Mutual Impedance in Parallel Lines – Protective Relaying and Fault Location Considerations

Fernando Calero
Schweitzer Engineering Laboratories, Inc.

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Mutual Impedance in Parallel Lines – Protective Relaying and Fault Location Considerations

Fernando Calero, *Schweitzer Engineering Laboratories, Inc.*

***Abstract*—When two or more lines are running parallel to each other, mutual impedances between the lines modify the voltage and current profile measured in the protective relays protecting each line. Analysis of transmission line impedance formulas can provide interesting data to the protection engineer. Fault location is an algorithm in protective relays that reports the distance to the fault. Ground fault location is discussed, as is the implication of requiring the measurement of the parallel line 3I0 for a more accurate calculation. Since the algorithm is slow and done after the trip decision, the 3I0 measurement does not necessarily have to be sampled in the same box. Protective relaying considerations for preventing overreach and loss of directionality under certain power system operating conditions are illustrated and discussed. The paper illustrates the benefit of measuring I0p (the parallel line zero-sequence current) for fault location.**

I. Introduction

In transmission systems throughout the world, it is very common to find double-circuit towers transmitting power in narrow physical corridors. There are also places in power systems where single-circuit towers are run in parallel in wide corridors. These are examples of parallel transmission lines. More complex structures and arrangements usually emerge from power plants where several lines originate. These could be run in parallel for considerable distances.

Fig. 1(a) is typical in double-circuit towers. The two lines start and arrive in the same buses of the power system. This arrangement is generally the one that has received most consideration in literature. Fig. 1(b) illustrates the partial parallel trajectory of the two lines for a distance “d.” The two lines originate in a common bus and end in separate buses. Fig. 1(c) and Fig. 1(d) illustrate independent lines running in parallel for a distance “d.” The parallel path may be the total run of the shortest line as in Fig. 1(c) or a partially parallel path as in Fig. 1(d).

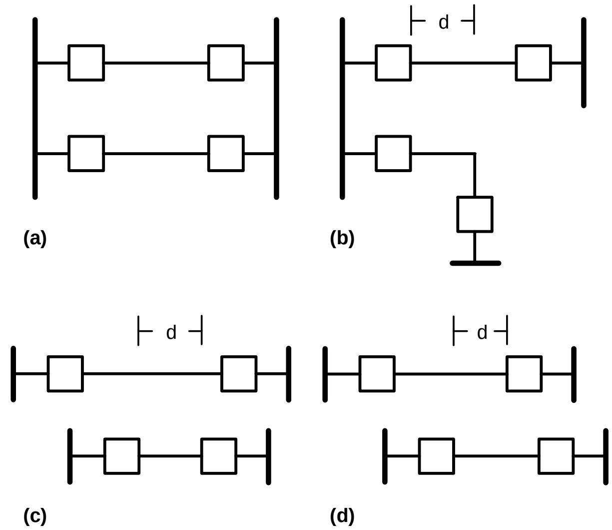

Fig. 1. Possible Configurations of Parallel Lines in Power Systems

II. Transmission Line Impedances: An Overview

Typical line protection distance relays require knowledge of transmission line positive- and zero-sequence impedances. It is sufficient for the algorithms in distance relays to approximate the transmission line with these two impedances. In reality, transmission lines have a suite of impedances represented in an impedance matrix. The impedance matrix reflects the mutual effects of the different phases in the same line as well as to any other conductor in the line arrangement. It is only under ideal conditions that a transmission line can be represented fully with its zero- and positive-sequence impedances.

A. Self and Mutual Impedances Using Modified Carson’s Equations

When the analysis of two conductors carrying currents in a parallel path, as shown in Fig. 2(a), is performed using basic electromagnetic flux linkage equations [1][2], the following equations define the self and mutual impedances:

$$Zxx = rx + j\,0.07537\left(\frac{f}{60}\right)\ln\left(\frac{1}{GMRx}\right) ohms/km \quad (1)$$

$$Zxy = j\,0.07537\left(\frac{f}{60}\right)\ln\left(\frac{1}{dxy}\right) ohms/km \quad (2)$$

Equations (1) and (2) are valid for two conductors in free space, running in parallel with a distance dxy between them. The term rx is the resistance of the conductor, and GMR is its geometric mean radius.

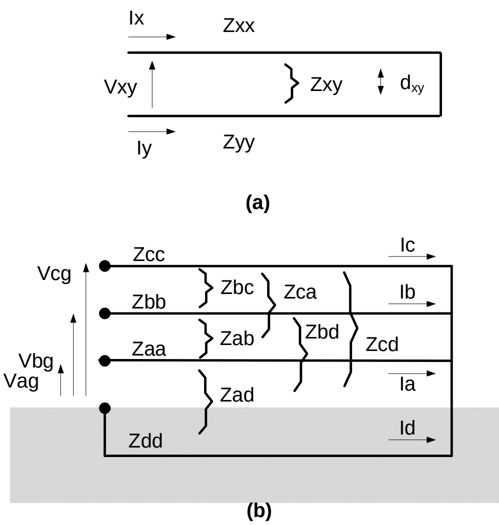

Fig. 2. (a) Two-Conductor Model (b) Three-Phase System With "Equivalent" Ground Conductor

In a three-phase power system, the ground return could be modeled with an equivalent ground conductor as shown in Fig. 2(b). The result to be obtained in the following development does not only apply to three conductors. It applies to an unlimited number of conductors and their currents returning through ground as shown in the figure. In the analysis of the three conductors, we take phase "a" as the "reference" conductor and write the equation for Vag:

$$\begin{aligned} \text{Vag} &= \text{Zaa Ia} + \text{Zab Ib} + \text{Zca Ic} + \text{Zad Id} \\ &\quad - \left(\text{Zdd Id} + \text{Zad Ia} + \text{Zbd Ib} + \text{Zcd Ic}\right) \end{aligned} \tag{3}$$

$$\begin{aligned} \text{Vag} &= \left(\text{Zaa} - \text{Zad}\right)\text{Ia} + \left(\text{Zab} - \text{Zbd}\right)\text{Ib} \\ &\quad + \left(\text{Zca} - \text{Zcd}\right)\text{Ic} + \left(\text{Zad} - \text{Zdd}\right)\text{Id} \end{aligned} \tag{4}$$

To simplify (4) and completely eliminate the influence of the ground current (Id), the following identity is used:

$$\text{Id} = -(\text{Ia} + \text{Ib} + \text{Ic}) \tag{5}$$

The equation simplifies to:

$$\begin{aligned} \text{Vag} &= \left(\text{Zaa} - 2\,\text{Zad} + \text{Zdd}\right)\text{Ia} + \\ &\left(\text{Zab} - \text{Zbd} - \text{Zad} + \text{Zdd}\right)\text{Ib} + \left(\text{Zca} - \text{Zcd} - \text{Zad} + \text{Zdd}\right)\text{Ic} \end{aligned} \tag{6}$$

and can be written:

$$\text{Vag} = \text{ZAA Ia} + \text{ZAB Ib} + \text{ZCA Ic} \tag{7}$$

where ZAA is the self impedance of the "a" conductor, and the ZAB and ZCA impedances are the mutual impedances to the "b" and "c" conductors respectively.

Using (1) and (2) to find the expressions for ZAA, ZAB, and ZCA and further mathematical simplifications, the impedances are defined by the following equations [2]:

$$\begin{aligned} \text{ZAA} &= \text{ra} + \text{rd} \\ &+ j\,0.07537\left(\frac{f}{60}\right)\left[\ln\left(\frac{1}{\text{GMRa}}\right) + \ln\left(\frac{\text{dad}^2}{\text{GMRd}}\right)\right] \text{ohms/km} \end{aligned} \tag{8}$$

$$\begin{aligned} \text{ZAB} &= \text{rd} \\ &+ j\,0.07537\left(\frac{f}{60}\right)\left[\ln\left(\frac{1}{\text{dab}}\right) + \ln\left(\frac{\text{dad dbd}}{\text{GMRd}}\right)\right] \text{ohms/km} \end{aligned} \tag{9}$$

$$\begin{aligned} \text{ZCA} &= \text{rd} \\ &+ j\,0.07537\left(\frac{f}{60}\right)\left[\ln\left(\frac{1}{\text{dca}}\right) + \ln\left(\frac{\text{dcd dad}}{\text{GMRd}}\right)\right] \text{ohms/km} \end{aligned} \tag{10}$$

Equations (8), (9), and (10) are valid for the phase "a" conductor where ra is the resistance of the "a" conductor, rd is the resistance of the return conductor, GMRa and GMRd are the geometric mean radius of the "a" and "d" conductors respectively, and dab, dca, dad, dbd, and dcd are the distances between the assumed conductors.

The same procedure could be followed for the "b" and "c" conductors, and expressions similar to (8), (9), and (10) could be derived. The above development has effectively removed the ground return from the self and mutual impedances of the three conductors in Fig. 2(b). While this simplifies the calculation, the unfortunate part is that the "equivalent" ground conductor is not physical nor is its GMR or the distance to the other conductors known.

