Advanced Sequence Elements for Line Current Differential Protection

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***Abstract*—Segregated phase current differential schemes normally consist of three phase elements. Load current limits the sensitivity of these elements, and these elements will not operate for highly resistive faults. In some advanced schemes, a zero-sequence element, negative-sequence element, or both supplement the three phase elements to provide additional sensitivity. In single-pole tripping applications, during the time one phase is open, the zero-sequence and negative-sequence elements lose significant sensitivity during a subsequent fault. This paper introduces a new sequence element logic that maintains element sensitivity irrespective of tripping type (three-pole or single-pole tripping). The basic principle involves retrieving the prefault current from the sequence fault current.**

I. Introduction

The Alpha Plane is a geometrical representation in the complex plane of the ratio of the two phase or sequence current phasors entering a transmission line at both ends (with the conventional CT polarity). Characteristics of digital line current differential relays introduced recently to the market are directly implemented into the Alpha Plane. These relays compute the ratio of the phase or sequence currents entering and leaving the transmission line and determine whether the location of this ratio falls within a stability area directly embedded into the Alpha Plane.

A Western Protective Relay Conference (WPRC) paper [1] last year presented the results of a study on the trajectories of the current ratio of phase and sequence elements under various fault conditions. This paper established that, in three-pole tripping applications, phase elements are limited in sensitivity. It is possible to extend this sensitivity through the use of sequence elements. In single-pole tripping applications, sensitivity of sequence elements decreases to the point that performance is at the same level of a phase element. The WPRC paper just discussed established that, to restore the sensitivity of a sequence element for a fault occurring during a pole-open, it is necessary to retrieve the prefault current from a sequence fault current.

The present paper first revisits the basic principles of current differential elements embedded in the Alpha Plane. The paper then reviews the factors limiting the sensitivity of phase and sequence elements, and it finally introduces a complete logic scheme that provides for the maintenance of sequence element sensitivity under all possible conditions.

II. Review of Line Current Differential Phase and Sequence Element Alpha-Plane Characteristics

Reference [2] introduced the concept of a digital characteristic implemented into the current-ratio plane (or Alpha Plane) for line current differential elements. Fig. 1 is a representation of this concept. The concept consisted of computing the ratio of the remote current IR (phase or sequence current) over the local current IL and verifying that the ratio lies within the shown stability area. In a no-fault situation, the ratio would be close to the minus one point (-1,0). There are two settings for this characteristic: the radius R of the greater arc (typically between 5 and 10) and the angle alpha (α) (typically between 160 and 210 degrees). Completely digital implementation and increased control over the angle alpha made this newly defined characteristic an improvement with respect to the so-called "rainbow" characteristic [6]. In this original concept, the angle alpha was set to a fixed value of 180 degrees.

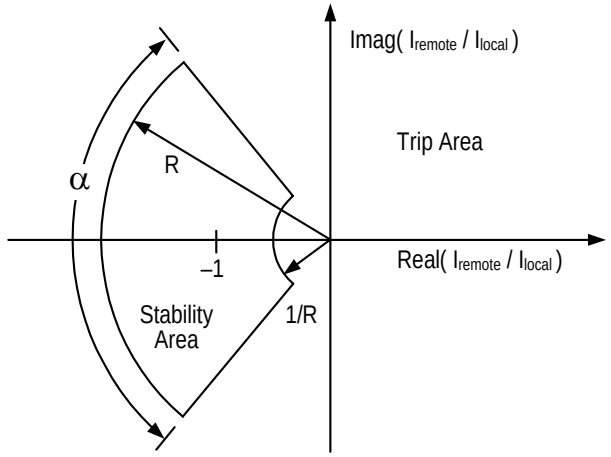


Fig. 1. Differential Element Characteristic Embedded in the Current-Ratio Plane

III. Protection Scheme Based on Characteristics in the Alpha Plane

In the present study, we assume that the line protection scheme, as Fig. 2 illustrates, includes five elements at each line extremity: three phase elements designated 87LA, 87LB, and 87LC; one zero-sequence or ground element designated 87LG or 87L0; and one negative-sequence element designated 87L2.

For a protection scheme to declare a fault, each element, phase or sequence, determines whether the sum of the two currents at the line extremities exceeds a set pickup value and then determines whether the current ratio falls outside the characteristic stability area.

A saturation detector supervises both the 87LG and 87L2 elements so that the protection scheme blocks operation of these elements if it detects CT saturation on any of the six phase currents involved. Reference [3] explains the rationale

for and the details of this saturation detector. Generally, if increasing the radius and the angle alpha of a phase element Alpha-Plane characteristic can make a phase element immune to CT saturation during an external fault, one cannot apply the same mitigation technique to a sequence element. A sequence element remains irremediably unstable when CT saturation occurs during an external fault.

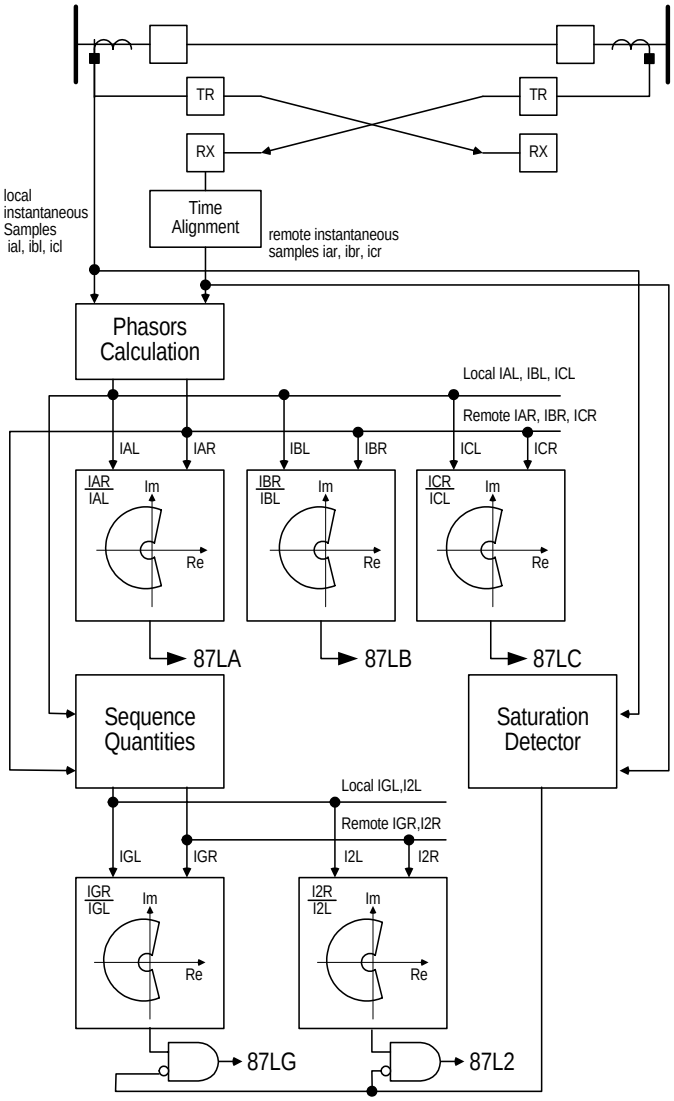


Fig. 2. Principle of line current differential protection scheme

IV. Review of Phase Element Sensitivity

A. Trajectories of Current Ratio in Phase Elements

Consider the elementary power network shown in Fig. 3. This network consists of a single transmission line with two generators. The angle θ between the two sources determines the amount of line loading. When we apply A-phase-to-ground faults at a distance, d, from the left bus, reference [1] shows that (1) provides the ratio of the two A-phase currents at the line extremities.

$$\frac{IAR}{IAL} = \frac{\left[2\left(1-C1\right)+\left(1-C0\right)\right]I1F - I_{LD}}{\left(2\,C1+C0\right)I1F + I_{LD}} = \frac{\left[2\left(1-C1\right)+\left(1-C0\right)\right] - \dfrac{I_{LD}}{I1F}}{\left(2\,C1+C0\right)+\dfrac{I_{LD}}{I1F}} \tag{1}$$

In (1), C1 and C0 are the sequence network positive-sequence and zero-sequence current distribution factors, I1F is the pure fault positive-sequence current at the fault, and I_{LD} is the load current. Appendix A provides analysis for the computation of the fault currents through use of the proper sequence network.

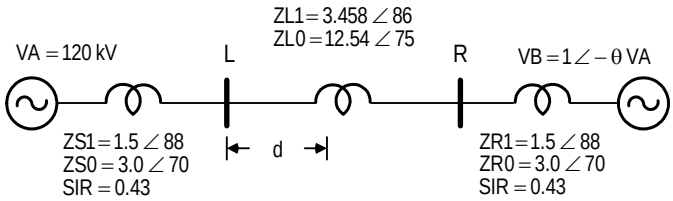


Fig. 3. 120 kV Elementary network

Examination of (1) shows that the current ratio at the relay depends upon the sequence current distribution factors and the ratio of the load current over the pure fault current at the fault location. The load current depends only upon the angle between the two sources and is equal to the result of (2):

$$I_{LD} = \frac{\left(1-e^{-j\theta}\right)VA}{ZS1+ZL1+ZR1} \tag{2}$$

The pure fault current depends upon the fault location, d, the current distribution factors, and the fault resistance, as in (3):

$$I1F = \left[VA - ILD\left(ZS1+d\;ZL1\right)\right] \div \left[\frac{2\left(ZS1+d\;ZL1\right)\left(ZR1+\left(1-d\right)ZL1\right)}{ZS1+ZL1+ZR1} + \frac{\left(ZS0+d\;ZL0\right)\left(ZR0+\left(1-d\right)ZL0\right)}{ZS0+ZL0+ZR0} + 3\,Rf\right] \tag{3}$$

As fault resistance increases, the pure fault current decreases. Let us define two constants a and b, as in (4):

$$a = 2\,C1 + C0 \qquad b = 2\left(1-C1\right)+\left(1-C0\right) \tag{4}$$

The A-phase current ratio can be expressed as a function of the load-to-pure-fault current ratio, as in (5):

$$\frac{IAR}{IAL} = \frac{b - \dfrac{I_{LD}}{I1F}}{a + \dfrac{I_{LD}}{I1F}} \tag{5}$$

The load-to-pure-fault current ratio can, in turn, be expressed as a function of the phase-current ratio, as in (6):

$$\frac{I_{LD}}{I1F} = \frac{b - a\dfrac{IAR}{IAL}}{1+\dfrac{IAR}{IAL}} \tag{6}$$

For a particular network and stability characteristic in the Alpha Plane, we can plot the contour corresponding to the load-to-pure-fault ratio when we travel around the stability perimeter. According to (6), we obtain a new perimeter that defines the limit of the element sensitivity as a function of the load-to-pure-fault current ratio.

As an example, consider the elementary network of Fig. 3. For a fault at a distance, d, equal to 0 or 1 (in per unit line length) from the left bus and for a stability perimeter with radius 6 and angle $\alpha = 180°$, we obtain the load-to-pure-fault current ratio sensitivity perimeter shown in Fig. 4. In the case of the load-to-pure-fault current ratio for a particular network and a given fault falling inside the sensitivity perimeter, the fault current ratio will fall outside the stability perimeter and the protection scheme will detect the fault. If the load-to-pure-fault current ratio falls outside the sensitivity perimeter, the protection scheme will not detect the fault. If the load equals zero, the load-to-pure-fault current ratio falls automatically inside the sensitivity perimeter and the protection scheme detects the fault.

