Rebirth of Negative-Sequence Quantities in Protective Relaying With Microprocessor-Based Relays

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REBIRTH OF NEGATIVE-SEQUENCE QUANTITIES IN PROTECTIVE RELAYING WITH MICROPROCESSOR-BASED RELAYS

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ABSTRACT

This paper focuses on the uses of negative-sequence quantities in protective relaying. The emphasis is on numerical relays since they have facilitated the calculation of symmetrical components. Negative-sequence quantities (the voltage and current denoted by V2 and I2) are very useful quantities in protective relaying. The simplicity in the calculation of these quantities in modern numerical relays has reinforced their use in the theory and methods used by current protective relaying devices.

The paper begins with discussion of some implementations of negative-sequence filters in older relays. Next is a brief review of symmetrical components and an analysis of unbalanced faults in power systems. This review leads to a discussion of the characteristics of negative-sequence quantities and illustrations of how these quantities are used in protective relaying. Because the discussion generally involves symmetrical component theory, the paper makes references throughout to the other two symmetrical components (positive-sequence and zero-sequence).

INTRODUCTION

A set of three phasors (for example, phase voltages Va, Vb, and Vc) can be represented by three sets of components (positive sequence, negative sequence, and zero sequence) such that two of the component sets (positive and negative) are balanced and the other set (zero) consists of three equal phasors.
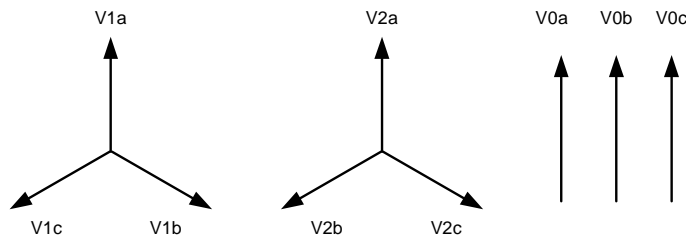

Figure 1 Positive-Sequence, Negative-Sequence, and Zero-Sequence Components

Figure 1 illustrates the three sets of phasors. Ideally, the positive-sequence set is the only one present during balanced operation. The presence of negative-sequence and zero-sequence components indicates unbalanced operation of the power system and power system faults.

All three-phase quantities in a power system can be represented by the sum of the symmetrical components. For example, the phase voltages can be expressed in terms of their symmetrical components, as shown in Equations (1), (2), and (3).

$$Va = V1a + V2a + V0a \tag{1}$$

1

$$Vb = V1b + V2b + V0b \tag{2}$$

$$Vc = V1c + V2c + V0c \tag{3}$$

Using the "a" operator $(a = e^{j120°})$, we can express the phase quantities in terms of the A-phase components, as shown in the matrix in Equation (4).

$$\begin{bmatrix} Va \\ Vb \\ Vc \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} V0a \\ V1a \\ V2a \end{bmatrix} \tag{4}$$

Equations 1, 2, and 3 allow calculation of phase quantities for known symmetrical components. Solving for the symmetrical components, for known phase quantities, (solving for the inverse of the matrix in Equation (4)) yields the following expressions:

$$V0a = 1/3 \ (Va + Vb + Vc)$$

$$V1a = 1/3 \ (Va + a \ Vb + a^2 \ Vc)$$

$$V2a = 1/3 \ (Va + a^2 \ Vb + a \ Vc)$$

In the literature, the suffix "a" is dropped because the A-phase components are the reference, and the components are denoted by V0, V1, and V2.

SEQUENCE FILTERS IN PROTECTIVE RELAYS

Numerical relays have introduced functions that were previously desired but difficult to implement in earlier technologies. One of these functions is the calculation of negative-sequence quantities from measured three-phase voltages and currents. Negative-sequence filters in electromechanical and solid-state technologies cannot compete for simplicity with the numerical filters of modern numerical relays. An example of a negative-sequence filter used in electromechanical relays is described in Figure 2 [1].
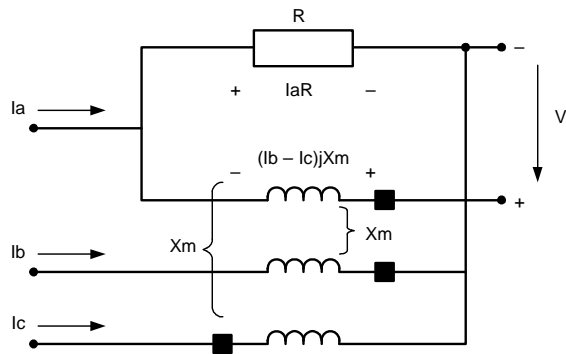