In 1926, John Carson published a classic paper deriving equations for electromagnetic waves propagating in electrical conductors and returning through ground [3]. While the mathematics remain complex and an obscure subject to many, the results can be equated to the previous analysis. Carson's results are equations that use hyperbolic functions, and approximations can be made for power system frequencies [4] using equivalent mathematical series for these hyperbolic functions. Equations (11) and (12) are the resulting modified Carson's equations for self and mutual impedances for any "i" and "j" conductors above ground with a typical earth resistivity of $\sigma_e = 100 \text{ ohms/m}^3$.

$$\begin{aligned} \text{Zii} &= \text{ri} + 0.05919\left(\frac{f}{60}\right) \\ &\quad + j\,0.07537\left(\frac{f}{60}\right)\left[\ln\left(\frac{1}{\text{GMRi}}\right) + 6.74580\right] \text{ohms/km} \end{aligned}$$

$$\begin{aligned} \text{Zii} &= \text{ri} + 0.09530\left(\frac{f}{60}\right) \\ &\quad + j\,0.12135\left(\frac{f}{60}\right)\left[\ln\left(\frac{1}{\text{GMRi}}\right) + 6.74580\right] \text{ohms/mile} \end{aligned}$$

(11)

$$Zij = 0.05919\left(\frac{f}{60}\right) + j\,0.07537\left(\frac{f}{60}\right)\left[\ln\left(\frac{1}{dij}\right) + 6.74580\right] \text{ohms/km}$$

$$Zij = 0.09530\left(\frac{f}{60}\right) + j\,0.12135\left(\frac{f}{60}\right)\left[\ln\left(\frac{1}{dij}\right) + 6.74580\right] \text{ohms/mile} \quad (12)$$

Notice the resemblance of (11) and (12) to (8) and (9). They have the same form and can be used to calculate the self and mutual impedances of any arrangement of conductors above ground.

For any arrangement of conductors (a, b, c) of a single-circuit transmission line, the matrix Zabc describes the line impedances using (11) and (12):

$$Zabc = \begin{bmatrix} Zaa & Zab & Zca \\ Zab & Zbb & Zbc \\ Zca & Zbc & Zcc \end{bmatrix} \quad (13)$$

For any arrangement of conductors of a double-circuit line or two parallel single-circuit lines (a, b, c, a’, b’, c’), the matrix Zabc” describes the line impedances:

$$Zabc" = \begin{bmatrix} Zaa & Zab & Zca & Zaa' & Zab' & Zc'a \\ Zab & Zbb & Zbc & Zba' & Zbb' & Zbc' \\ Zca & Zbc & Zcc & Zca' & Zb'c & Zcc' \\ Zaa' & Za'b & Zca' & Za'a' & Za'b' & Zc'a' \\ Zab' & Zbb' & Zb'c & Za'b' & Zb'b' & Zb'c' \\ Zc'a & Zbc' & Zcc' & Zc'a' & Zb'c' & Zc'c' \end{bmatrix} \quad (14)$$

Equations (13) and (14) are referred to as the phase impedance matrix. When ground wires are present, they can be included in the above matrices using Kron’s reduction technique [2][4]. When bundled conductors are used in the transmission line phases, the impedance matrix becomes quite large. With proper matrix reduction techniques, an equivalent impedance matrix, as in (14), can also be obtained.

B. *Symmetrical Component Impedances*

Phase impedances are useful, but the symmetrical component impedances are of interest to the protection engineer because the positive- and zero-sequence impedances are the ones that characterize the transmission line. Using the parallel line impedance matrix in (14), the voltage drop, ΔV, across the parallel section of length “l” is:

$$\left[\Delta Vabc"\right] = \left[Zabc"\right]\left[Iabc"\right] l \quad (15)$$

The phase voltages and currents can be substituted in (15) with the appropriate symmetrical component voltages and currents using the symmetrical component matrix:

$$\begin{bmatrix} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} & 0 \\ 0 & \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \end{bmatrix} \left[\Delta V012"\right] = \left[Zabc"\right] \begin{bmatrix} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} & 0 \\ 0 & \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \end{bmatrix} \left[I012"\right] l \quad (16)$$

The symmetrical component matrix is therefore:

$$Z012" = \begin{bmatrix} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} & 0 \\ 0 & \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \end{bmatrix}^{-1} \left[Zabc"\right] \begin{bmatrix} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} & 0 \\ 0 & \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \end{bmatrix} \quad (17)$$

Equation (17), for a parallel line, will yield the symmetrical component impedances. The main diagonal impedances of the 6 x 6 matrix are the zero-, positive- and negative-sequence self impedances of the conductor arrangement. The off-diagonal impedances correspond to the mutual impedances. Equation (17) characterizes the conductor arrangement and identifies the mutual impedances between symmetrical component networks.

C. *Phase Arrangement and Transposition*

When parallel lines are designed, the phase arrangement can make quite a bit of difference in the magnitude of the different impedances of the transmission lines [4][5]. Theoretically, perfectly equidistant conductors would yield the smallest mutual impedances (small off-diagonal terms in the Z012” matrix). Physically, however, there is not such an arrangement, and the most efficient arrangement will be selected [5].

When arranging the phase position in parallel lines, unbalance studies are performed along the lines of reference [5]. It is desirable to obtain the smallest unbalance coefficients (I2/I1 and I0/I1) and the smallest positive-sequence impedance for power transfer. Interestingly enough, the zero-sequence mutual impedance is the same for any arrangement.

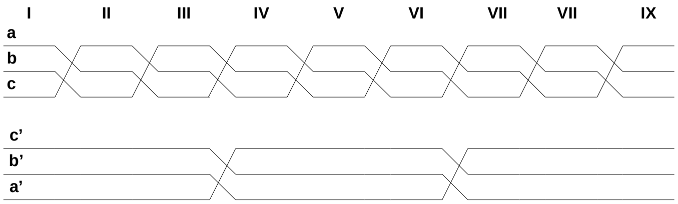

Fig. 3. Totally Transposed Parallel Lines

When the position of the phases is rearranged in the same physical setup, it is said that the line is transposed. For a transmission line to be totally transposed, the physical arrangement should be changed at exactly the same distance for 3^n times (where n is the number of lines). Fig. 3 illustrates a totally transposed arrangement of two parallel lines. There are $3^2 = 9$ transpositions. If the Z012" impedance matrix is calculated, it would be the sum of the symmetrical component impedances of each segment.

$$Z012'' = \left(\sum_{i=I}^{IX} Z012''_i \right) \frac{1}{9} = \begin{bmatrix} Z00 & 0 & 0 & Z00m & 0 & 0 \\ 0 & Z11 & 0 & 0 & 0 & 0 \\ 0 & 0 & Z22 & 0 & 0 & 0 \\ Z00m & 0 & 0 & Z00' & 0 & 0 \\ 0 & 0 & 0 & 0 & Z11' & 0 \\ 0 & 0 & 0 & 0 & 0 & Z22' \end{bmatrix} \quad (18)$$

The purpose of line transposition is to eliminate the mutual terms from the impedance matrix, but (18) indicates that even if the line arrangement were totally transposed, the zero-sequence mutual (Z00m = Z0m) would not be zeroed.

Magnetic flux linkages depend on the total current flowing in one circuit and link this circuit to the other circuit. In Fig. 4, the magnetic flux linking one line to the other is shown. Therefore, for positive- and negative-sequence currents, the effective current in one transmission line is zero, and the flux linkages to the parallel line are negligible. However, for zero-sequence currents flowing in one of the lines, the zero-sequence flux linking the other transmission line is significant because the currents do not add to zero. This is physically the reason for the existence of the zero-sequence mutual coupling, regardless of the number of transpositions along the line.

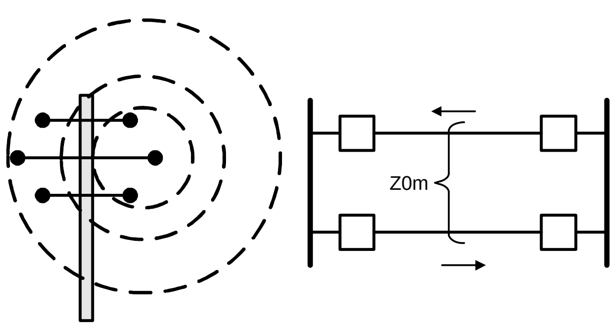

Fig. 4. Flux Linkage From One Line to the Other

In this section, the important message is that the Z0m (zero-sequence mutual) will always be present, regardless of the phasing arrangement of the conductors or the number of transpositions along the way. Its magnitude will vary according to the geometry, phasing, and transpositions, but Z0m will always be measurable. In some instances, it will be comparable to the positive-sequence impedance magnitude.

When zero-sequence flows in one transmission line, the mutual effect can be visualized as in Fig. 5. Just like in a current transformer when the current flows in a polarity mark, Fig. 5(a), the current induced will flow out of the parallel line polarity mark. Fig. 5(b) illustrates the same concept except with the induced voltage in the parallel line that is proportional to Z0m • I0. Both of these facilitate the visualization of the mutual impedance effect between two transmission lines and produce the same voltage and current across a fictitious impedance Z.