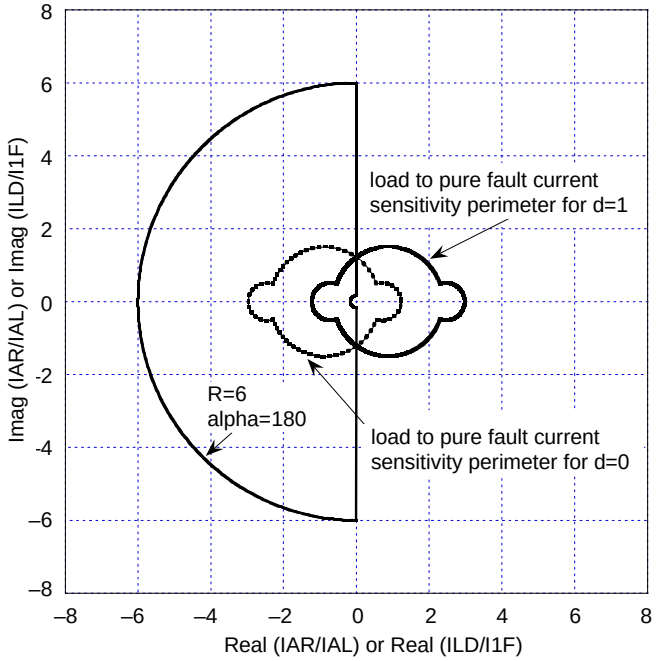


Fig. 4. Load-to-pure-fault current ratio sensitivity perimeter for phase-A-to-G faults

From studying (3), we can see two situations in which the pure fault current decreases to the point that the load-to-pure-fault current ratio becomes so large that the phase element loses sensitivity and will not detect a fault:

- Situation I: Increased fault resistance value. For a phase-to-ground fault, there is a maximum value of fault resistance beyond which the phase element becomes blind to a fault.
- Situation II: Increased source impedance value, as would happen in a system where the System Impedance Ratio (SIR) is high at both line extremities. In such a situation, the load angle between the two sources must assume a higher value to supply the same load current.

Fig. 5 illustrates Situation I. This figure exhibits the trajectories of the A-phase current ratio for the elementary network of Fig. 3 for application of an A-phase-to-ground fault at three different line locations. In all cases, the load angle between the two sources is 5 degrees. For each of the three fault locations, the fault resistance varies from zero to 100 ohms primary, with increments of 1 ohm. As the fault resistance increases, the ratio of the load current over the pure fault current increases to the point that the IAL/IAR trajectory enters the stability area and the phase element becomes blind to the fault.

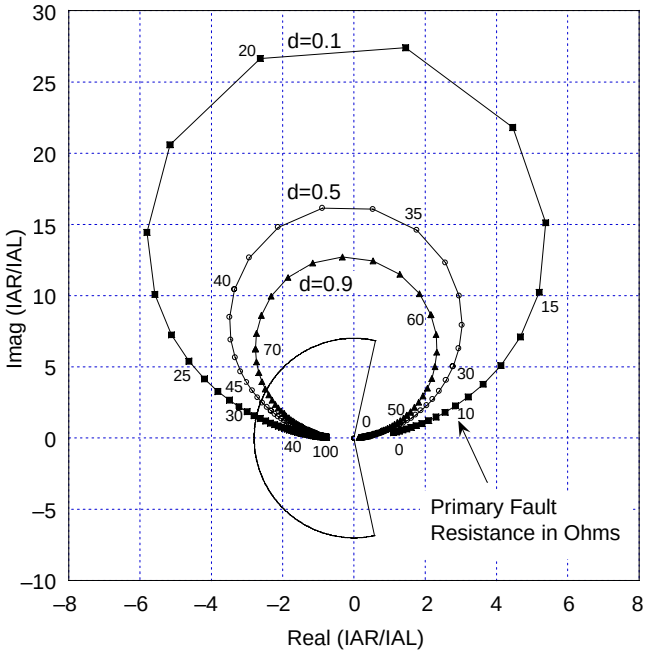


Fig. 5. 87LA element trajectories for an A-phase-to-G fault at three locations and variable fault resistance (d expresses the fault location in per unit of line length)

V. Review of Sequence Element Sensitivity

A. Review of Sensitivity in Three-Pole Tripping Applications

From Appendix A, (7) provides the ratio of the zero-sequence currents at the line extremities:

$$\frac{I0R}{I0L} = \frac{(1-C0)\,I0F}{C0\;\;I0F} = \frac{(1-C0)}{C0} = \frac{d\;ZL0 + ZS0}{(1-d)\,ZL0 + ZR0} \tag{7}$$

In the same fashion, (8) provides the ratio of the negative-sequence current at the two line extremities:

$$\frac{I2R}{I2L} = \frac{(1-C1)\,I1F}{C1\;\;I1F} = \frac{(1-C1)}{C1} = \frac{d\;ZL1 + ZS1}{(1-d)\,ZL1 + ZR1} \tag{8}$$

By studying (7) and (8), we can see that the current ratios of the zero-sequence and negative-sequence currents are completely independent from the load current and angle, the pure fault current, and, consequently, the fault resistance. The ratio depends only on the current distribution factors and, consequently, upon the fault location, d. If the two sources had the same impedance, and if the fault location were the middle of the line, the current ratio of both 87LG and 87L2 elements

would be the point (1,0) of the Alpha Plane, located in the element trip area.

We could say that the 87LG and 87L2 elements have a theoretical infinite sensitivity to resistive ground faults. However, we could say this only for perfectly transposed networks and perfect CTs. In reality, a minimum sequence (negative or zero) differential pickup current limits this sensitivity to take into account such factors as natural unbalances in the network and CT errors.

As an example, Fig. 6 represents the locus of the zero-sequence current ratio for application of an A-phase-to-ground fault at locations from 0 to 1 in per unit of line length for the elementary network of Fig. 3. Note that this current ratio trajectory is independent of fault resistance and load angle. Because all the network impedances are inductive, the zero-sequence current ratio is near the horizontal axis on the right-hand side half-plane that belongs to the trip area. The same observations would apply to a negative-sequence element.

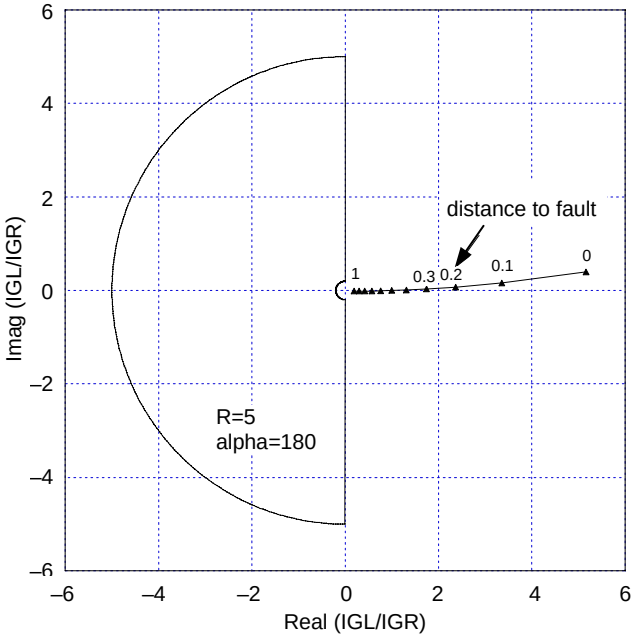


Fig. 6. 87LG element trajectories for an A-phase to-ground fault at different locations

B. Review of Sensitivity in Single-Pole Tripping Applications

Consider the elementary network of Fig. 3 and assume that the line protection scheme is using single-pole tripping. Let us further assume, as an example, that B-phase is open and that a subsequent A-phase-to-ground fault occurs. We want to investigate the sensitivity of the phase and sequence elements in this new situation.

Appendix B presents a thorough analysis of an A-phase-to-ground fault during an open B-phase. This analysis includes computation, through use of the proper sequence network, of A-phase and sequence currents during the fault.

Equation (9) provides the current ratio of the 87LA element:

$$\frac{IAR}{IAL} = \frac{IAR_{preflt} + \left(2 + \frac{p + 2q - 0.5(m_1 + 2n_1)}{m + 2n} + \frac{3m_1}{2m}\right) IF}{IAL_{preflt} - \frac{3}{2}\left(\frac{m_1 + 2n_1}{m + 2n} + \frac{m_1}{m}\right) IF} \quad (9)$$

where the current through the fault, IF, is a function (see (46) in Appendix B) of the distance to the fault, d, the network impedances, the source voltages, and the fault resistance, Rf, as in (10):

$$IF = \text{func}(d, ZS1, ZL1, ZR1, ZS0, ZL0, ZR0, Rf, VA, VB) \quad (10)$$

Equation (39) in Appendix B defines variables p, q, m, n, m_1, n_1. These variables depend only upon the network impedances and the distance to the fault, d.

As in the case of the three-pole trip application, (9) indicates that the trajectory of the 87LA element in a single-pole trip application depends upon the distance to the fault, the network impedances, the source voltages, and the fault resistance, R_f. Regarding a phase element, therefore, a fault during an open-pole situation is no different than the case of a fault when all three poles are closed.

Equation (11) provides the current ratio for the 87L2 element:

$$\frac{I2L}{I2R} = \frac{\frac{-a\,\Delta V\,n}{m(m+2n)} + \left(\frac{a^2}{2}\frac{(m_1 + 2n_1)}{m+2n} + \frac{m_1(1-a)}{2m}\right) IF}{\frac{a\,\Delta V\,n}{m(m+2n)} + \left(1 - \frac{a^2}{2}\frac{m_1 + 2n_1}{m+2n} + \frac{m_1(1-a)}{2m}\right) IF} \quad (11)$$

Equation (12) provides the sequence ratio for the 87L0 element:

$$\frac{I0L}{I0R} = \frac{\frac{-a^2\,\Delta V}{m+2n} - \frac{m_1 + 2n_1}{m+2n} IF}{\frac{a^2\,\Delta V}{m+2n} + \frac{p+2q}{m+2n} IF} \quad (12)$$

By studying (11) and (12), we can see that, unlike the three-pole tripping application, the current ratio in the 87L2 and 87LG elements is no longer independent from the fault resistance, R_f, the source voltages, and the current at the fault, IF.

Fig. 7 and Fig. 8 show the trajectory of the current ratio for the 87L2 and 87LG elements during application of an A-phase-to-ground fault at 33 percent of the line length with B-phase open. The primary resistance varies from 0 to 100 Ohms. Examining these two plots, we can see that, unlike the three-pole trip application, the 87L2 and 87LG elements undergo a significant loss of sensitivity in a single-pole trip application with respect to resistive faults.