Figure 2   Negative-Sequence Filter in an Electromechanical Relay

The output of the filter is a voltage proportional to the negative-sequence component of the currents:

$$Vf = IaR + (Ib - Ic)jXm$$

Xm is a mutual reactance, and the choices for R and Xm are such that $Xm = R/\sqrt{3}$. If we apply only positive-sequence currents (Ia, Ib = a^2Ia, and Ic = aIa), the output of the filter is zero (Vf = 0). When negative-sequence currents are applied (Ia, Ib = aIa, and Ic = a^2Ia), the output of the filter has a value proportional to the negative-sequence component (Vf = 2RI2). The output, Vf, is the input to an electromechanical measuring unit. Because there is no ground return for the input currents, the filter does not respond to zero-sequence components. Figure 2 is a typical example of the inventiveness and ingenuity demonstrated by protective relaying designers of electromechanical units.
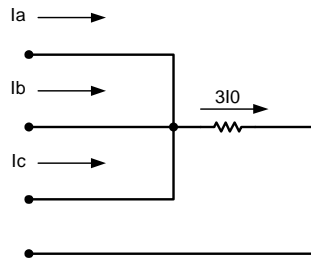

Figure 3   Zero-Sequence Filter

Obtaining zero-sequence quantities has not been a problem because the component (3I0, for example) does not require phase shifting by the "a" operator. Figure 3 shows a zero-sequence filter. The sum of the three currents is proportional to the zero-sequence component of the set of phase currents. If a measuring unit required zero-sequence current, it would be fed directly.

Zero-sequence components and negative-sequence components are both measurable indications of abnormal conditions. However, the complexity of implementing the zero-sequence filter is substantially less than that of the negative-sequence filter shown in Figure 2. While it was possible to measure and use negative-sequence quantities in electromechanical relays, the techniques required for the negative-sequence filters were more expensive; zero-sequence quantities were easier to measure.

Solid-state technology in protective devices brought the advantages of smaller devices and more functionality per panel space. However, the implementation of filters for negative-sequence quantities was still involved. Circuits based on phase shifts with operational amplifiers, or other solid-state components, capacitors, and resistors, were used to implement the phase shifts needed for the "a" operator ($a = e^{j120°}$).
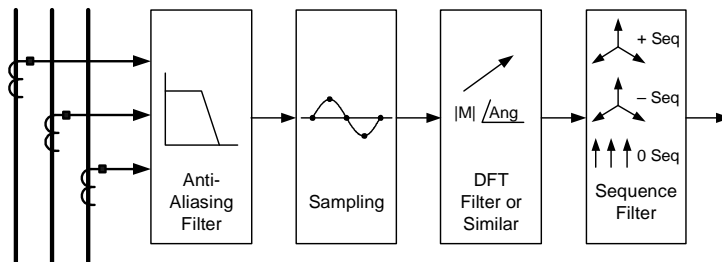

Figure 4   Processes for Obtaining the Sequence Quantities in a Numerical Relay

Numerical relays have brought a large number of well-known advantages and new functions to protective relaying. One of the hidden benefits is the simplicity and accuracy of calculating symmetrical components from phase quantities. A simpler and more understandable mathematical process takes place in the A/D (analog-to-digital) subsystem and firmware of the

device, as shown in Figure 4. The voltage or current inputs are fed into an anti-aliasing filter to condition the phase quantities. Numerical protective relays are sampled data systems, so the sampling block in the figure denotes the capture of instantaneous samples of the phase quantities. A digital filter based on Fourier techniques calculates the fundamental component from the samples captured in the memory of the device. This fundamental component is denoted by a phasor quantity with a magnitude ($|M|$) and an angle or the real and imaginary components. For example, the popular Cosine filter (a DFT variation), with a sampling rate of 4 samples-per-cycle, calculates the phasor in the following way:

$$Ireal_k = \tfrac{1}{4} (I_k - I_{k-1} - I_{k-2} + I_{k-3})$$

$$Iimag_k = Ireal_{k-1}$$

A sequence filter in a numerical protective relay is a simple mathematical technique that implements the equations for the symmetrical components, described above, with the mathematical capabilities of the microprocessor [2].

The procedure is part of the endless loop in the device firmware. It is simpler and more accurate than the complex circuitry in older technologies. In addition, the powerful mathematical capabilities of modern processors allow the designer to calculate all of the components per phase (for example, I2a, I2b, and I2c).

Signal processing, performed in modern numerical relays, allows for the design of relays capable of equally measuring zero-sequence quantities and negative-sequence quantities without increasing processor burden or cost. Within the firmware of a numerical relay, it is no more difficult to calculate negative-sequence components than it is to calculate zero-sequence components.