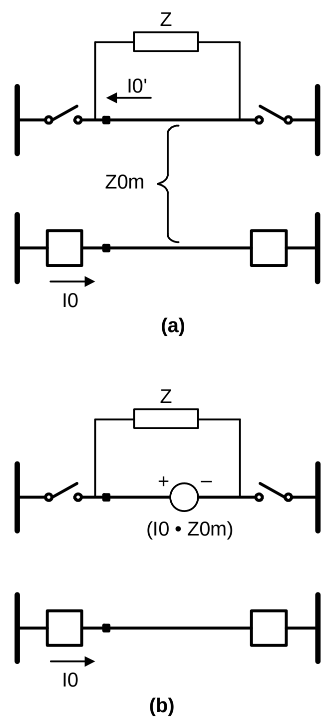

Fig. 5. Simple Ways to Visualize the Zero-Sequence Mutual Coupling in Parallel Lines

III. Fault Location and Protective Relaying

In modern numerical line protection relays, there are several processes running concurrently. These processes are protection function algorithms, communications algorithms, fault location algorithms, etc.

The fault location algorithm is a reporting function of the estimate of the fault location in the transmission line. There is generally sufficient time for the protective relay to utilize the voltage and current information to make use of mathematical techniques to report the location of the fault. The fault location algorithm is run after the line protection has issued a trip and should use the data available from the trip signal until the line breaker opens its contacts.

Protection algorithms may include distance units, directional elements, current differential algorithms, etc. These are processes that have priority in their processing and should decide the detection of power system faults instantaneously. Protection algorithms are executed at a high rate. Time frames are usually a few executions per power system cycle, depending on the hardware and type of protective relay.

The analysis above shows that even if the parallel lines were fully transposed, the zero-sequence mutual would still be present. Moreover, positive- and negative-sequence mutual impedances are much smaller than the zero-sequence mutual impedance. Therefore, Fig. 6 illustrates that the traditional A-phase-to-ground fault symmetrical component network interconnection can be used for analysis of this fault. It is traditional to evaluate the “apparent impedance” to the fault with this analysis. Both fault location and protective relaying distance algorithms benefit from the analysis. The “apparent impedance” expression can be used to estimate and/or study the effects of the zero-sequence mutual impedance [6].

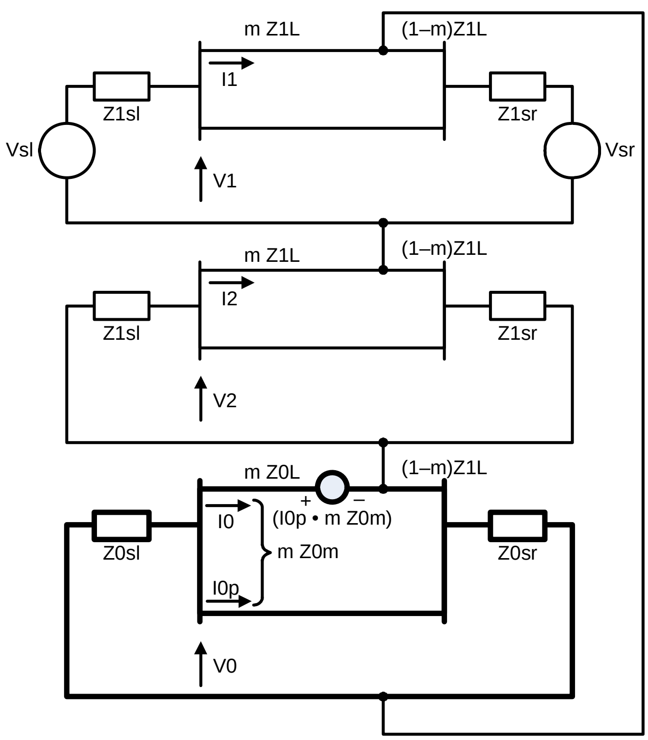

Fig. 6. Phase-to-Ground Fault in One of Two Parallel Lines With Zero-Sequence Mutual coupling

At the fault location, with no fault resistance considered:

$$\begin{aligned}&[\mathrm{V1}-(\mathrm{m\ Z1L})\ \mathrm{I1}]+[\mathrm{V2}-(\mathrm{m\ Z1L})\ \mathrm{I2}]\\&\quad+[\mathbf{V0-(m\ Z0L)\ I0-(m\ Z0m)\ I0p}]=0\end{aligned} \tag{19}$$

$$\begin{aligned}\mathrm{V1}+\mathrm{V2}+\mathrm{V0}&=[(\mathrm{m\ Z1L})\ \mathrm{I1}]+[(\mathrm{m\ Z1L})\ \mathrm{I2}]\\&\quad+[\mathbf{(m\ Z0L)\ I0+(m\ Z0m)\ I0p}]\end{aligned} \tag{20}$$

$$\mathrm{VA}=(\mathrm{m\ Z1L})\left[\mathrm{IA}+\frac{\mathrm{Z0L}-\mathrm{Z1L}}{\mathrm{Z1L}}\mathrm{I0}+\frac{\mathbf{Z0m}}{\mathbf{Z1L}}\mathbf{I0p}\right] \tag{21}$$

$$\mathrm{m\ Z1L}=\frac{\mathrm{VA}}{\left[\mathrm{IA}+\frac{\mathrm{Z0L}-\mathrm{Z1L}}{3\,\mathrm{Z1L}}3\mathrm{I0}+\frac{\mathbf{Z0m}}{\mathbf{3\ Z1L}}\mathbf{3I0p}\right]} \tag{22}$$

Equation (22) implies that the zero-sequence mutual impedance (Z0m) is needed to accurately measure the apparent impedance to the fault. Equation (22) also defines the relay voltage and relay current to be used in a distance relay.

The zero-sequence mutual impedance of parallel lines affects the fault location and protective relaying for ground faults.

A. Fault Location Considerations

It is highly inconceivable today to have line protection devices without the fault location reporting function [7]. The algorithms implemented in modern numerical line protection devices are called “single-ended” fault location algorithms since they use the information of one terminal only. Two-ended algorithms are also available in literature and are considered to be more accurate, but the discussion of these is outside the scope of this paper.

Depending on the device design, the fault location reporting is a number obtained with a single calculation during the fault or the average of several calculations throughout the duration of the fault. Regardless of the calculation methodology, the function is very valuable to operators who need to have a good idea of the fault location. In some instances, the location of the fault may indicate that the fault is in a forbidden section of the line for reclosing, and no reclosing attempt will happen.

The effect of fault resistance (Rf) and infeed and outfeed currents makes the apparent impedance (22) not useful for fault location purposes. If it is a bolted fault with zero fault resistance, the apparent impedance can provide an accurate calculation. Most faults, and especially ground faults, will occur with fault resistance.

High-resistance faults are an issue when considering fault location algorithms. Mutual effects from parallel lines, inaccuracy of the line impedance calculation, and errors in CTs and VTs are examples of other issues concerning fault location. An original methodology presented by Takagi [8] showed a way to disregard the effects of high ground fault resistance in fault location. Several other methodologies have been proposed based on this method, but we will focus on one in this paper. This method, a modified Takagi algorithm, utilizes negative-sequence quantities [9].

To simplify the derivation, we use a single-phase arrangement of the impedances, as shown in Fig. 7. The derivation can be extended to the different loop impedances for phase-to-ground and phase-to-phase faults.

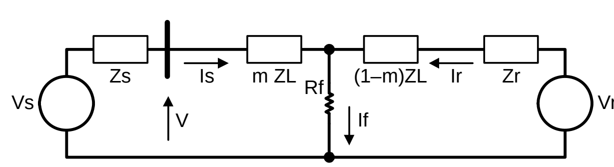

Fig. 7. Single-Phase Development of the Takagi Algorithm

Equation (23) describes Fig. 7.

$$V = Is(mZL) + (If)(Rf) \quad (23)$$

where "Is" is the fault current measured in the terminal where the fault location algorithm is performed, and "If" is the unknown total fault current (not a measured quantity by the relay) flowing through Rf.

The components of If are the fault currents contributed from sources Vs and Vr, where If = Ifs + Ifr. The component Ifs is easily related to the measured Is current using the prefault (Ispf) terminal current, as shown in (24):

$$\Delta Is = Is - Ispf \quad (24)$$

The largest source of error in the equation comes from fault resistance, which we eliminate through use of a mathematical technique. Both sides of the equation are multiplied by the complex conjugate of ΔIfs to get (25):

$$V\ \Delta Ifs^{*} = m(ZL\ Is\ \Delta Ifs^{*}) + Rf\left(If\right)\Delta Ifs^{*} \quad (25)$$

Note that If and ΔIfs have the same phase for an homogeneous system (similar impedance angles). The term in the equation containing Rf is a real number. Therefore, if the imaginary components of the equation are isolated, we can determine the distance to the fault (m).

$$m = \frac{Im\left\{V\ \Delta Ifs^{*}\right\}}{Im\left\{ZL\ Is\ \Delta Ifs^{*}\right\}} \quad (26)$$

Equation (26) indicates the need to know the prefault current at the terminal. A modified version of this algorithm recognizes that negative-sequence currents are incremental quantities, similar to Ifs, where the prefault value is zero.

$$m = \frac{Im\left\{V\ I2^{*}\right\}}{Im\left\{ZL\ Is\ I2^{*}\right\}} \quad (27)$$

Equation (27) is a modified Takagi algorithm for fault location. For an A-phase-to-ground fault, using (27) and the apparent impedance (22), the fault location (in per unit) is calculated.

$$m = \frac{Im\left\{VA\ \ I2A^{*}\right\}}{Im\left\{Z1L\left[IA + \frac{Z0L - Z1L}{3\,Z1L}3I0 + \frac{\mathbf{Z0m}}{\mathbf{3\,Z1L}}\mathbf{3I0p}\right]I2A^{*}\right\}} \quad (28)$$

The following equation makes (28) more generic for more than two circuits:

$$m = \frac{Im\left\{VA\ \ I2A^{*}\right\}}{Im\left\{Z1L\left[IA + \frac{Z0L - Z1L}{3\,Z1L}3I0 + (\frac{\mathbf{Z0m}}{\mathbf{3\,Z1L}}\mathbf{3I0p1} + \frac{\mathbf{Z0m}}{\mathbf{3\,Z1L}}\mathbf{3I0p2} + \mathbf{......)}\right]I2A^{*}\right\}} \quad (29)$$

Equations (28) or (29) can be optimized further with the consideration of the nonhomogeneity in the negative-sequence network to make the estimation of the fault location more accurate [9][10][11].