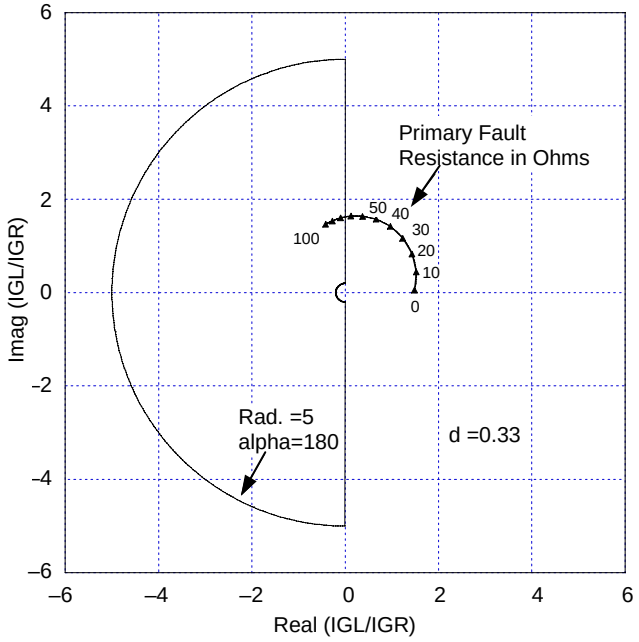


Fig. 7. 87LG element trajectory during a B-phase open with an A-phase-to-G fault with varying fault resistance

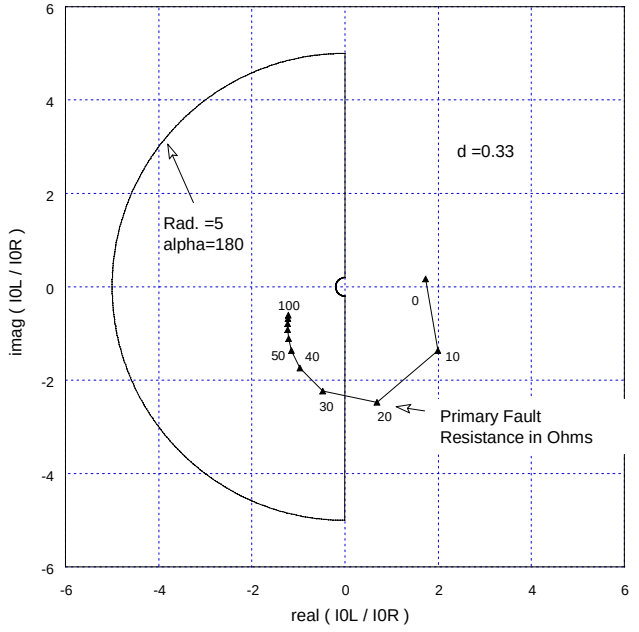


Fig. 8. 87L2 element trajectory during a B-phase open with an A-phase-to-G fault with varying fault resistance

C. Removal of the Prefault Current in the Sequence Elements During an Open Pole

As Appendix B discusses, negative-sequence and zero-sequence currents flow into the line at one end and out of the line at the other end during an open pole condition. The 87L2 and 87LG elements process these sequence currents as if these currents belong to an external fault, so these elements will not pick up. If, during an open pole, we systematically remove the prefault sequence currents when we compute the current ratio in the 87L2 and 87LG elements, we obtain (12) and (13):

$$\frac{I0L - I0L_{preflt}}{I0R - I0R_{preflt}} = \frac{-\dfrac{m_1 + 2\,n_1}{m + 2\,n}\,IF}{\dfrac{p + 2\,q}{m + 2\,n}\,IF} = \frac{-(m_1 + 2\,n_1)}{p + 2\,q} \tag{13}$$

$$\frac{I2L - I2L_{preflt}}{I2R - I2R_{preflt}} = \frac{\dfrac{a^2}{2}\dfrac{m_1 + 2\,n_1}{m + 2\,n} - \dfrac{m_1\,(1-a)}{2\,m}}{1 - \dfrac{a^2}{2}\dfrac{m_1 + 2\,n_1}{m + 2\,n} + \dfrac{m_1\,(1-a)}{2\,m}} \tag{14}$$

By studying (13) and (14) we can see that removal of the prefault current for a fault during an open-pole situation renders the element independent from the pure fault current, IF, and, consequently, independent from the fault resistance. It is possible to once again make the sequence elements almost infinitely sensitivity to resistive faults.

Fig. 9 shows the locations of the 87L2 element current ratio for an A-phase-to-ground at 33 percent of line length during a B-phase pole-open situation with 50 Ohms primary fault resistance for the elementary network of Fig. 3. Fig. 9 shows two loci: one locus with the prefault currents kept in the current ratio and a second locus with the prefault currents removed from the current ratio. Removal of the prefault currents restores the 87L2 element sensitivity by moving the current ratio locus from the stability area to the trip area.

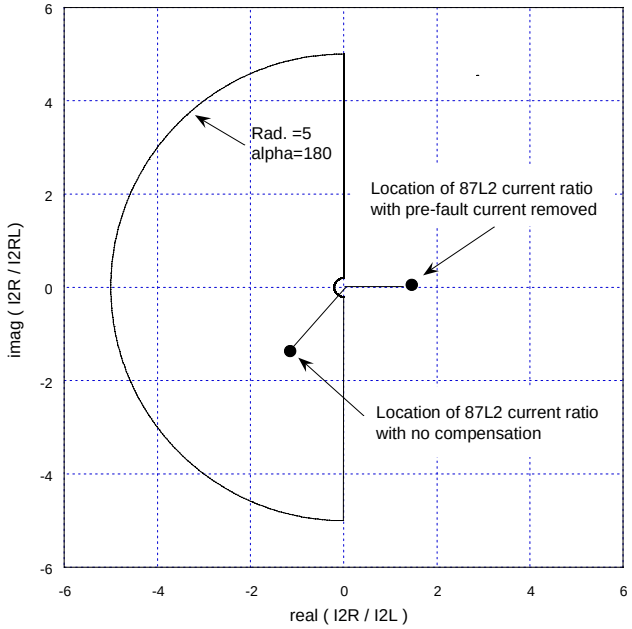


Fig. 9. 87L2 element current ratio loci during a B-phase open with an A-phase-to-G fault with prefault current present and removed

VI. The Retrieval of the Prefault Current Using a Delta Filter

From the previous discussion, we can see that one must retrieve the prefault current from the sequence current to compensate for the loss of sensitivity of a sequence element during a pole open. Protection engineers have developed compensation techniques equivalent to this retrieval that include the use of so-called delta-filters applied traditionally to derive superimposed components [5].

A. The Conventional Delta Filter

Fig. 10 represents a delta filter such as one would apply to the local negative-sequence phasor, I2L. The input to the delta-filter is the time-invariant form of the I2L phasor (phasor that does not rotate with time but is still in the complex plane). The delta-filter output is the time-invariant input phasor minus the same input delayed by a constant time-interval, DT. The output of the delay filter is called the reference signal or phasor. Assuming that a fault occurs on a line, one can see that the delta-filter output will occur during an interval of time, DT, and that it will equal the negative-sequence fault current minus the pre-fault current. This is exactly what we wanted to achieve. After the delay, DT, the delta-filter output returns to zero.

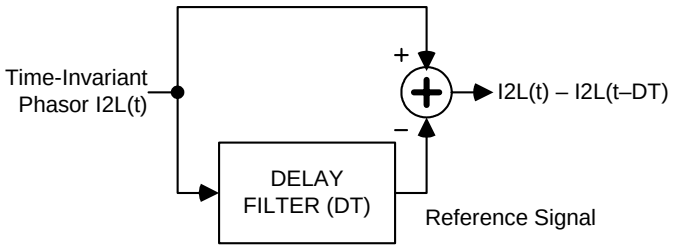


Fig. 10. Structure of a conventional delta filter

B. The Latching Delta Filter

It is well established that one shortcoming of the delta filter of Fig. 10 is that it will detect a power system fault during an interval equivalent to the embedded delta-filter time delay. This shortcoming results from the fact that the reference signal is constantly moving. If the reference signal that triggered a fault detection latches into a memory register so that the signal remains constant, it is possible to extend the detection interval to any value at will. Fig. 11 illustrates this principle.

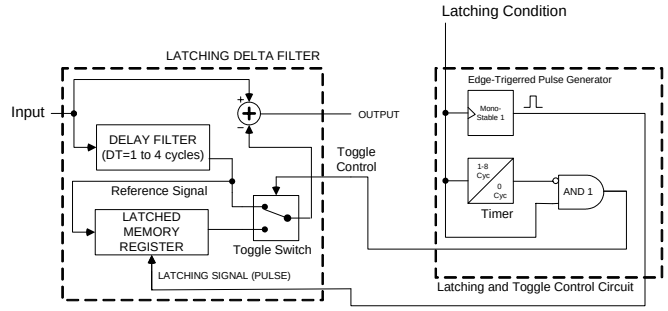


Fig. 11. The latching delta filter concept

Assume that the latching condition corresponds to a fault that the protection logic has just detected. At the moment the logic detects the fault, a latching pulse from a rising-edge-triggered monostable stores the reference signal to a memory register. Operation of a toggle switch in the delta filter then causes subtraction of the stored reference signal from the present signal. This operation occurs for as long as the timer remains unasserted. As an example, assume that the delta filter has a 2-cycle delay and that the timer pickup time is set at 4 cycles. The fault detection time in this example will now be extended to an interval equal to the timer pickup time, or 4 cycles, provided that the latching (the fault) condition is always present.

VII. The Long-Line, Low-Load, Open-Pole Special Issue

A long line exhibits shunt capacitances (see the example in Fig. 17). A consequence of these shunt capacitances is that each phase current at each line extremity consists of two components. There is the line-charging or shunt current component that is the capacitive current the shunt capacitor draws, and there is a load component that is the current flowing into the line from one side to the other. At low load, only the line-charging component will be significant. Remember that a phase element of a line current differential relay will determine the two shunt currents at the line extremities to be a fault because the two currents have a phase-to-phase difference close to 0 degrees. It is necessary to make the phase differential pickup value at least equal to twice the maximum phase shunt current.

When one uses an 87L2 or 87LG element in three-pole tripping applications, the three phase shunt currents are balanced so that the corresponding negative or zero sequence will be close to zero. In three-pole tripping applications, therefore, the impact of shunt currents on a sequence element is negligible.

The situation is different in cases where one uses an 87L2 or 87LG element in single-pole tripping applications. During a pole open, the shunt currents are no longer balanced and a sequence element will determine, as will the phase element, that the shunt currents are an internal fault. During a pole open, the zero-sequence or negative-sequence shunt current at each line extremity will equal one-third the magnitude of each shunt phase current. If we use three times the sequence current (3 • I2 or 3 • I0), each multiplied shunt sequence current becomes equal to a corresponding shunt phase current (see Fig. 12).

To prevent a sequence element from tripping during a pole open, one must ensure that the sequence differential pickup during the pole open is at least equal to twice the maximum phase shunt current. We assume here that we use the multiplied-by-three sequence current.

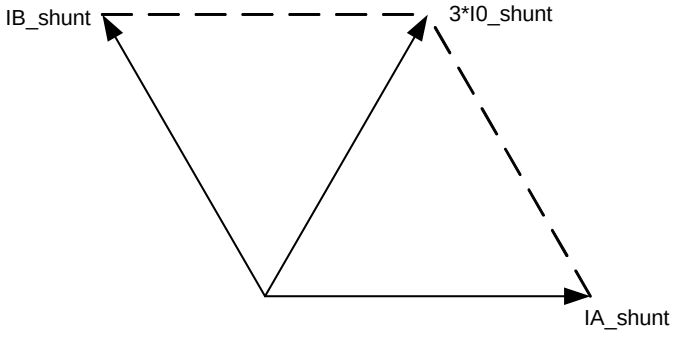


Fig. 12. Zero sequence current during a pole-open B

VIII. Nature of Unbalances in Networks Where One Line Has a Pole Open

Consider the network of Fig. 13 with one double-circuit line and one line in series and assume an open pole exists on A-phase on the lower line between buses X and Y. A significant current unbalance will exist on the upper line between buses X and Y and on the line between buses Y and Z. On these two lines, conventional sequence elements 87L2 and 87LG will consider the circulating sequence currents as belonging to an external fault. If a fault were to occur on one of these two lines during the pole open, the sensitivity of the sequence elements would be affected because of the significant unbalance. On these two lines also, the pole-open situation on the lower line between Buses X and Y cannot be detected. It is therefore necessary to have a scheme that restores sensitivity even on lines that are adjacent to the line with the pole open. It is also interesting to note that if B-phase would be open between Y and Z, no current would circulate in the same phase in both parallel lines.