CLASSICAL SYMMETRICAL COMPONENTS ANALYSIS OF THREE-PHASE SYSTEMS

Using symmetrical components, we can analyze the distribution of currents and voltages in the power system during unbalanced conditions [1][3]. As a review, two brief examples illustrate the formulation of the sequence network connection.

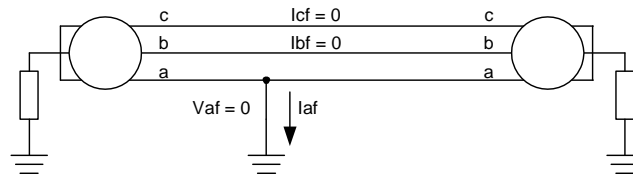The A-to-ground fault in Figure 5 is an example of a "shunt" unbalance in the power system.

Figure 5   A-to-Ground Fault

At the fault location, Vaf = 0. This implies that the A-phase fault-voltage symmetrical components add to zero, i.e., Vaf = 0 = V1f + V2f + V0f. The fault current symmetrical components can be found by noticing that Ibf = Icf = 0. This implies that I1f = I2f = I0f = (1/3) Iaf.
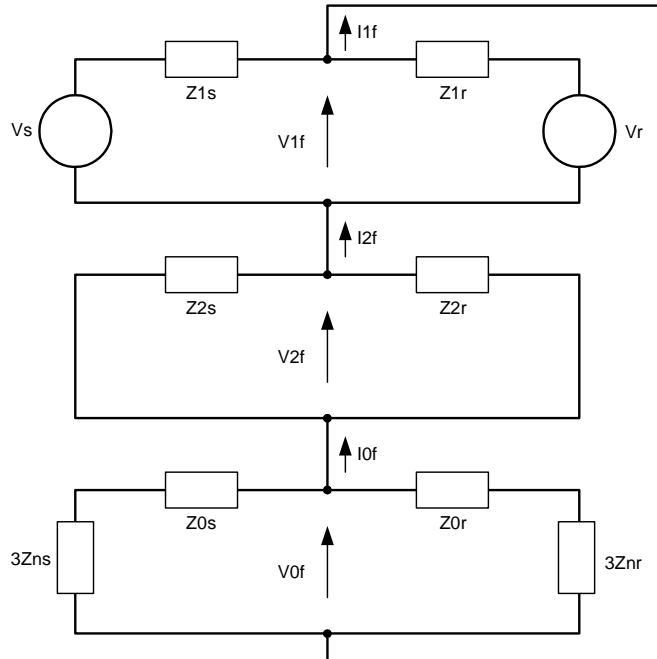
Figure 6   Sequence Network Connection for an A-to-Ground Fault

Figure 6 illustrates the network that satisfies the two requirements for the distribution of currents and voltages. Notice the following:

- There are three subnetworks representing the positive-sequence, negative-sequence, and zero-sequence equivalents. These networks represent the distribution of the respective components throughout the power system.

- The positive-sequence and negative-sequence networks are basically the same networks except for the generator equivalents present only in the positive-sequence network. Sources generate positive-sequence quantities; the negative-sequence quantities that a generator produces are negligible.

- The negative-sequence impedances are more homogenous than the zero-sequence impedances; this means the impedance angles in the network are very similar. In the zero-sequence network, the ground return is always considered. This makes the impedances in that sequence dependent on the ground resistivity of the terrain, the type of power system grounding, and the connection of three-phase transformers. Figure 6 illustrates the different grounding possibilities at both ends of the system with Zns and Znr.

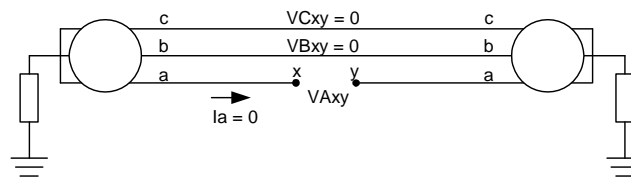Figure 7 shows a different unbalance condition. An open A-phase in the power system is a "series" unbalance.