B. Protective Relaying Considerations

Parallel lines are protected with the same principles as other transmission lines. The influence of the zero-sequence mutual impedance has prompted development of protective equipment specifically designed for double-circuit lines [12]. Measuring the six currents and three voltages in a protective relay can provide flexible protection schemes yet create other practical concerns for the user like training, replacement, backup, etc.

Mutual effects do not affect current-only line protection schemes. These protective schemes measure the current into the line terminal and compare it to the current out of the remote terminal. The channel requirements may be the main obstacle for using this protection scheme in parallel line applications.

Line pilot protection schemes (POTT schemes, for example) are directional comparison systems generally implemented with distance elements. The overreaching zone setting may require some consideration due to the zero-sequence mutual effect, but overall, the performance of pilot relaying schemes for line protection is as good as for single-circuit lines.

Perhaps the greatest concern in the protective relaying of parallel transmission lines is the application of Zone 1 ground distance elements and ground directional elements. While the underreach of a Zone 1 ground directional element is of little consequence, the overreach should be of concern. Ground directional elements are used for sensitive ground fault protection in directional comparison schemes; the loss of directionality may cause a pilot scheme to misoperate.

1) Ground Directional

Ground directional overcurrent elements are used in pilot relaying schemes for transmission line protection. These are sensitive elements used in directional comparison systems to identify the direction to the fault. They are more sensitive than ground distance elements. If the two ground directional elements of both terminals have determined their directions into the transmission line, the pilot relaying scheme will determine an internal fault.

The zero-sequence mutual impedance between two parallel lines can affect directional comparison systems using ground directional elements polarized with zero-sequence quantities. These quantities are the zero-sequence voltage, zero-sequence current of the line, or a zero-sequence current from the neutral of a transformer [13][11]. Zero-sequence polarized ground directional units are the traditional elements used in transmission line protection.

Negative-sequence polarized directional elements have been suggested [14] in modern line protection schemes mainly due to the ease of calculating negative-sequence quantities in numerical relays. Negative-sequence ground directional elements are little affected by the small magnitude of negative-sequence mutual impedances of parallel lines. If two parallel lines are fully transposed, the negative-sequence mutual impedance is zero, as seen in (18). For parallel lines, negative-sequence ground directional elements operate reliably since the zero-sequence mutual impedance does not affect the negative-sequence network.

Focusing on zero-sequence polarized ground directional elements, a situation can be described when the two terminals determine that the direction to the fault is into the line. In a directional comparison system, this would indicate an internal fault.

Consider the zero-sequence ground directional that determines its direction based on the sign of the V0/I0 ratio [9][10]. For a forward fault, V0/I0 = –Zs0 (negative impedance). For a reverse fault, the impedance is at least the line impedance V0/I0 = +ZL (positive impedance). Traditional ground directional elements use V0 as the polarizing voltage and I0 as the operating current. The idea, however, is similar.

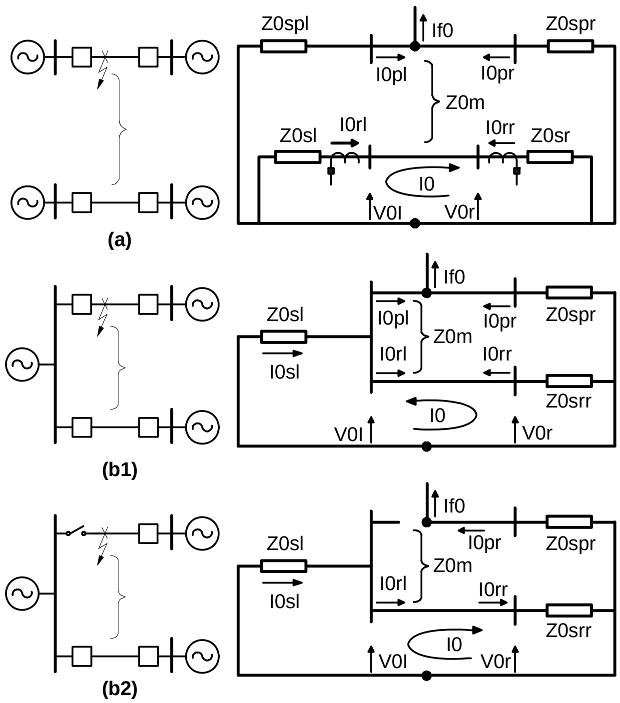

Fig. 8. Wrong Directional Determinations for Ground Directional Relays

Fig. 8(a) illustrates a ground fault in the top line. The parallel lines start and terminate in different buses or ground sources. The equivalent zero-sequence network is also shown, and in the parallel line (bottom line), there is a circulating zero-sequence current induced due to the fault. The polarity marks of the CTs are shown to indicate the direction of the measured current. For the relay on the left, (V0l/I0rl = –Z0sl) is negative, indicating a forward fault. For the relay on the right, (V0r/I0rr = –Z0sr) is negative as well, indicating a forward fault. In a directional comparison scheme, the two healthy terminals trip due to the fault in the parallel line.

This also happens when, due to switching, the parallel lines are connected to separate ground sources. This is illustrated in Fig. 8(b1) and Fig. 8(b2). During a ground fault, the directional determination is correct in the unfaulted line. The directional unit on the left determines a reverse fault, and the directional unit on the right determines a forward fault. Due to the location of the fault, the left breaker of the faulted line opens, as shown in Fig. 8(b2), and two separate ground circuits are formed. The situation is analogous to the one described in Fig. 8(a), and the healthy line may be opened unnecessarily.

The above illustrates the fact that the zero-sequence mutual can create problems with directional comparison systems that use ground directional elements for ground fault detection, if by virtue of the switching (of circuit breakers) or configuration (line proximity), two isolated zero-sequence networks are formed.

Negative-sequence ground directional elements are not subject to the zero-sequence mutual and therefore are more secure for parallel line applications.

2) Ground Distance

Line protection schemes using ground distance units are widely used in the industry. Diverse polarizing principles have been used to achieve desirable characteristics [10]. It is out of the scope of this paper to discuss the characteristics of ground distance elements, but the general idea will be used to illustrate the effect of mutual coupling on distance element operation. In the implementation of an A-phase-to-ground distance unit, two quantities are compared using a phase comparator:

$$S1 = VA - \left[IA + \left(\frac{ZL0 - ZL1}{3\,ZL1} \right) (3\,I0) \right] Zc \qquad (30)$$

$$S2 = V1 \qquad (31)$$

The quantity S1 (30) is the operating quantity and is the mathematical expression that determines the reach of the distance unit. The quantity S2 is the polarizing quantity that should be a stable quantity to provide a reference for directionality. Notice the behavior of S1 and S2 for different fault locations in Fig. 9. In Fig. 9(a) for a reverse fault, the current is flowing in the opposite direction, and instead of subtracting from the voltage, it actually adds, creating a large S1, which falls in the restrain region. Fig. 9(b) represents a forward fault inside the reach of the distance relay and the currents subtract from the voltage in such a way that S1 ends up in the operating zone. Fig. 9(c) represents a forward fault outside the reach of the distance element, and although the currents subtract from the voltage, they cannot overcome it, and S1 ends up in the restrain zone.