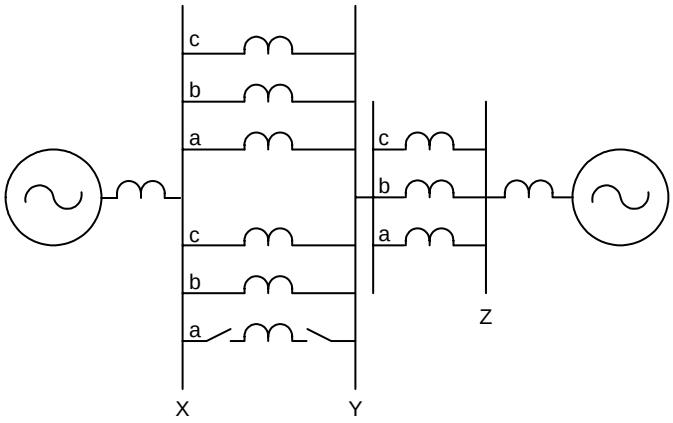


Fig. 13. Impact of a pole open on adjacent lines

IX. A Universal Logic Scheme for Sequence Elements

A. Sequence Element Loss of Sensitivity Mitigation Basic Protection Scheme

Fig. 14, which is based on use of the delta filter, represents a basic protection scheme that will restore sequence element sensitivity during a pole-open situation. It works as follows.

If a pole-open situation is not detected on the line, the scheme works in a conventional way. The toggle Switches 1 and 2 connect the input phasors I2L and I2R to the element, and element processing is not blocked. If a pole-open situation occurs, after the pickup time of Timer 1, the Toggle Switches 1 and 2 will connect to the element to the delta filter outputs, and there will be further processing of the output from the two delta filters. If a subsequent fault occurs, the output of the two delta filters will be the sequence fault current minus the pre-fault current over an interval equal to the filter delay. Following the single-pole open assertion, the delta filters need an interval equal to the filter delay to establish the subtraction. During that interval, delta-filter outputs are erroneous, and we need to inhibit element processing. The inhibiting circuit consisting of Timer 1 and the AND Gate 1 perform this function. As an example, if the delta-filter delay is 2 cycles, the Timer 1 pickup time would be 3 cycles and the protection logic scheme would block the element for as long as 3 cycles after the scheme detected the open-pole condition.

Remember at this point that the logic scheme of Fig. 14 takes care of the long line charging current issue automatically, so there is no need to readjust the sequence differential pickup current during a pole open. As soon as the logic scheme detects a pole-open condition on the line, it blocks or inhibits operation of the sequence element during an interval equal to the timer pickup time. The scheme employs the delta filters at the end of the same interval. Assume, as an example, that the delta filters have a delay of 2 cycles and that the timer pickup time is 4 cycles. When the delta filters are in operation after 2 cycles, the output of these filters will have subtracted from the signal the existing sequence current resulting from the unbalance. After 4 cycles, the sequence current at each delta filter output will be zero and the element will operate as if the shunt currents were balanced.

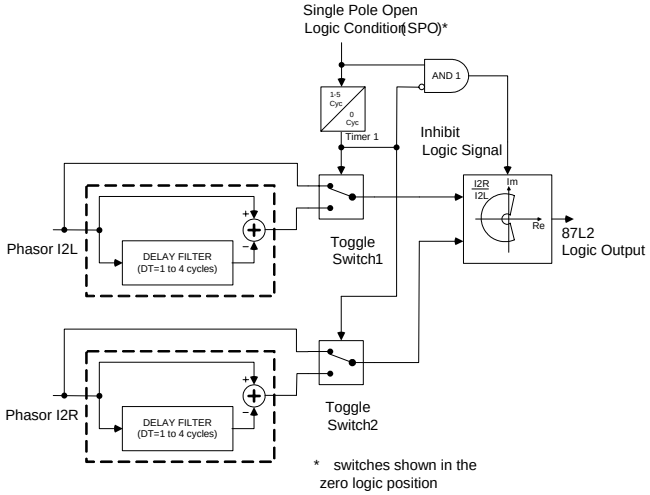


Fig. 14. Basic switch-compensated 87L2 element with conventional delta filters

B. An Advanced Scheme Taking Into Account Adjacent Lines

There is a major shortcoming in the logic represented in the diagram of Fig. 14. The relays on which the logic implements the sequence elements are to be connected to the line on which the pole-open condition exists so that the logic can detect this condition. As this paper discussed previously, sequence elements must compensate also for adjacent lines. We can accommodate this need through use of the dual-compensated element illustrated in Fig. 15. In this figure, we have two independent sequence elements, 87L2_A and 87L2_B. The element 87L2_A works in the same fashion as a conventional element. The only difference is that logic inhibits or blocks processing of this element upon detection of a pole-open condition.

The element 87L2_B works all the time and receives phasor information from the two delta filters. Logic blocks this element for a few cycles (Timer 1) only when logic detects a pole-open condition on the line to which it is connected or when the line to which it is connected is energized (Timer 2). Another advantage of the element 87L2_B is that it

restores sequence element sensitivity every time a fault occurs within the context of a current unbalance that the element determines to be an external fault. Such an occurrence would include a pole-open condition on an adjacent line, such as Fig. 13 illustrates, or a cross-country fault.

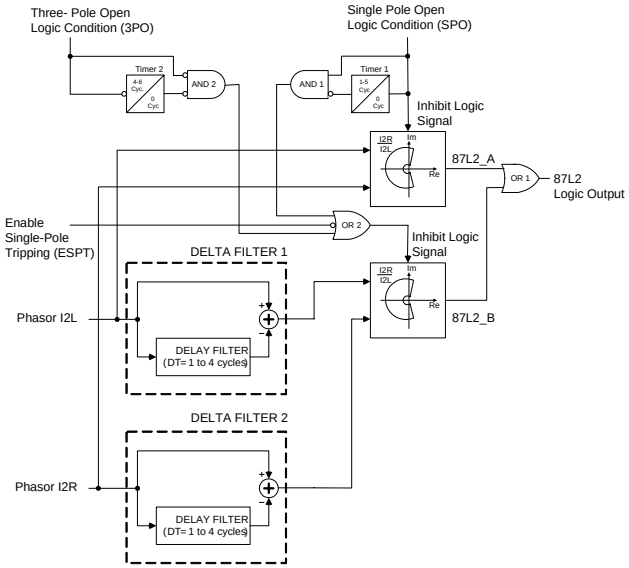


Fig. 15. Basic dual-compensated 87L2 element with conventional delta filters

C. Dual-Compensated Sequence Element Using Latching Delta Filter

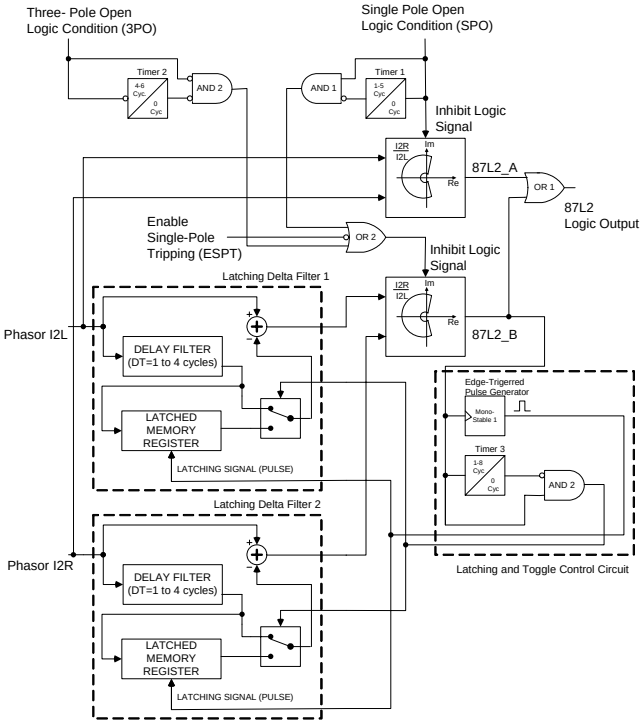


Fig. 16. Advanced dual-compensated 87L2 element with latching delta filters

In the dual-compensated element logic represented in Fig. 15, we can expand detection time at will by replacing conventional delta filters with the latched delta filters illustrated in Fig. 11. We then obtain the logic of Fig. 16. This logic is identical to Fig. 15 logic, except that you can control the detection time in Fig. 16 logic at will.

X. Validation and Testing

A. Example of a Long Line

Consider the 500 kV line in Fig. 17 and a resistive A-phase-to-ground fault occurring at 33 percent of the line length. The primary fault resistance is 150 Ohms. The fault occurs at 200 ms. In all examples, the radius, R, is 6, the angle, α, is 180° and the differential pickup current is 0.1 A for the sequence element characteristics. In all cases, the line CT ratio is 600.

If the fault were to occur in a three-pole tripping application, the A-phase element would not detect the fault. A conventional 87L2 element, however, would detect the fault. Fig. 18a shows the negative-sequence currents during the fault. On all current plots, dots represent the left-hand-side sequence current, dashes represent the right-hand-side current, and a solid line represents the differential current. Both elements 87L2_A and 87L2_B in the logic of Fig. 16 would also detect the fault as shown in the logic signal representation of Fig. 18b. The same analysis is applicable to a zero-sequence 87LG element. Fig. 19a shows the zero-sequence currents, and Fig. 19b shows the logic signals. Note that, as with the 87L2 elements, all 87LG elements (conventional and new) detect the fault.

Let us now consider a single-pole tripping application in which B-phase is open and in which there is a subsequent A-phase-to-ground fault (same resistance of 150 Ohms) also at 200 ms. Fig. 20a illustrates the negative-sequence currents. Prior to the fault, there exists a substantial sequence current as a result of the pole-open situation. With a conventional scheme (with no compensation), neither the 87LA nor any of the sequence elements (87LG and 87L2) will detect the fault because the pole open and the fault resistance keep the different current ratios inside stability areas. When we apply the dual-compensated element of Fig. 16, one can see that the new element, 87L2_B, will detect the fault, as in Fig. 20b. This first example demonstrates the performance of the new principle. Note also that the logic automatically takes care of the issue of unbalance in the charging current.

