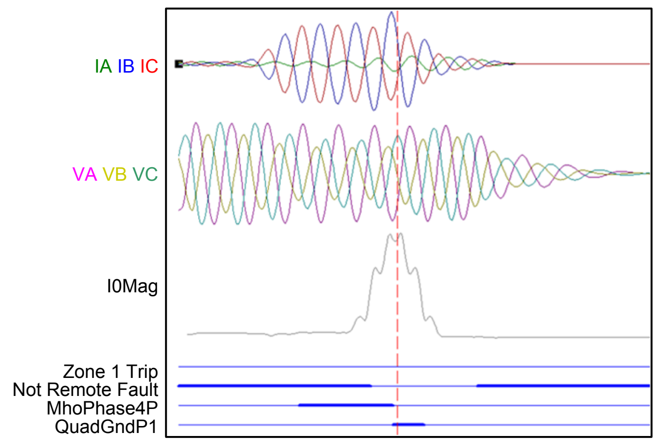

Fig. 21. The proposed logic delays Zone 1 trip and prevents unintended operation for an actual remote fault with high breaker pole scatter in the remote breaker (actual COMTRADE file playback).

In the RTDS modeling tests, several faults with different fault types and locations and different breaker pole scatter conditions were simulated. The involved section of the FPL power system shown in Fig. 11 was modeled in the RTDS. A relay was connected to the RTDS to receive the RTDS output voltages and currents.

To reproduce the actual unintended operation, the relay was initially set using the same settings as the Substation RI relay. In addition, breaker pole scatter was modeled similar to that of the actual event.

The proposed logic was configured in the relay and tested by applying different faults on Line 2 followed by a delayed interruption of one of the breaker poles. High breaker pole scatter was modeled on one breaker at a time for all of the breakers at Substation PL and Substation LA. The proposed logic prevented the unintended operation of Zone 1 tripping for all the breaker pole scatter conditions.

For example, Fig. 22 shows that the proposed logic correctly prevents a Zone 1 trip even though Zone 1 of the quadrilateral ground distance element picks up for a remote BC fault with high breaker pole scatter of the Substation PL breaker.

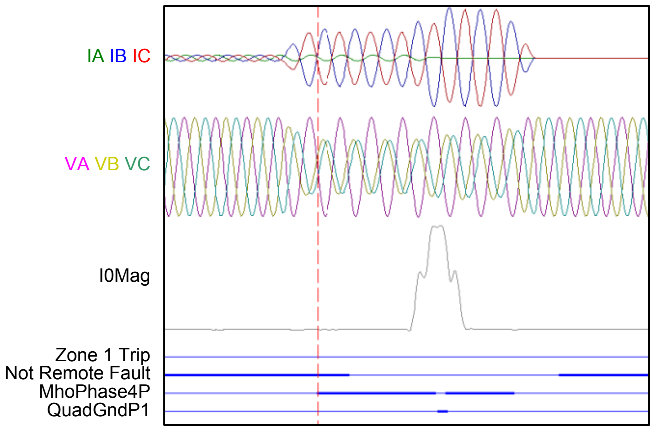

Fig. 22. The proposed logic delays Zone 1 trip and prevents unintended operation for a remote RTDS-simulated fault with high breaker pole scatter of the remote breaker.

In addition, several faults of different types within the relay Zone 1 reach region were applied to show that the relay is sensitive to these faults. The Zone 1 quadrilateral ground distance element tripped for all faults without any delay.

Fig. 23 shows an instantaneous trip for a BG fault in the Zone 1 reach region.

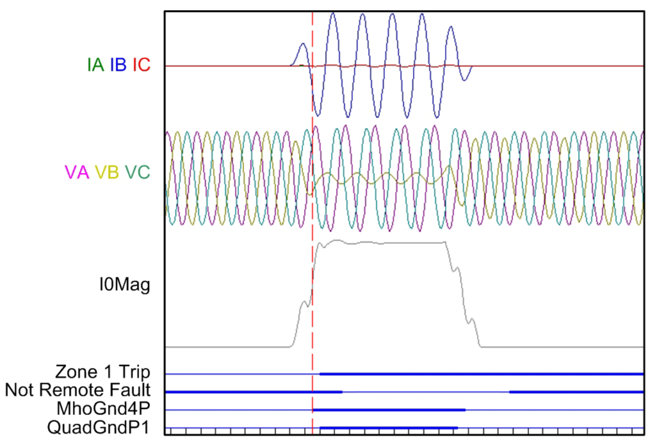

Fig. 23. The proposed logic does not delay Zone 1 trip for an internal BG fault simulated using RTDS.

The results from the COMTRADE playback test and the RTDS modeling tests prove that the proposed logic successfully blocks the unintended operation during breaker pole scatter conditions for external faults while maintaining fast operation for internal Zone 1 faults.

VI. Conclusion

Breakers interrupt the current when the current waveform reaches a zero crossing or when the current is very close to zero. Because of the phase shift between the three phase currents, the breaker poles interrupt current at different times. This phenomenon is known as breaker pole scatter. For normal interruption, the breaker poles interrupt with a time separation of 1/6th cycle. With modern breaker design, the statistical variation of breaker pole scatter time is negligible. However, because of equipment wear and interrupting medium deterioration after extended use, breaker current interruption can be delayed by 0.5 cycles on one or more poles. Depending on the power system conditions, high breaker pole scatter can cause ground protection elements to operate unintentionally and result in an undesirable system outage. Modern relays have functions to monitor breaker pole scatter time. As the breaker ages and the number of fault interruptions increases, breaker pole scatter time can be monitored to check the health of the pole interrupters.

The example of an actual unintended operation of a Zone 1 quadrilateral ground distance element in the FPL system discussed in the paper shows that high breaker pole scatter can cause unintended ground fault element operations. Further simulation studies using a simple two-source power system model with two short lines demonstrate the effect of the delayed opening of a faulted phase on the protection system.

A simple solution to this problem is to program the relay logic to introduce a short delay in Zone 1 ground elements when the fault is first detected only by an overreaching distance element. The proposed logic was tested using a COMTRADE file of an actual fault and simulation studies of a simplified FPL power system model were performed using an RTDS. The test results prove that the solution provides security for external faults with high breaker pole scatter without impairing Zone 1 operating speed for internal faults.

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VIII. Biographies

James Ryan received his BS in electrical engineering from Texas A&M University in 2003. He has worked as a protection and control engineer at Florida Power & Light Company for the last ten years. Currently, he works in the technical services department, providing operational support and serving as a subject matter expert for transmission protection equipment. He is a registered Professional Engineer in the state of Florida and an IEEE member.

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Thanh-Xuan Nguyen received her BS degree in electrical engineering and computer science from the University of California at Berkeley in 2001 and her master of engineering degree in electrical engineering from the University of Idaho in 2012. She has worked at Schweitzer Engineering Laboratories, Inc. since 2001 and has been involved with designing, testing, and validating a variety of generation, distribution, and transmission products. Presently, she is a marketing program manager in the marketing division. Thanh-Xuan holds two United States patents. She is a registered Professional Engineer in the state of Washington, an IEEE member, and an SWE member.

Previously presented at the 2015 Texas A&M
Conference for Protective Relay Engineers.

20150218 • TP6667-01