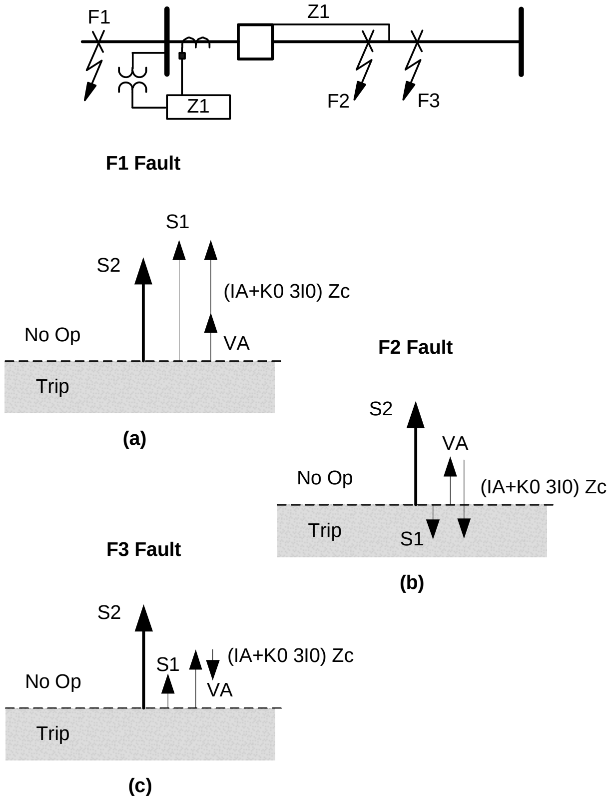

Fig. 9. Distance Relay Operation

The choice of S2 provides the distance element with certain beneficial characteristics required in line distance protection [10]. These include the expansion, directionality, single-pole trip suitability, and the adaptivity to load flow.

The operating quantity S1 is the difference between a "restraining voltage" and the appropriate fault current. The appropriate voltage and current are derived from the apparent impedance analysis. Therefore, using (22) as the basis to eliminate the effect of the zero-sequence mutual impedance, the proper operating quantity (S1) should be:

$$\mathrm{S1} = \mathrm{VA} - \left[\mathrm{IA} + \left(\frac{\mathrm{ZL0} - \mathrm{ZL1}}{3\,\mathrm{ZL1}}\right)(3\,\mathrm{I0}) + \left(\frac{\mathbf{Z0m}}{\mathbf{3\,ZL1}}\right)(\mathbf{3I0p})\right]\mathrm{Zc} \quad (32)$$

Whether S1 is expressed as (30) or (32), the voltage (in the example VA) is the restraining quantity. The sum of the currents (IA, I0, and I0p with their respective zero-sequence compensating factors) and the reach setting (Zc) determines the operation of the unit. In a very simplistic way, if the voltage is larger than the current (S1 > 0), the unit does not operate. If the currents are larger than the voltage (S1 < 0), the unit operates.

Equation (30) is the traditional distance element operating equation, and (32) includes the parallel line zero-sequence current influence. When a distance relay is not measuring the parallel line zero-sequence current, the extra term is the error in the measurement due to the zero-sequence mutual impedance. It can be concluded that the error of not measuring the parallel line zero-sequence current shows as an additional term adding to the restraining voltage.

$$\mathrm{S1} = \left(\mathrm{VA} + \left(\frac{\mathbf{Z0m}}{\mathbf{3\,ZL1}}\right)(\mathbf{3I0p})\,\mathbf{Zc}\right) - \left[\mathrm{IA} + \left(\frac{\mathrm{ZL0} - \mathrm{ZL1}}{3\,\mathrm{ZL1}}\right)(3\,\mathrm{I0})\right]\mathrm{Zc} \quad (33)$$

$$\mathrm{Vres} = \left(\mathrm{VA} + \left(\frac{\mathbf{Z0m}}{\mathbf{3\,ZL1}}\right)(\mathbf{3I0p})\,\mathbf{Zc}\right) \quad (34)$$

The parallel line mutual modifies the restraining voltage, (34). When the parallel line zero-sequence current (I0p) is into the line, the restraining voltage (Vres) is larger, and the unit underreaches. When I0p is out of the line, Vres is smaller, and the unit overreaches [15].

a) Parallel lines with common buses:

The configuration of Fig. 1(a) is used widely. Double-circuit towers carry the two lines from one bus to the other. It is not surprising that this is the configuration mostly discussed in literature.

In a parallel line application, I0p (zero-sequence current of the parallel line) will flow into the line for remote ground faults, as illustrated in Fig. 10(a). The remote ground faults are considered because when evaluating the reach of a distance unit (Zone 1 would be the appropriate ground distance unit), (33) indicates an underreach. I0p flows into the transmission line.

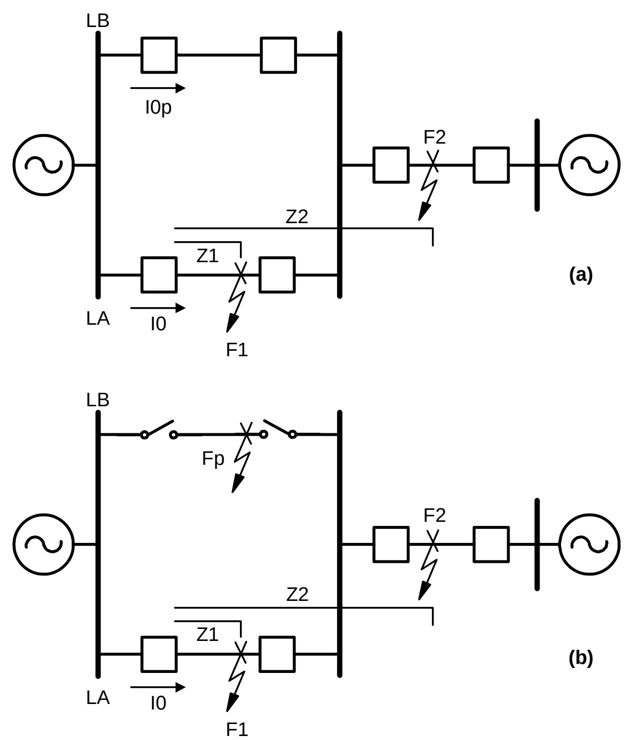

Fig. 10. Underreaching and Overreaching Zones in a Parallel Line Application

The Zone 1 ground distance reach can be confidently set from 80 to 90 percent of the line because this independent zone will not overreach. The mutual effect of the parallel line will not allow Zone 1 to reach past F1, the relay setting, as shown in Fig. 10(a). An overreach factor may be calculated for Zone 1, but the risk is to overreach when the parallel line has both of its terminals open (for example, for a fault Fp), as shown in Fig. 10(b). It is generally recommended to set the reach of Zone 1 like any other Zone 1 application.

Overreaching zones, like Zone 2, should be compensated to make sure that the zero-sequence mutual does not reduce the desired reach. Overreaching zones are used in directional comparison systems (POTT for example), and the relay settings should make sure that the overreaching zones reach past the remote terminal or more. For the F2 fault in Fig. 10(a), both parallel lines carry the same direction and magnitude of zero-sequence current (I0 = I0p), therefore the ground distance calculation in (32) becomes:

$$S1 = VA - \left[IA + \left(\frac{ZL0 - ZL1 + Z0m}{3\,ZL1} \right) (3\,I0) \right] Zc \qquad (35)$$

Traditionally, the ratio of impedances in (32) and (35) are relay settings [11] and denominated “zero-sequence compensation factors.” For a parallel line application, therefore, one would set [16]:

$$K01 = \frac{ZL0 - ZL1}{3\,ZL1} \qquad (36)$$

$$K0F = \frac{ZL0 - ZL1 + Z0m}{3\,ZL1} \qquad (37)$$

The K01 factor is the setting for the underreaching zone (Zone 1), and K0F is the setting for the overreaching zone (Zone 2). With this choice of K0 factors, it is acknowledged that the Zone 1 element may underreach but never overreach, and the Zone 2 element will always overreach the remote terminal with the appropriate reach. This is important for pilot relaying schemes that require overreaching zones for directional comparison schemes, like POTT.

Another philosophy for parallel lines to ensure that Zone 2 will overreach is to extend the reach to a safe margin. Minimum settings of 120 to 150 percent are also used for this purpose.

An interesting case for parallel lines is pointed out in reference [6]. It is illustrated in Fig. 11, where only one terminal has the ground source. Concentrating in the lower line, the F1 fault would make the 3I0 currents flow in opposite directions, but their magnitude would be the same. Because of the direction of I0, the effect is to make the Zone 1 ground distance element overreach.

Using (32), and knowing that the measured 3I0 equals –3I0p, an appropriate K0 factor can be found.

$$S1 = VA - \left[IA + \left(\frac{ZL0 - ZL1 - Z0m}{3\,ZL1} \right) (3\,I0) \right] Zc \qquad (38)$$

$$K01 = \frac{ZL0 - ZL1 - Z0m}{3\,ZL1} \qquad (39)$$

Selecting a K0 factor equal to (39) ensures that the Zone 1 element does not overreach for the configuration in Fig. 11.