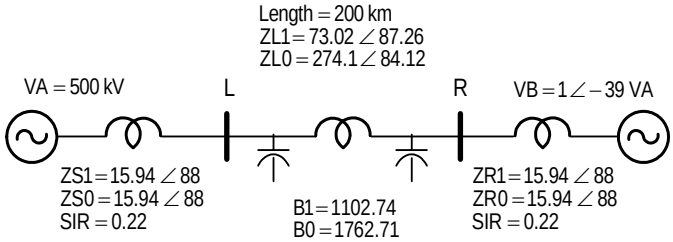
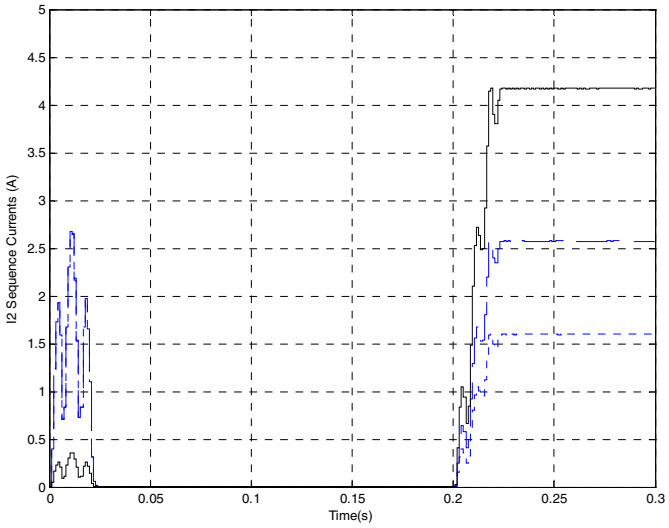
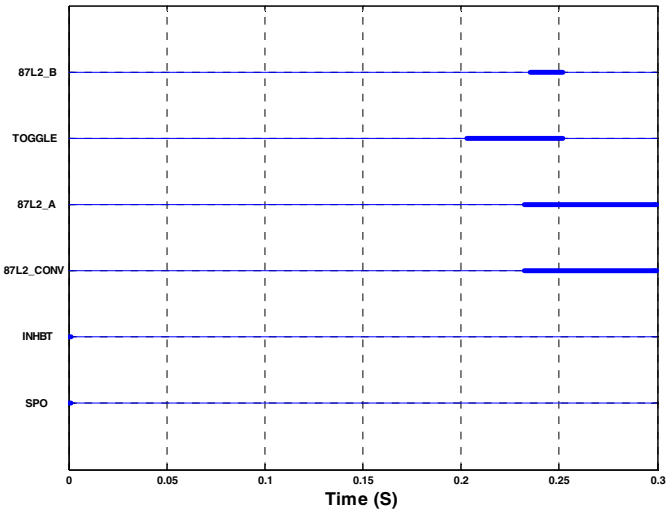


Fig. 17. 200 km 500 kV long line model

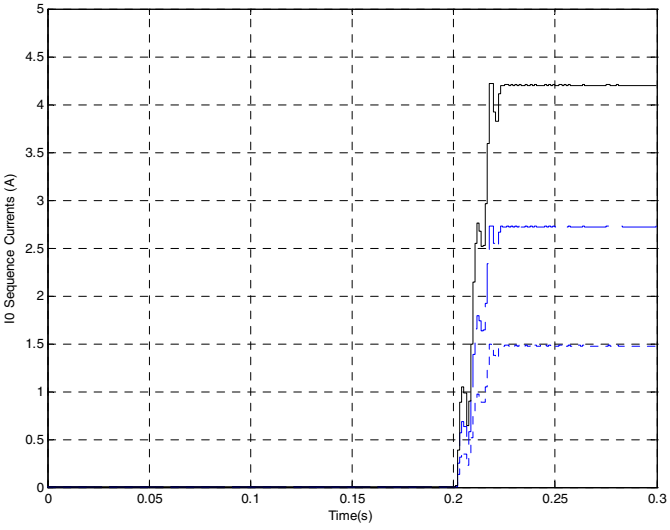


a) Negative-sequence currents

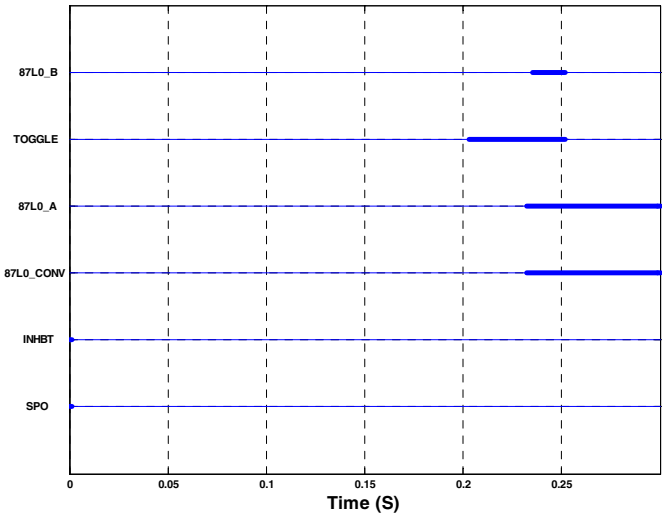


b) Logic signals

Fig. 18. 87L2 element operation during a long line A-phase-to-ground fault

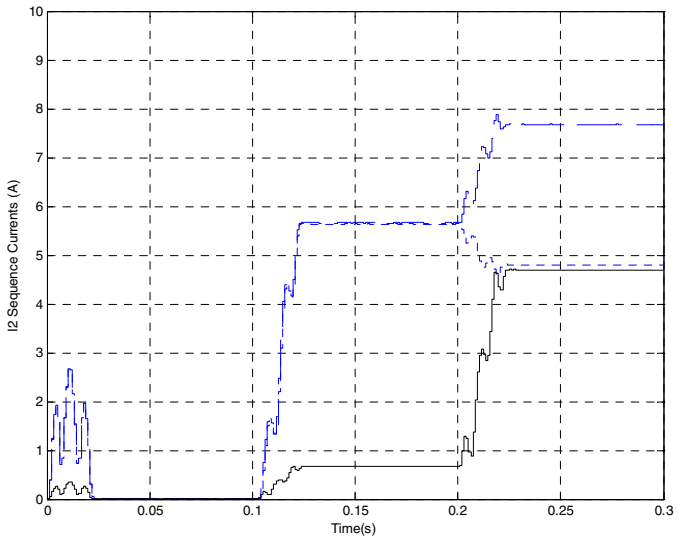


a) Zero-sequence currents

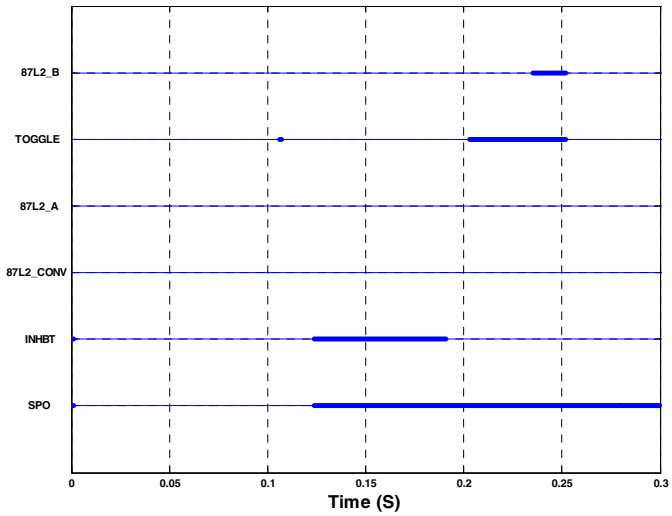


b) Logic signals

Fig. 19. 87LG element operation during a long line A-phase-to-ground fault



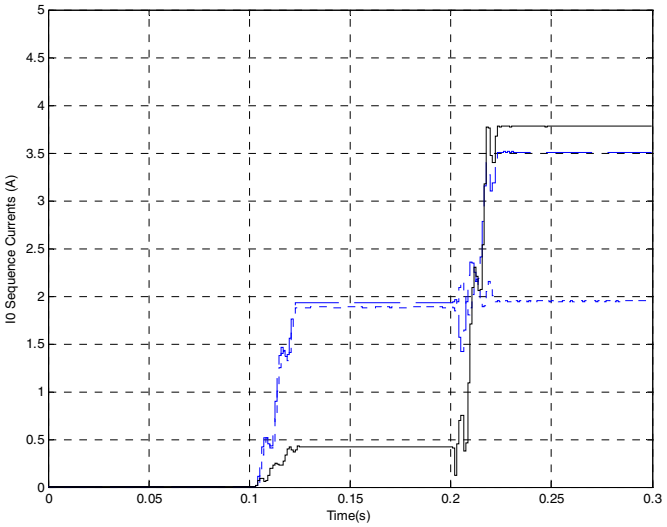
a) Negative-sequence currents



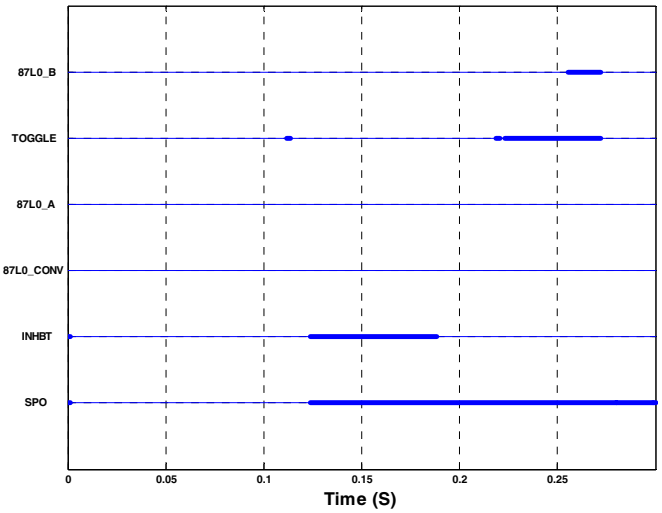
b) Logic signals

Fig. 20. 87L2 element operation for a long line A-phase-to-ground fault with B-phase open

One can perform the same analysis for the zero-sequence elements. Fig. 21 illustrates the zero-sequence currents. Once again, a substantial sequence current exists during the pole open. When the A-phase-to-ground fault occurs at 200 ms, only the new compensated 87LG_B element operates, as the logic diagram of Fig. 21b illustrates.



a) Zero-sequence currents



b) Logic signals

Fig. 21. 87LG element operation during a long line A-phase-to-ground fault and B-phase open

B. *Example of a Dual-Circuit Line*

Consider the 230 kV dual-circuit line of Fig. 22, in which we use single-pole tripping. Application of a 10-Ohm A-phase-to-ground resistive fault at 160 ms causes the opening at 260 ms of A-phase on the upper circuit. At 560 ms, a second 150-Ohm resistive fault occurs on B-phase of the same circuit.