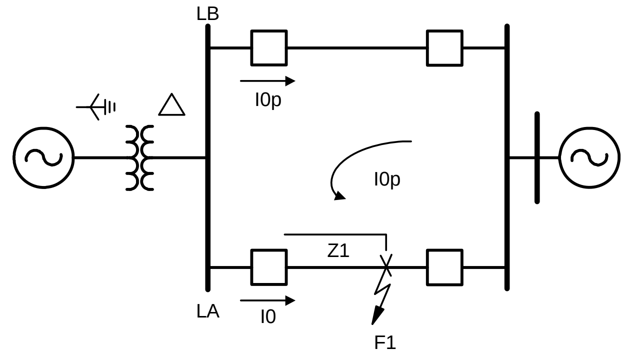

Fig. 11. Single Ground Source

Fig. 12 is not an uncommon condition in a power system. For maintenance purposes, the parallel line is grounded at both ends, and the other line is in service. A ground fault in the operating line will produce a zero-sequence current in the parallel line (for simplicity at the end of the line):

$$I0p = \left(\frac{Z0m}{ZL0} \right) I0 \qquad (40)$$

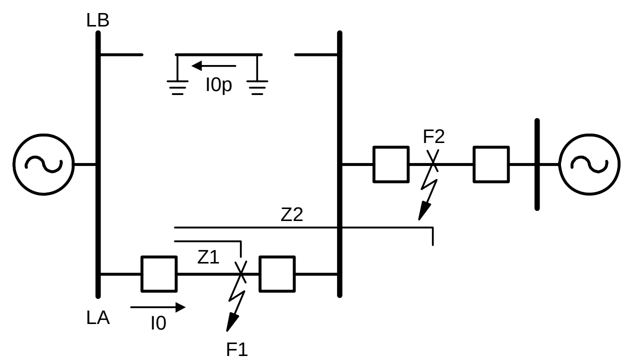

Fig. 12. One Line Grounded

The I0p current is in the opposite direction as I0 per the flux linkage laws and the discussion regarding Fig. 5. The effect is to make the distance elements overreach, as illustrated in (33). For a ground distance unit, when (40) is substituted in (32):

$$S1 = VA - \left[IA + \left(\frac{ZL0 - ZL1}{3\,ZL1} \right) (3\,I0) + \left(\frac{Z0m}{3\,ZL1} \right) \left(\left(\frac{Z0m}{ZL0} \right) (-3I0) \right) \right] Zc \qquad (41)$$

$$S1 = VA - \left[IA + \left(\frac{ZL0 - ZL1 - \left(\frac{Z0m^2}{ZL0} \right)}{3\,ZL1} \right) (3\,I0) \right] Zc \qquad (42)$$

The zero-sequence compensating factor can therefore be set to:

$$K01 = \left(\frac{ZL0 - ZL1 - \left(\frac{Z0m^2}{ZL0} \right)}{3\,ZL1} \right) \quad (43)$$

Numerical relays are provided with K0 factors for Zone 1 and the other zones to make use of the formulas derived above. Moreover, different settings groups are also available that will tell the protective relay to use a different K0 factor when switching occurs (for example, when the parallel line is under maintenance and grounded at both ends). Appropriate reaches can also be changed according to the topology of the power system using settings groups.

b) Parallel lines with a single common bus:

The configuration in Fig. 13(a) with equal line impedances may be possible in certain circumstances (for example, a power plant with an intentionally split bus). It is more generic, however, to visualize Fig. 13(a) with partial effect of the mutual impedance as described in Fig. 1(b). When the mutual effect is partial, it may be necessary to evaluate the effect of the mutual impedance with short-circuit calculation methods or software. The effect on Zone 1 most likely will be ignored, but the overreaching Zone 2 should be verified. A K0 factor mitigating the underreach derived for (37) can be derived, or an increase of the Zone 2 reach can be used. Ground faults at the end of the parallel-coupled section may deserve some consideration.

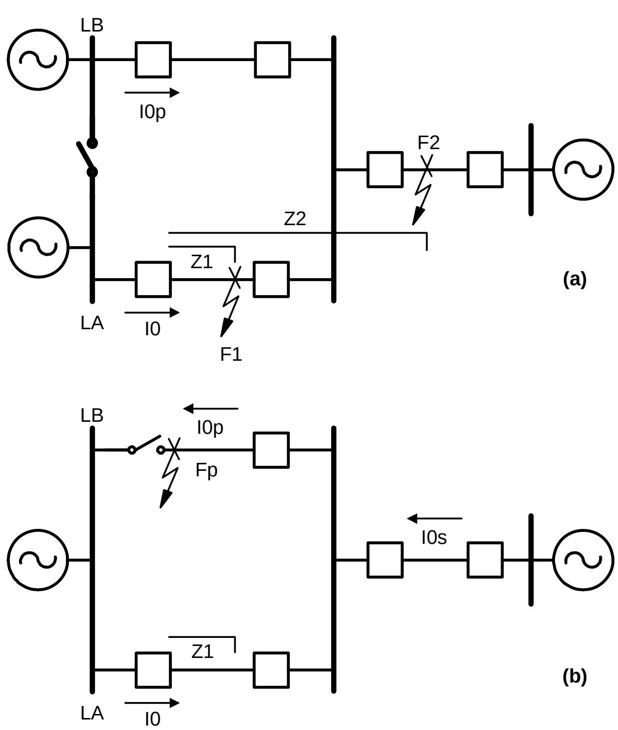

Fig. 13. Parallel Lines With a Single Common Bus

Since the lines are not totally parallel through their whole lengths, it is very difficult to find an appropriate K0 factor. The reach of Zone 2 is enhanced, and to ensure overreaching, typical settings would fall between 120 to 150 percent.

The situation illustrated in Fig. 13(b) is likely to happen even if the two lines do not share two common buses. Fig. 13(b) shows a fault in the parallel line and the breaker closer to the fault open. If the system on the right is very strong, resulting in a very high “I0s,” the equivalent parallel line zero-sequence current (I0p = I0s + I0) can be very large. If the line is short, the Zone 1 setting calculation should evaluate this very large current since the I0p is outflowing, therefore Zone 1 may overreach. This case is somewhat similar to the one discussed in Fig. 11. This is not likely to be of concern for long lines.

c) Parallel lines with no common bus:

The configurations of Fig. 1(c) and Fig. 1(d) are not unusual in power systems. Most likely, different voltage levels will be sharing the section of the corridor, d. Ground directional elements can be affected as discussed in Fig. 8. Most likely, the lower voltage line will become more affected by zero-sequence currents induced from ground fault currents in the higher level. However, in real applications, the flow of zero-sequence currents in the parallel line seems not to adversely affect the operation of ground distance elements.

IV. Practical Considerations

The discussion in the previous sections has provided a basis for some practical considerations. Fault location algorithms and ground distance units found in numerical line distance relays are two separate processes. Whereas fault location algorithms are meant to provide an estimate of the fault location, the algorithm can be processed a single time after the trip decision. On the other hand, ground distance units need to be evaluated constantly and trip decisions made from their evaluation.

It is evident from the equations derived that the measurement of the parallel line zero-sequence current is a datum in the apparent ground fault impedance (22) and the other derived equations.

Measuring the zero-sequence current of the parallel line, I0p, is not possible at all if the physical location of the terminals is distant. Except for Fig. 1(a), where the parallel lines share two common buses, the line configurations in Fig. 1 physically limit the ability to measure the parallel line zero-sequence current (I0p).

A. Ground Fault Location

Ground fault location can benefit greatly from the measurement of the parallel line zero-sequence current, I0p. The algorithm is a background algorithm and does not require being fast or making trip decisions.

There are circumstances where the zero-sequence current is not available due to physical limitations. Fig. 1(a), where the lines share two common buses, is suitable for measuring the zero-sequence currents of both lines. Fig. 1(b) will generally not have the zero-sequence mutual impedance in the full length of one of the lines, and the measurement of the two currents at the common terminal is generally not considered. Configurations in Fig. 1(c) and Fig. 1(d) do not share common buses at all, so it is not physically practical to measure the zero-sequence currents.

Therefore, for fault location, the configuration in Fig. 1(a) is generally evaluated for measuring the zero-sequence currents of the parallel line. The measurement of I0p will be used in the fault location equation described in (28).

It has been noticed that for practical purposes, parallel lines in a double-circuit structure will show a strong zero-sequence mutual coupling, and the measurement of I0p will benefit the fault location algorithms. Single-circuit lines running in parallel do not seem to have that high of a zero-sequence mutual coupling, and for practical purposes, the measurement of I0p does not provide significant benefits to the fault location algorithm. Equation (28), however, can provide insight into the resolution. The decision to use the measurement can be based on the influence of K0m ($\frac{Z0m}{3\,ZL1}$) compared to K0 ($\frac{ZL0-ZL1}{3\,ZL1}$) in the fault location equation, (28). If K0m is significantly smaller than K0, then the benefits of measuring I0p for fault location are not that significant.

Two 230 kV lines in a double-circuit tower configuration were simulated to illustrate the amount of error at different fault locations between a fault location algorithm with no mutual compensation and a fault location algorithm with mutual compensation. The system used for illustration is shown in Fig. 14. The source impedances are the same on purpose, so the mutual effect is zeroed at 50 percent. The lines are 40 km in length.

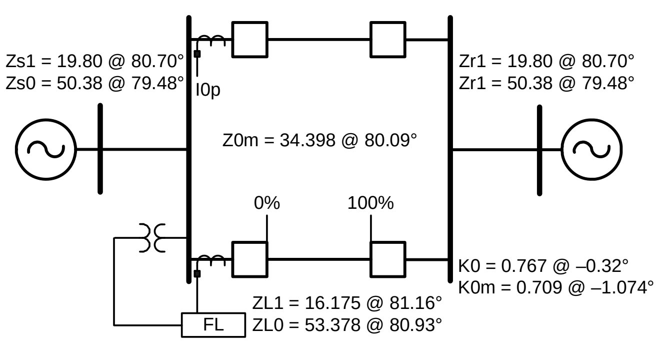

Fig. 14. 230kV Parallel Line Example

Table I shows the results of the simulation. The results speak for themselves and clearly illustrate the error induced by the zero-sequence mutual. Although the above is a simple simulation, it helps to illustrate the benefit of using the parallel line 3I0 current as an input to the fault locator. The fault location estimates are much better.