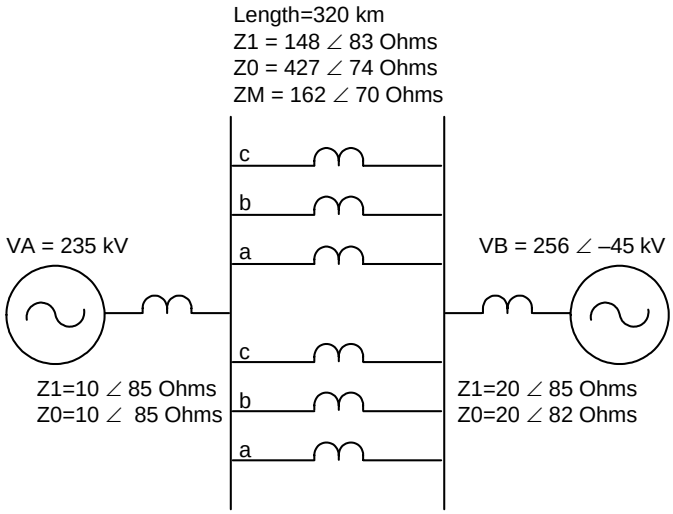


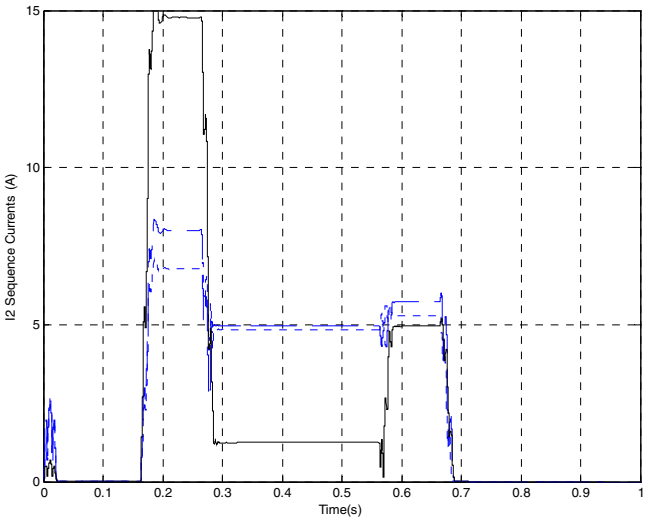
Fig. 22. 230 kV double-circuit line

1) *Two consecutive faults in the same circuit*

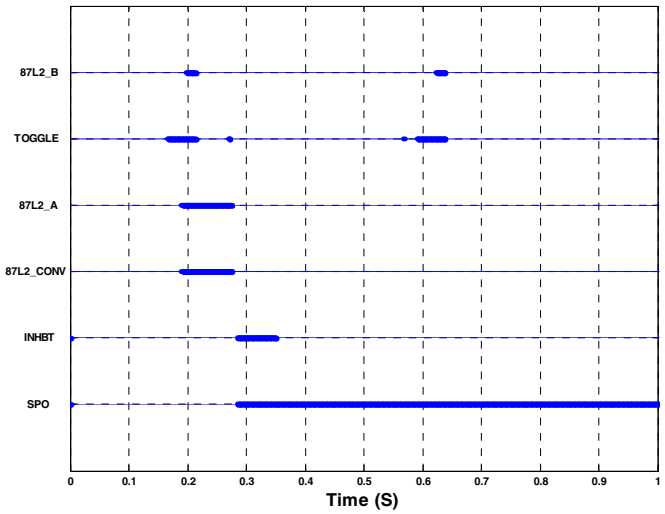
When the first A-phase fault occurs, the phase element, 87LA, operates together with the sequence elements, 87LG and 87L2. When the second fault occurs on B-phase, the phase element, 87LB, does not operate because the fault resistance is too high. The question here is whether the sequence elements will operate for the second fault.

Fig. 23a shows the negative-sequence currents during the first and second faults. Fig. 23b shows the logic signals for the 87L2 elements. For the first A-phase fault, all elements (conventional and new) detect the fault. For the second fault, only the newly defined sequence element, 87L2_B, detects the fault.

Fig. 24a shows the zero-sequence currents under the same conditions, whereas Fig. 24b shows the corresponding element logic signals. We can infer the same observations and conclusions as for Fig. 23a and Fig. 23b.

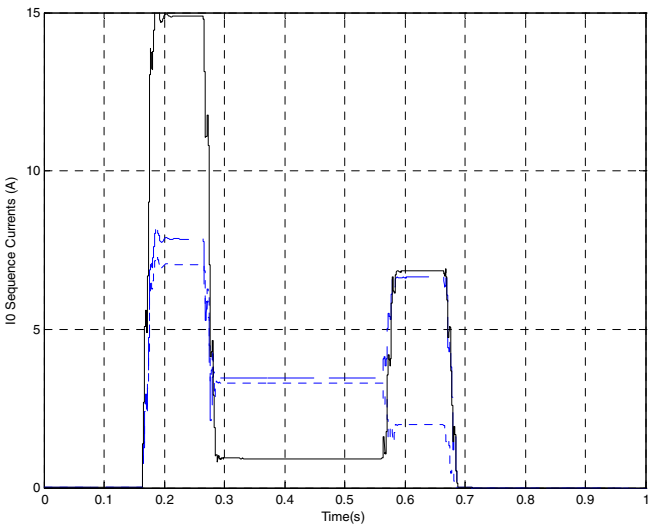


a) Negative-sequence currents

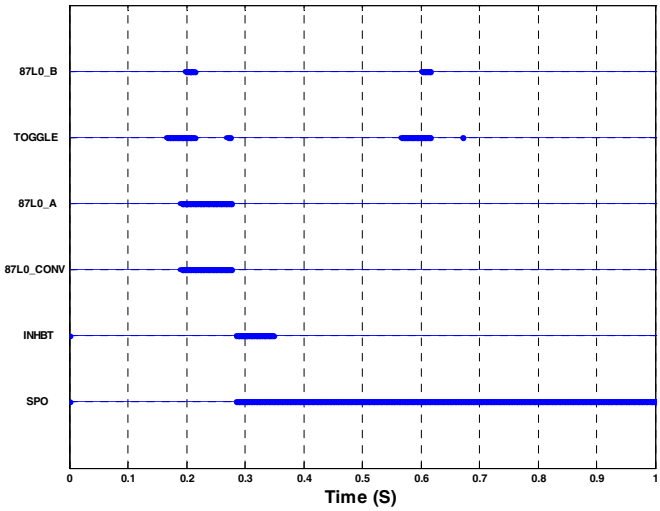


b) Logic signals

Fig. 23. 87L2 element operation during evolving fault from A-phase to B-phase-to-ground fault with A-phase open



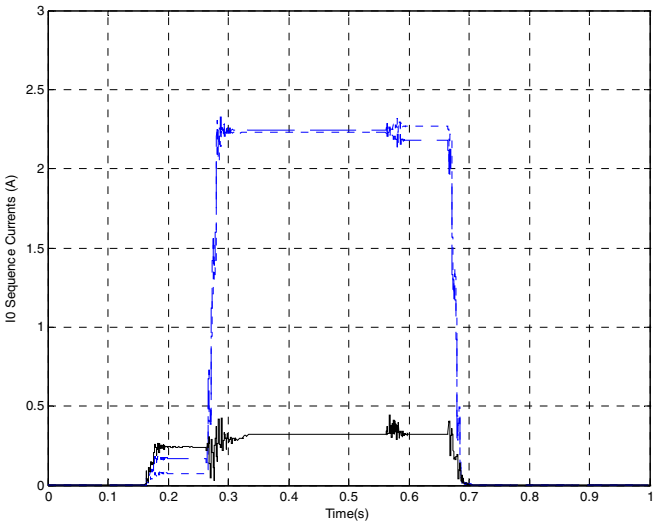
a) Zero-sequence currents



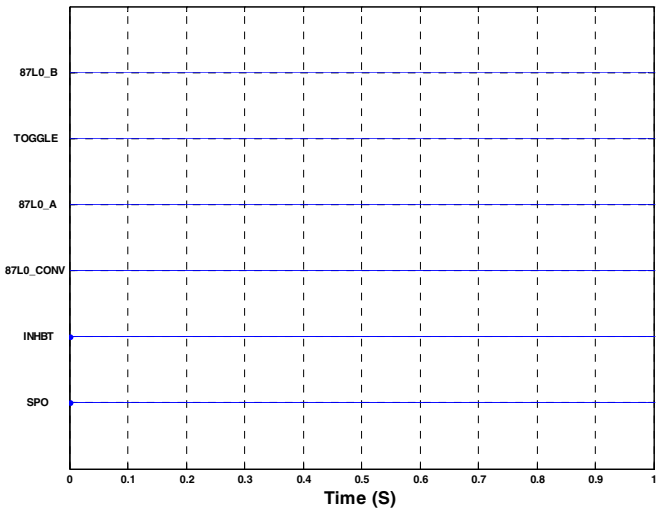
b) Logic signals

Fig. 24. 87LG element during evolving fault from A-phase to B-phase-to-ground fault with A-phase open

Fig. 25a shows the zero-sequence currents on the adjacent lower circuit. This circuit has no fault. Fig. 25b shows the 87LG element logic signals. As expected, neither the conventional nor newly defined zero-sequence elements sees a fault. We could apply the same analysis with the negative-sequence elements.

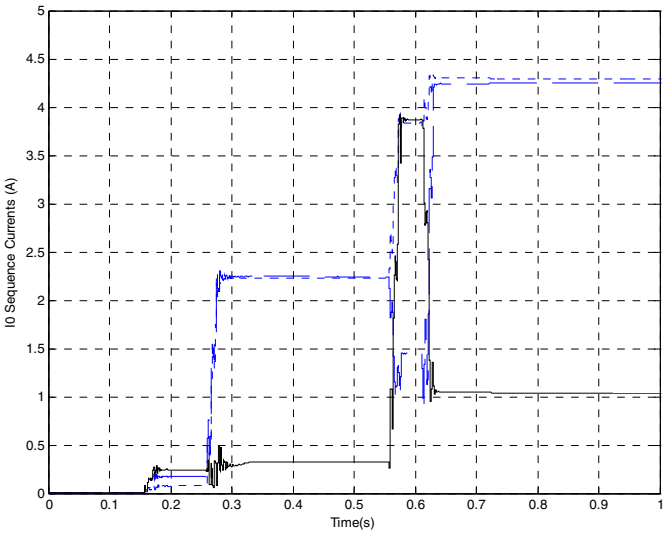


a) Zero-sequence currents

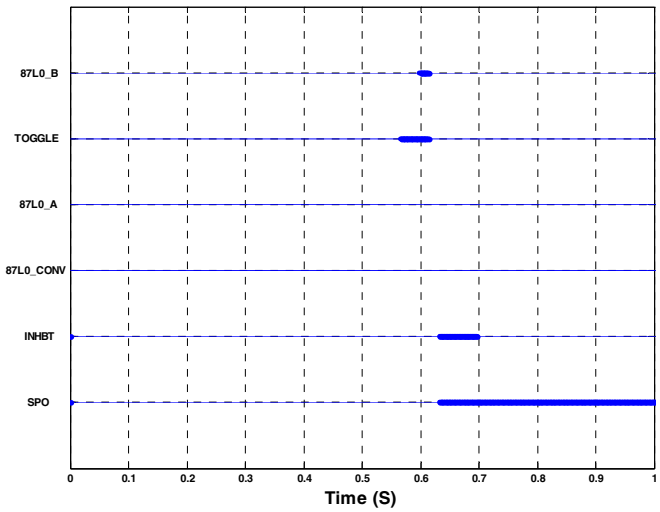


b) Logic signals

Fig. 25. 87LG element on the adjacent line element during an A-phase-to-ground fault followed by a B-phase-to-ground with pole open on the upper circuit



a) Zero-sequence currents



b) Logic signals

Fig. 26. 87LG element operation on the adjacent line element during a B-phase-to-ground fault following an A-phase-to-ground fault on the upper circuit

2) Two consecutive faults in different circuits

Let us assume now, after the first A-phase-to-ground fault occurs in the upper circuit and is cleared by opening A-phase, that a second 250-Ohm B-phase-to-ground fault occurs at 560 ms on the lower circuit, on which there is no pole open. Fig. 26a shows the zero-sequence currents on the lower circuit. After detection of the B-phase fault, B-phase opens. Fig. 26b shows the logic diagram of the 87Lg element. One can see that only the newly defined 87LG_B element detects the fault. Remember here that the newly defined sequence element, 87LG_B, does not detect the fault on a circuit containing a pole open. Rather, the element detects a fault on a circuit on which there is a substantial unbalance prior to the fault as a result of a pole open on the adjacent circuit.

XI. Conclusion

1. At low load and in the absence of load, phase elements will have about the same sensitivity as sequence elements, irrespective of whether the tripping application is for a single or three-pole trip.
2. In three-pole tripping applications, at moderate and high load, the 87LG and 87L2 sequence elements provide sensitivity. The current ratio of these elements will be located entirely in the right-hand side of the complex plane close to the horizontal axis. These elements are immune to any load effect and to the value of the fault resistance.
3. In single-pole-tripping applications, sequence elements will lose sensitivity and perform in some applications no better than a phase element when a subsequent fault occurs during a pole open condition. Subtracting the pre-fault current (current during the pole-open condition) from the fault current restores the original sensitivity of sequence elements.

4. As a general rule, when a fault occurs in the situation of an unbalanced network, line current differential sequence elements, 87L2 and 87LG, could undergo some loss of sensitivity. These elements will then not detect some faults that they normally detect if the unbalance does not exist.
5. Filters known as delta filters can fulfill the task of removing pre-fault current from a fault current for the purpose of restoring sequence element sensitivity.
6. The newly defined latching delta filter provides the ability for one to prolong almost indefinitely the action of a conventional delta filter.

APPENDIX A
RESOLUTION OF AN EXTERNAL SINGLE-A-PHASE-TO-GROUND FAULT USING THE SEQUENCE NETWORK

For the single-line network of Fig. 27, we can resolve a single A-phase-to-ground internal fault at location d from the left bus, L, through the use of the sequence network of Fig. 28, in which the superposition principle is applied. The superposition principle involves the application of a voltage to the faulted network (sequence network) at the fault location that equals the voltage existing at the same point before the fault. The total fault current at some network location equals the load current existing before the fault plus the pure-fault current (current void of any load) existing on the faulted network.

For the circuit of Fig. 27, the voltage at the fault location prior to the fault is according to (15):

$$\mathrm{Ef} = \mathrm{VA} - \mathrm{I_{LD}}\,\mathrm{Z1M} \tag{15}$$

where Z1M is the impedance between the source VA and the fault location at distance d, as in (16):

$$\mathrm{Z1M} = \mathrm{ZS1} + \mathrm{d}\ \mathrm{ZL1} \tag{16}$$

The load current in the line is provided by (17):

$$\mathrm{I_{LD}} = \frac{\left(1 - \mathrm{e}^{-\mathrm{j}\theta}\right)\mathrm{VA}}{\mathrm{Z1M} + \mathrm{Z1N}} \tag{17}$$

where Z1N is defined as in (18):

$$\mathrm{Z1N} = \mathrm{ZR1} + \left(1 - \mathrm{d}\right)\mathrm{ZL1} \tag{18}$$

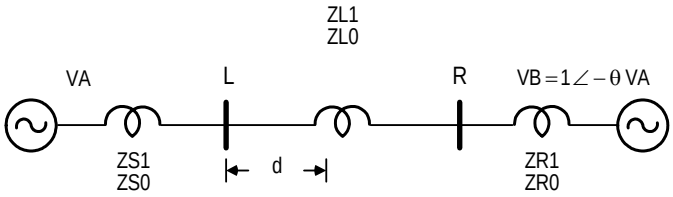


Fig. 27. Single-line network

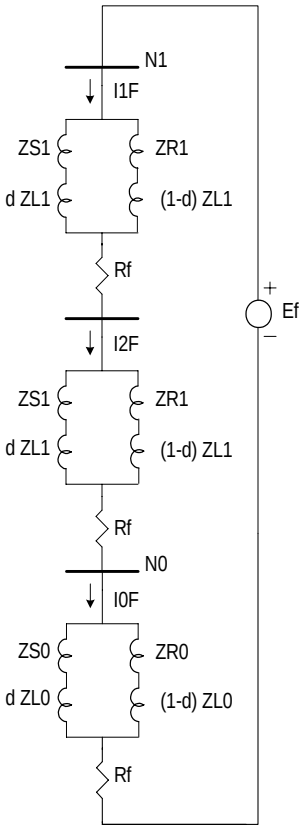


Fig. 28. A-phase-to-ground fault at R pure-fault sequence network

The total impedance, ZSOM, in front of the source, Ef, on the faulted circuit is provided by (19):

$$\mathrm{ZSOM} = \frac{2\ \mathrm{Z1M}\ \mathrm{Z1N}}{\mathrm{Z1M} + \mathrm{Z1N}} + \frac{\mathrm{Z0M}\ \mathrm{Z0N}}{\mathrm{Z0M} + \mathrm{Z0N}} + 3\,\mathrm{Rf} \tag{19}$$

with Z0M and Z0N defined according to (20) and (21):

$$\mathrm{Z0M} = \mathrm{ZS0} + \mathrm{d}\ \mathrm{ZL0} \tag{20}$$

$$\mathrm{Z0N} = \mathrm{ZR0} + \left(1 - \mathrm{d}\right)\mathrm{ZL0} \tag{21}$$

The positive-sequence current at the fault equals the source voltage divided by the total impedance, as in (22):

$$\mathrm{I1F} = \frac{\mathrm{Ef}}{\mathrm{ZSOM}} \tag{22}$$

For a single A-phase-to-ground fault, the negative-sequence and zero-sequence currents at the fault equal the positive-sequence current, as in (23) and (24):

$$\mathrm{I2F} = \mathrm{I1F} \tag{23}$$

$$\mathrm{I0F} = \mathrm{I1F} \tag{24}$$

The positive-sequence, negative-sequence, and zero-sequence currents at the relay location close to the L bus are provided by (25), (26), and (27):

$$I1L = C1\, I1F \tag{25}$$

$$I2L = C1\, I1F \tag{26}$$

$$I0L = C0\, I1F \tag{27}$$

where C1 and C0 are the current distribution factors at the relay location defined by (28) and (29):

$$C1 = \frac{Z1N}{Z1M + Z1N} \tag{28}$$

$$C0 = \frac{Z0N}{Z0M + Z0N} \tag{29}$$

The positive-sequence, negative-sequence, and zero-sequence currents at the relay location close to the R bus are provided by (30), (31), and (32):

$$I1R = (1 - C1)\, I1F \tag{30}$$

$$I2R = (1 - C1)\, I1F \tag{31}$$

$$I0R = (1 - C0)\, I1F \tag{32}$$

The A-phase current at the relay location close to the L bus is according to (33):

$$\begin{aligned} IAL &= C1\, I1F + C2\, I2F + C0\, I0F + I_{LD} \\ &= (2\, C1 + C0)\, I1F + I_{LD} \end{aligned} \tag{33}$$

The A-phase current at the relay close to the R bus is according to (34):

$$IAR = [2\,(1 - C1) + (1 - C0)]\, I1F - I_{LD} \tag{34}$$

APPENDIX B
RESOLUTION OF AN INTERNAL SINGLE-A-PHASE-TO-GROUND FAULT WITH B-PHASE OPEN USING THE SEQUENCE NETWORK

Consider the elementary network in Fig. 27 and then see Fig. 29 for a representation of the sequence network corresponding to a B-phase open situation.

To draw the sequence network for a B-phase open situation, we must embed two constraints into the network. The first of these is a voltage constraint. The second is a current constraint. Let us assume that B-phase is open between two points, x and y. The following conditions provide the sequence voltages between points x and y:

$$\begin{pmatrix} V1_{xy} \\ V2_{xy} \\ V0_{xy} \end{pmatrix} = \frac{1}{3} \cdot \begin{pmatrix} 1 & a & a^2 \\ 1 & a^2 & a \\ 1 & 1 & 1 \end{pmatrix} \cdot \begin{pmatrix} VA_{xy} \\ VB_{xy} \\ VC_{xy} \end{pmatrix} \tag{35}$$

In (35), "a" is the conventional complex operator $1\angle 120°$. Values for VA_{xy} and VC_{xy} are zero, so we obtain the results in (36):

$$\begin{aligned} V1_{xy} &= (1/3)\, a\, VB_{xy} \\ V2_{xy} &= (1/3)\, a^2\, VB_{xy} \\ V0_{xy} &= (1/3)\, VB_{xy} \end{aligned} \tag{36}$$

Regarding the current constraint, we can express this according to the condition that the B-phase current must be equal to zero, as in (37):

$$IB = a^2\, I1L + a\, I2L + I0L = 0 \tag{37}$$

The three ideal transformers represented in the sequence network of Fig. 29 implement the two voltage and current constraints.

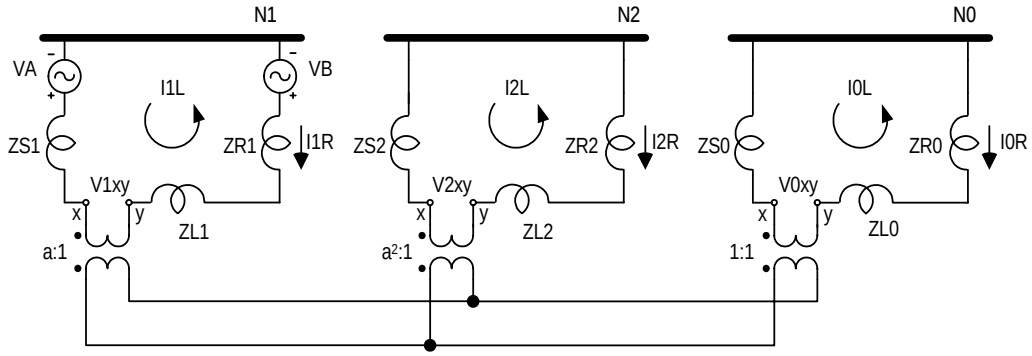


Fig. 29. Sequence network of B-phase open elementary network

We can resolve the sequence network of Fig. 29 for the unknown sequence currents by solving the linear matrix equation in (38):

$$\begin{pmatrix} ZL1 + ZS1 + ZR1 & 0 & 0 & a \\ 0 & ZL1 + ZS1 + ZR1 & 0 & a^2 \\ 0 & 0 & ZL0 + ZS0 + ZR0 & 1 \\ a^2 & a & 1 & 0 \end{pmatrix} \cdot \begin{pmatrix} I1L \\ I2L \\ I0L \\ (1/3)VB_{xy} \end{pmatrix} = \begin{pmatrix} VA - VB \\ 0 \\ 0 \\ 0 \end{pmatrix} \tag{38}$$

Let us define the variables in (39):

$$\begin{aligned}\Delta V &= VA - VB \\ m &= ZL1 + ZS1 + ZR1 = ZL2 + ZS2 + ZR2 \\ n &= ZL0 + ZS0 + ZR0 \\ m_1 &= -(1-d)\,ZL1 - ZR1 \\ n_1 &= -(1-d)\,ZL0 - ZR0 \\ p &= m + m_1 = d\,ZL1 + ZS1 = d\,ZL2 + ZS2 \\ q &= n + n_1 = d\,ZL0 + ZS0 = d\,ZL0 + ZS0\end{aligned} \tag{39}$$

Through use of the Gaussian elimination process, we can resolve the system of equations in (38) and obtain the solutions for the three sequence currents as in (40), (41), and (42):

$$I1L_{preflt} = -I1R_{preflt} = \frac{\Delta V\,(m+n)}{m\,(m+2\,n)} \tag{40}$$

$$I2L_{preflt} = -I2R_{preflt} = -\frac{a\,\Delta V\,n}{m\,(m+2\,n)} \tag{41}$$

$$I0L_{preflt} = -I0R_{preflt} = -\frac{a^2\,\Delta V}{m+2\,n} \tag{42}$$

Note that the three sequence currents the protection logic determined during the B-phase open condition constitute the prefault currents before any other fault occurring at a later stage. For this reason, (40) through (42) show the sequence currents with a prefault subscript.