TABLE I
FAULT LOCATION RESULTS WITH AND WITHOUT I0P COMPENSATION

Fault Location	**Rf = 0**		**Rf = 10 ohms**	
	No compensation (% error)	With compensation (% error)	No compensation (% error)	With compensation (% error)
0%	0.168	0.1844	0.1276	0.1375
10%	9.384 (6.16%)	10.138 (1.38%)	9.426 (5.74%)	10.179 (1.79%)
20%	18.941 (5.30%)	20.167 (0.84%)	18.972 (5.14%)	20.193 (0.97%)
30%	28.831 (3.90%)	30.171 (0.57%)	28.840 (3.87%)	30.173 (0.58%)
40%	39.163 (2.09%)	40.145 (0.36%)	39.133 (2.17%)	40.109 (0.27%)
50%	50.100 (0.2%)	50.008 (0.02%)	50.095 (0.19%)	49.985 (0.03%)
60%	61.913 (3.18 %)	59.964 (0.06%)	61.714 (2.86%)	59.779 (0.37%)
70%	75.025 (7.18%)	69.777 (0.32%)	74.651 (6.64%)	69.449 (0.79%)
80%	90.003 (12.50%)	79.490 (0.64%)	89.540 (11.92%)	78.928 (1.34%)
90%	109.021 (21.13%)	89.050 (1.06%)	107.797 (19.77%)	88.086 (2.12%)
100%	134.857 (34.86%)	98.148 (1.85%)	132.268 (32.27%)	96.602 (3.4%)

B. Ground Distance Relaying

Ground distance relaying can accommodate the overreach and underreach effects of the zero-sequence mutual impedance using the modified zero-sequence compensation factor (K0) as derived in (37), (39), and (43). The measurement of the parallel line zero-sequence current for ground distance relaying is not totally justified [6][13][15]. Parallel line pilot schemes (a POTT or Blocking scheme, for example) provide 100 percent ground fault coverage without the measurement of the zero-sequence mutual current (I0p) of the parallel line.

Moreover, the relaying scheme with no I0p compensation does not have to account for the situation illustrated in Fig. 15. A very strong equivalent source contributes a very large zero-sequence current (I0s) to the ground fault in the parallel line. The unfaulted ground distance relay receives the very large ground fault zero-sequence measurement from the parallel line relay. If 3I0p is very large, the ground distance unit of the healthy line will measure a small impedance, as shown in (44). Most likely there is logic in the protective relay to account for this problem, but it is another complication in the design.

$$Z1L = \frac{VA}{\left[IA + \frac{Z0L - Z1L}{3\,Z1L}3I0 + \frac{\mathbf{Z0m}}{\mathbf{3\,Z1L}}\mathbf{3I0p}\right]} \approx \frac{VA}{\left[\frac{\mathbf{Z0m}}{\mathbf{3\,Z1L}}\mathbf{3I0p}\right]} \quad (44)$$

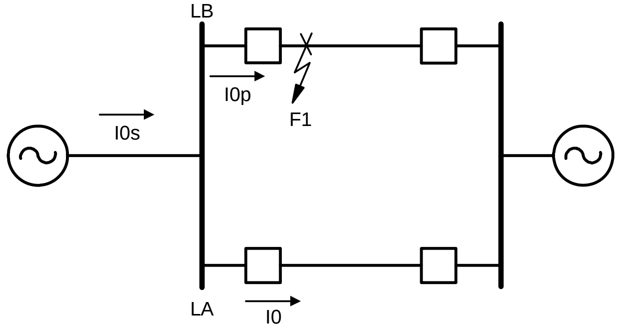

Fig. 15. Strong Source, Parallel Line Ground Fault Effect on the Healthy Line-Relay

Ground distance zones of protection should ensure that Zone 1 does not overreach and that Zone 2 covers the whole line under all conditions. The use of Zone 2 is very important in pilot relaying schemes like POTT, where the local tripping and the permissive signal transmission are based on it. The K0 factor of (37) ensures that this is the case for parallel lines with common buses or increasing the Zone 2 coverage.

C. Fault Location Importance

The fault location result is a useful report from the line protection relay. It is used by utilities to quickly identify the location of a permanent fault and send the required crew to restore service.

For long lines, fault location is very important. In most cases, the fault locations are repetitive; that is, there are sections of the lines which are prone to the occurrence of faults. These may include places like forests, ridges, or places where due to geography the chances of clearances getting exceeded are high. This may happen due to growth of vegetation under the lines or due to a storm which may swing the conductor so much that the fault occurs in narrow line corridors. Long transmission lines may have two or three fault-prone areas. The fault location algorithm can point to the fault location.

Even in cases where the fault location algorithm is not very accurate, the most probable location of the fault is the nearest fault-prone area to the fault location shown by the fault locator. The exact location can be determined during the line patrolling. Using the fault location estimate rather than patrolling the whole line for the fault, the patrol may just have to scrutinize a small area.

D. Measurement of the Parallel Line Zero-Sequence Current

When considered necessary, the line protection relays will accommodate an additional current input to measure the parallel line zero-sequence current. Fig. 16 illustrates the required connections to measure the currents.

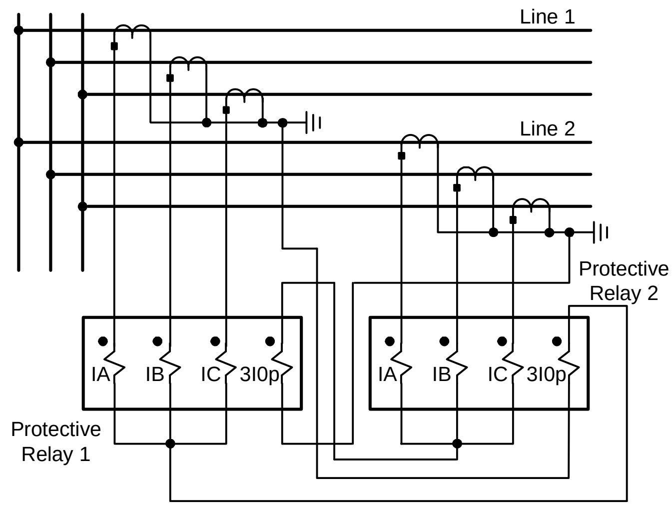

Fig. 16. Parallel Line 3I0 Current Circuits Cabling

Subject to discussion, the wiring is more complex than the traditional three-CT wiring, and an additional current input (3I0p) is required. It may be that the parallel line protection relays are next to each other, and the wiring may require a few short runs between the terminal blocks of the appropriate relay circuits. It is also possible that the relays are physically distant from each other, as they would be in the “kiosk” of a substation bay. A long run to feed the parallel current to the appropriate relay implies more burden to the CTs for ground faults, increasing the probability of saturation. Moreover, there are instances where more than two lines are coming out of a substation in parallel paths. Four-circuit structures are not unheard of, and the wiring of the zero-sequence currents for distance relay compensation is a formidable task involving several auxiliary transformers.

The complication of additional wiring to test blocks and terminal blocks is considered by many to be costly and not justifiable [6][15]. On the other hand, there are many other users that have no issue with the wiring and the associated cost.

For more than two circuits and to implement (29), the hardwiring solution becomes cumbersome due to the use of additional auxiliary transformers.

With the newer communications techniques, it is possible to propose an alternate solution for exchanging the 3I0 current between protective relays.

V. Exchange of 3I0 Measurements Between Relays With Communications Techniques for Fault Location

Numerical relays are provided with several communications ports. Serial communications ports can be used to transfer digital status signals and/or analog measurements [11][17] from relay to relay. Moreover, the proposed IEC 61850 analog GOOSE messages and/or the sampled data values [18] seem to fit perfectly in the data transfer of the 3I0 measurement between relays.

As discussed in the previous sections, fault location would benefit from the 3I0 measurement of the parallel line. The algorithm in some implementations makes a single measurement after the fault; other implementations take an average of several measurements after the fault.

Fig. 17 illustrates the typical behavior of the 3I0 current for a ground fault. Using appropriate filtering techniques [19] that typically utilize a 1-cycle window for calculating the magnitude and angle of the phasors, the figure clearly illustrates the buildup of the 3I0 current during a fault. Not necessarily related to this is the fact that protective relays for transmission can be high speed, with fault detection times of less than 1 cycle [11].