According to this same reasoning, we can compute the A-phase prefault current on the left side as the sum of all three-sequence currents, as in (43):

$$IAL_{preflt} = \frac{m\,\Delta V\,(1-a^2) + n\,\Delta V\,(1-a)}{m\,(m+2\,n)} \tag{43}$$

The A-phase current on the right side, as shown by (44) is the opposite of (43):

$$IAR_{preflt} = -\frac{m\,\Delta V\,(1-a^2) + n\,\Delta V\,(1-a)}{m\,(m+2\,n)} \tag{44}$$

Let us assume now that, during the open B-phase condition, a subsequent A-phase-to-ground fault occurs at a distance, d, from the left bus of the line. Fig. 30 represents this faulted sequence network, where the new condition of an A-phase-to-G fault has been added to the already represented pole-open B condition. We can now resolve the sequence currents by solving the next set of linear equations. Through use of the same Gaussian elimination process as before, we can compute the current at the fault, IF, and the sequence currents at the left-hand-side line bus according to (46), (47), (48), and (49):

$$\begin{pmatrix} ZL1+ZS1+ZR1 & 0 & 0 & -(1-d)\,ZL1 - ZR1 & a \\ 0 & ZL2+ZS2+ZR2 & 0 & -(1-d)\,ZL2 - ZR2 & a^2 \\ 0 & 0 & ZL0+ZS0+ZR0 & -(1-d)\,ZL0 - ZR0 & 1 \\ ZS1 + d\,ZL1 & ZS2 + d\,ZL2 & ZS0 + d\,ZL0 & 3R & 0 \\ a^2 & a & 1 & 0 & 0 \end{pmatrix} \begin{pmatrix} I1L \\ I2L \\ I0L \\ IF \\ (1/3)VB_{xy} \end{pmatrix} = \begin{pmatrix} \Delta V \\ 0 \\ 0 \\ VA \\ 0 \end{pmatrix} \tag{45}$$

$$IF = \frac{-2\,a^2\,m\,\Delta V\,(-0.5\,p-q) - \Delta V\,p\,(1-a)(m+2\,n) + 2\,m\,VA\,(m+2\,n)}{2\,m\,(-0.5\,p-q)(m_1+2\,n_1) - 3\,p\,m_1\,(m+2\,n) + 6\,R_f\,m\,(m+2\,n)} \tag{46}$$

$$I0L = \frac{-a^2\,\Delta V}{m+2\,n} - \frac{m_1+2\,n_1}{m+2\,n}\,IF \tag{47}$$

$$I2L = \frac{-a\,\Delta V\,n}{m\,(m+2\,n)} + \left(\frac{a^2}{2}\,\frac{m_1+2\,n_1}{m+2\,n} - \frac{m_1\,(1-a)}{2\,m}\right) IF \tag{48}$$

$$I1L = \frac{\Delta V\,(m+n)}{m\,(m+2\,n)} + \left(\frac{a}{2}\,\frac{m_1+2\,n_1}{m+2\,n} + \frac{m_1\,(a^2-1)}{2\,m}\right) IF \tag{49}$$

As we can see in (50), the A-phase fault current on the left side equals the sum of the three sequence currents:

$$\begin{aligned} IAL = {} & \frac{\Delta V\,(m+n)}{m\,(m+2\,n)} + \frac{-a\,\Delta V\,n}{m\,(m+2\,n)} - \frac{a^2\,\Delta V}{m+2\,n} \\ & + \left(\left(\frac{a^2}{2} + \frac{a}{2} - 1\right)\left(\frac{m_1+2\,n_1}{m+2\,n}\right) + \frac{m_1\,(a^2-2+a)}{2\,m}\right) IF \end{aligned} \tag{50}$$

The sequence currents at the right-hand side bus can be computed according to (51), (52), and (53):

$$I0R = \frac{a^2\,\Delta V}{m+2\,n} + \frac{p+2\,q}{m+2\,n}\,IF \tag{51}$$

$$I2R = \frac{a\,\Delta V\,n}{m\,(m+2\,n)} + \left(1 - \frac{a^2}{2}\,\frac{m_1+2\,n_1}{m+2\,n} + \frac{m_1\,(1-a)}{2\,m}\right) IF \tag{52}$$

$$I1R = -\frac{\Delta V\,(m+n)}{m\,(m+2\,n)} + \left(1 - \frac{a}{2}\,\frac{m_1+2\,n_1}{m+2\,n} - \frac{m_1\,(a^2-1)}{2\,m}\right) IF \tag{53}$$

As we can see in (54), the A-phase fault current on the right-hand side equals the sum of the three sequence currents:

$$\begin{aligned} IAR = {} & \frac{\Delta V\,(m+n)}{m\,(m+2\,n)} + \frac{a\,\Delta V\,n}{m\,(m+2\,n)} + \frac{a^2\,\Delta V}{m+2\,n} \\ & + \begin{pmatrix} p+2\,q - \left(\frac{a^2}{2} + \frac{a}{2}\right)(m_1+2\,n_1) \\ \hline m+2\,n \\ 2 + \\ - \frac{m_1\,(a^2-2+a)}{2\,m} \end{pmatrix} IF \end{aligned} \tag{54}$$

If we examine (47) through (49) for the left-hand-side bus and (51) through (53) for the right-hand-side bus and considering (40) through (42) for the sequence currents in the open-pole situation only, we can notice that the sequence currents at both line extremities consist of a prefault term and a second term proportional to IF. We can, therefore, write (55) through (60):

$$I0L = I0L_{preflt} - \frac{m_1 + 2\,n_1}{m + 2\,n}\,IF \tag{55}$$

$$I2L = I2L_{preflt} + \left(\frac{a^2}{2}\,\frac{m_1 + 2\,n_1}{m + 2\,n} - \frac{m_1\,(1-a)}{2\,m}\right)IF \tag{56}$$

$$I1L = I1L_{preflt} + \left(\frac{a}{2}\,\frac{m_1 + 2\,n_1}{m + 2\,n} + \frac{m_1\,(a^2-1)}{2\,m}\right)IF \tag{57}$$

$$I0R = I0R_{preflt} + \frac{p + 2\,q}{m + 2\,n}\,IF \tag{58}$$

$$I2R = I2R_{preflt} + \left(1 - \frac{a^2}{2}\,\frac{m_1 + 2\,n_1}{m + 2\,n} + \frac{m_1\,(1-a)}{2\,m}\right)IF \tag{59}$$

$$I1R = I1R_{preflt} + \left(1 - \frac{a}{2}\,\frac{m_1 + 2\,n_1}{m + 2\,n} - \frac{m_1\,(a^2-1)}{2\,m}\right)IF \tag{60}$$

Following the same line of thinking, we can express the two A-phase currents in (50) and (54) at both line extremities in the form of (61):

$$IAL = IAL_{preflt} + \left(\left(\frac{a^2}{2} + \frac{a}{2} - 1\right)\left(\frac{m_1 + 2\,n_1}{m + 2\,n}\right) + \frac{m_1\,(a^2 - 2 + a)}{2\,m}\right)IF \tag{61}$$

and in the form of (62):

$$IAR = IAR_{preflt} + \left(\begin{array}{l} 2 + \dfrac{p + 2\,q - \left(\dfrac{a^2}{2} + \dfrac{a}{2}\right)(m_1 + 2\,n_1)}{m + 2\,n} \\ -\dfrac{m_1\,(a^2 - 2 + a)}{2\,m} \end{array}\right)IF \tag{62}$$

Equation (63) expresses the next identity:

$$a^2 + a = -1 \tag{63}$$

We can rewrite (61) and (62) according to (64) and (65):

$$IAL = IAL_{preflt} - \frac{3}{2}\left(\frac{m_1 + 2\,n_1}{m + 2\,n} + \frac{m_1}{m}\right)IF \tag{64}$$

$$IAR = IAR_{preflt} + \left(2 + \frac{p + 2\,q - 0.5\,(m_1 + 2\,n_1)}{m + 2\,n} + \frac{3\,m_1}{2\,m}\right)IF \tag{65}$$

Examination of (55) through (60), which provide the sequence currents at both line extremities, and at (64) and (65), which provide the A-phase currents, one can see that we can express any current in the general form corresponding to (66):

$$I = I_{preflt} + \text{func}(d, ZS1, ZL1, ZR1, ZS0, ZL0, ZR0)\,IF \tag{66}$$

In Equation (66), we can express any current (phase or sequence) as the sum of the current existing before the fault and the product of a function "func" by the current, IF, flowing into the fault in the sequence network. The function "func" in turn is a function of the distance to the fault and the network impedances only.

The current, IF, flowing into the fault is a function of the distance to the fault, the network impedances, the source voltages, and (most important of all) the fault resistance, Rf, as shown in (67).

$$IF = \text{func}\,(d, ZS1, ZL1, ZR1, ZS0, ZL0, ZR0, Rf, VA, VB) \tag{67}$$

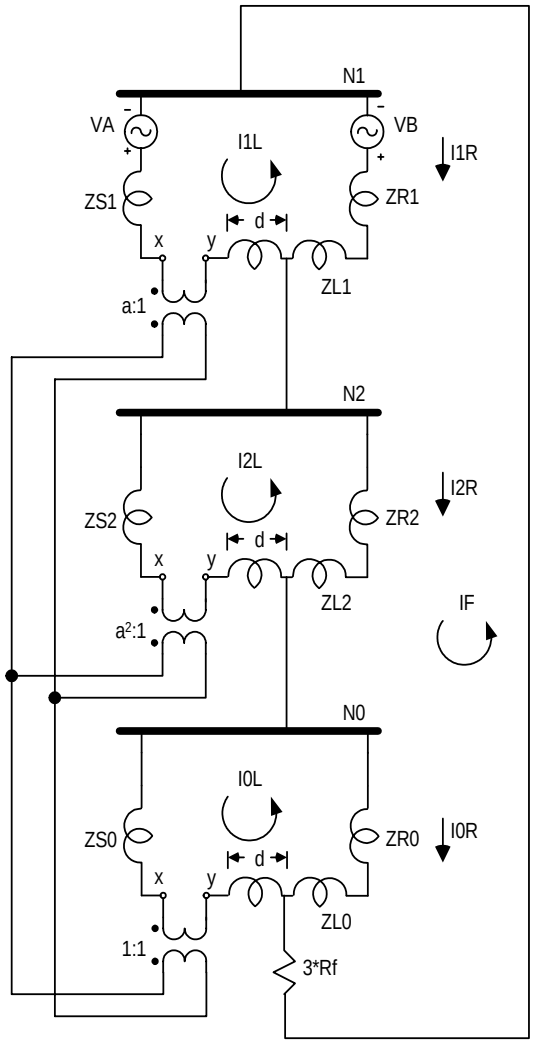


Fig. 30. Sequence network of B-phase open with A-phase-to-ground fault element in any network

XII. References

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XIII. Biographies

Gabriel Benmouyal, P.E. received his B.A.Sc. in Electrical Engineering and his M.A.Sc. in Control Engineering from Ecole Polytechnique, Université de Montréal, Canada in 1968 and 1970, respectively. In 1969, he joined Hydro-Québec as an Instrumentation and Control Specialist. He worked on different projects in the field of substation control systems and dispatching centers. In 1978, he joined IREQ, where his main field of activity has been the application of microprocessors and digital techniques for substation and generating-station control and protection systems. In 1997, he joined Schweitzer Engineering Laboratories in the position of Principal Research Engineer. He is a registered professional engineer in the Province of Québec, is an IEEE Senior Member, and has served on the Power System Relaying Committee since May 1989. He holds over six patents and is the author or co-author of several papers in the field of signal processing and power networks protection.

Joe Mooney, P.E. received his B.S. in Electrical Engineering from Washington State University in 1985. He joined Pacific Gas and Electric Company upon graduation as a System Protection Engineer. In 1989, he left Pacific Gas and Electric and was employed by Bonneville Power Administration as a System Protection Maintenance District Supervisor. In 1991, he left Bonneville Power Administration and joined Schweitzer Engineering Laboratories as an Application Engineer. Shortly after starting with SEL, he was promoted to Application Engineering Manager where he remained for nearly three years. He is currently the manager of the Power Engineering Group of the Research and Development department at Schweitzer Engineering Laboratories. He is a registered Professional Engineer in the State of California and Washington.

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