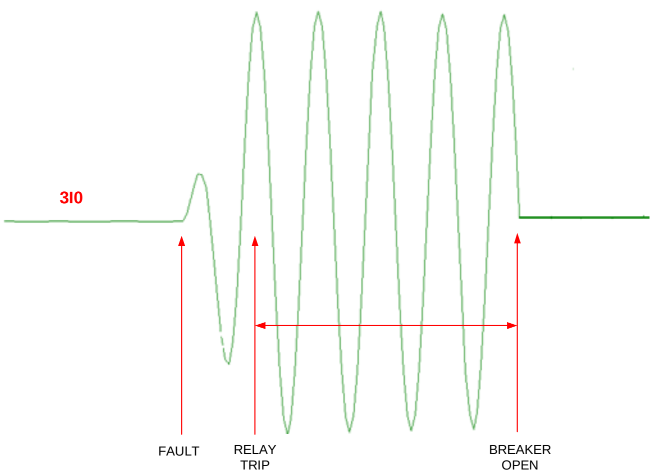

Fig. 17. Filtered 3I0 and Fault Clearing Sequence

After the line protective relays issue the trip signal, the breaker takes its own time to open the faulted phase or all three phases. The breaker time includes any mechanical and arcing time associated with opening the breaker poles. Very fast high-voltage breakers have the capability of opening the breaker poles in 2 cycles. Typical breakers in transmission systems are 3- to 4-cycle breakers.

Fault location estimation is done with the measurement information after the line protection relay decides to trip. The time frame is from the moment the relay issues the trip signal to the moment the current is interrupted.

A. Serial Communications Channel

Numerical relays have serial communications ports that can send digital (binary 1s or 0s) and/or analog information from relay to relay [11]. Many purposes have been thought of for this exchange of information, and the applications include teleprotection schemes, remedial action schemes (RAS), control, etc. Taking advantage of the possibility of two line relays to exchange data, a serial link can be used to exchange the 3I0 magnitude and angle between two relays protecting two parallel lines for fault location improvement.

If the two protective relays are in very close proximity (e.g., in the same panel or two neighboring panels in the substation), a simple shielded serial cable is required. On the other hand, if the panels are relatively distant from each other, a simple multimode fiber converter can be used to link the two line protection relays.

The technology allows for the continuous monitoring of the data exchange. A problem in the serial link will be reported in both protective relays. Moreover, the communications are done at protective relaying speeds with 8 to 10 millisecond delay between the sending and the receiving of the data.

Serial communications are slow for any real-time exchange of analog data. The magnitude and angle of 3I0 are long numbers that require a few milliseconds. Fault location, fortunately, is an algorithm that can be implemented with a single measurement. Fig. 18 illustrates the mechanism.

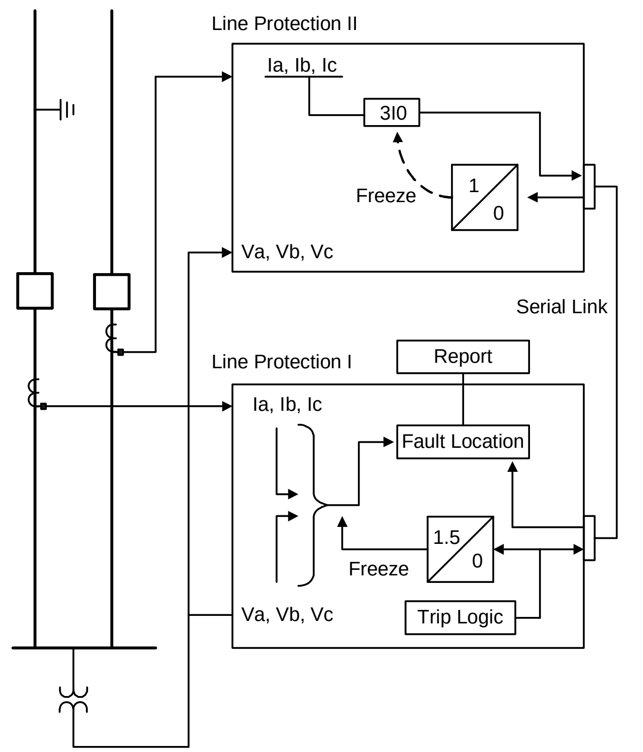

Fig. 18. Fault Location 3I0p Compensation With a Serial Link

Assuming a ground fault in one of the parallel lines, the protective relay associated with that line issues a trip. As shown in Fig. 18, the relay trip logic sends a bit to the other protective relay. The transmission delay is about 0.5 cycles. On the receiving relay, an intentional 1 cycle is used to freeze the value of the 3I0 current magnitude and phase. That magnitude and phase will be reported back to the tripping relay, sending analog information through the same serial link.

In the tripping relay, the 1.5 cycles are accounted for, and the voltage and current of the tripping relay are also frozen. A design choice of 1.5 after the trip command has been chosen to allow for fast breakers. Since the internal software trip signal is used, the output contact operating time may take 0.5 cycles to close its contact, so the actual capture of the voltage and current phasors is at 1 cycle of the breaker opening time. For a fast 2-cycle breaker, this would be acceptable. Moreover, Fig. 17 shows that the relay has had enough time for its internal filtering algorithm to accurately calculate the magnitude and phase of the 3I0 current.

Beneficial to this algorithm mechanism is the fact that both line relays are measuring the same bus voltages. This allows referencing of all the measurements to a voltage in both protective relays. The 3I0p measurement will have a useful phase reference for the tripping relay, and there will be no need for synchronization of any external timing signal.

At the tripping relay, with the captured "local" voltages and currents, and the received 3I0p from the parallel line relay, (28) is calculated. The resulting fault location, m, is then displayed in the front panel of the relay and also made available for SCADA.

B. *IEC 61850*

Recently, the IEC 61850 suite of substation protocols has received much attention from the industry [18]. The idea of a substation network(s) (station bus/process bus) to reduce the wiring required in the substation IEDs is very appealing.

One of the protocols in IEC 61850 defines the transmission and reception of event messages called GOOSE (Generic Object Oriented Substation Event), capable of sending digital information (breaker status, trip signals, etc.) and analog quantities. Most applications today implement transmission and reception of digital GOOSE messages [11]. In the not too distant future, analog GOOSE messages will be very common in substation IEDs. With the capability of exchanging analog values with GOOSE messages, the same methodology described for serial communications can be replicated.

Moreover, IEC 61850 defines the Sampled Values (SV) protocol to be implemented in a process bus (process network where the IEDs get their measurements). The device sending the measurements is called a "merging unit" and makes the measurements (currents and voltages) available to all the devices connected to the process bus. With this technology, it will be possible to obtain the parallel line currents for fault location.

VI. Conclusions

With increasing environmental constraints and the need for more transmission capabilities in electric power systems around the world, the use of more parallel lines is likely. The proximity of two transmission lines yields an array of impedances that characterize the conductor arrangement.

- Transposition and appropriate phase arrangement allow smaller natural unbalance in the transmission lines but do not eliminate the zero-sequence mutual impedance between the parallel lines.
- The zero-sequence mutual impedance that cannot be eliminated even with transposition can be comparable to the positive-sequence impedance of the line.

Fault location is a background algorithm executed in the line protection relay after it has issued a trip.

- Zero-sequence mutual compensation (measurement of the parallel line current) benefits single-ended fault location algorithms.

Parallel transmission lines are protected with the same elements as traditional lines. It is, however, the zero-sequence mutual impedance that can drastically affect the performance of ground relaying elements.

- Ground directional elements polarized with zero-sequence quantities and used in pilot relaying schemes can determine a forward direction at both terminals when the zero-sequence sources are independent. For parallel lines, negative-sequence polarized ground directional elements are preferred due to the negligible mutual impedance in the negative-sequence network.
- Ground distance protection should ensure that:
  - Zone 1 does not overreach due to the zero-sequence mutual.
  - Overreaching zones, like Zone 2, should not underreach the remote terminal.
  - With the proper choice of K0 factors, the above goals can be achieved.
- It is considered by many that the measurement of 3I0p for ground distance relaying brings more complications than benefits, due to the extra wiring and additional logic in the line protection. Pilot relaying schemes (POTT, for example) provide the required high-speed tripping for internal faults.

Due to the importance for operational purposes, fault location can benefit from the measurement of the 3I0p current from the parallel line.

- Since the algorithm does not need to be evaluated at protection speeds, sending the measurement via serial communications is an alternative to hard wiring the 3I0p current. This simplifies wiring and associated extra burden to the CTs if the line relays are far from each other.
- The same methodology could be used in IEC 61850 installations where the IEDs are capable of sending and receiving analog GOOSE messages.

These two techniques can be adapted for multicircuit lines in an easier and more straightforward way than with hardwiring.

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IX. Biography

Fernando Calero has a BSEE (86) from the University of Kansas, Lawrence KS, an MSEE (87) from the University of Illinois at Urbana-Champaign, Urbana, IL, and an MSEPE (89) from Rensselaer Polytechnic Institute, Troy, NY. He started his professional career with Westinghouse as a transformer design engineer (89) and later transferred to the ABB Relay Division in Coral Springs, Florida when ABB acquired Westinghouse’s T&D business. In ABB’s relay division, Mr. Calero worked in the support, training, testing, and design of protective relays (90–96). Mr. Calero later worked for Itec Engineering (97), Florida Power & Light in the EMS group (98) and for Siemens Energy Automation in Norcross, GA (99). Since 2000, Mr. Calero has worked for SEL as an International Field Application Engineer. Mr. Calero is a registered professional engineer in the state of Florida.