Figure 7   A-Phase Open

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In the circuit, Ia = 0. This implies that Ia = 0 = I1 + I2 + I0. In the fault location, VBxy = VCxy = 0. This implies that V1xy = V2xy = V0xy = (1/3)VAxy. The sequence network connection for this unbalance is shown in Figure 8.
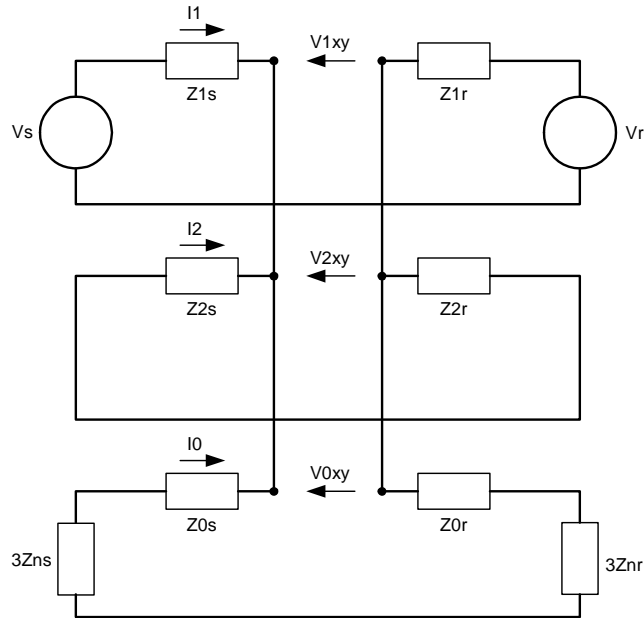

Figure 8 Open A-Phase Sequence Network Connection

The same observations about Figure 6 can be made about Figure 8. The different ways that the sequence networks are interconnected allow for the study of the distribution of sequence currents and voltages throughout the network. An open-phase condition, like the one shown in Figure 8, generates negative-sequence and zero-sequence components.

SEQUENCE NETWORK CONNECTION FOR DIFFERENT TYPES OF FAULTS [1][3]

Using A-phase as our reference, we can analyze the different shunt faults possible in a power system. The analysis is the same as described above for the A-to-ground and open A-phase unbalances. When B or C phases are the reference, that analysis is very similar.
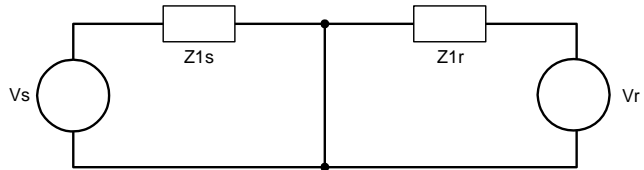

Figure 9 Three-Phase Fault

A three-phase fault in a power system is not really an unbalance; however, it can be analyzed as such. Figure 9 shows a three-phase fault sequence network connection. This is the only fault that does not involve negative-sequence quantities.
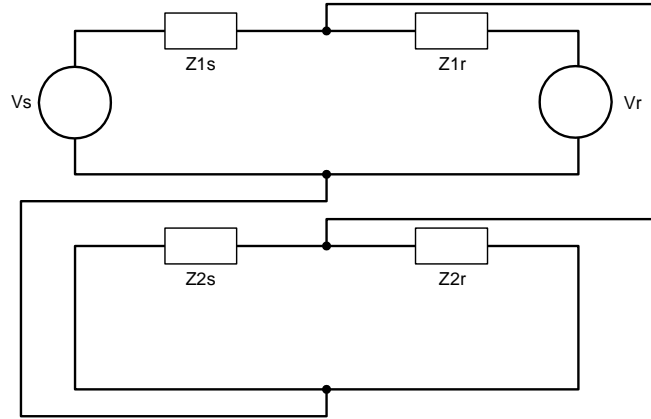
Figure 10 BC Fault

A phase-to-phase fault involves positive-sequence and negative-sequence networks. Figure 10 shows the sequence network connection.
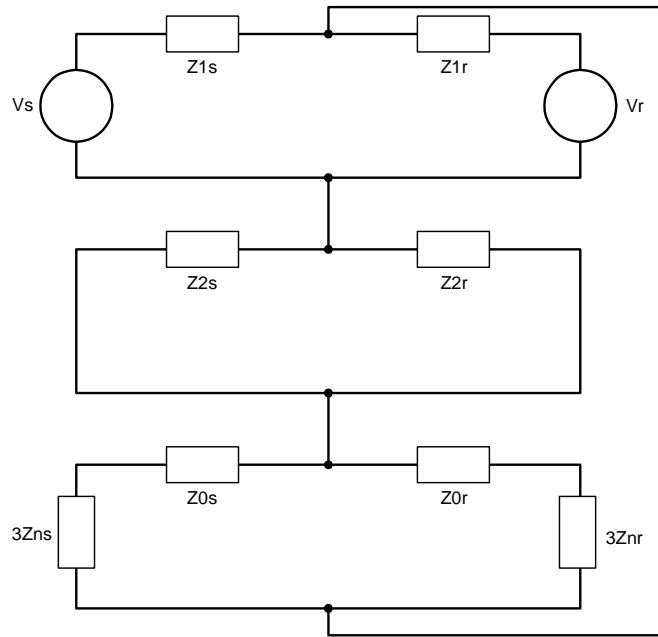

Figure 11 A-to-Ground Fault

For an A-to-ground fault, the sequence networks are in series, as shown in Figure 11.
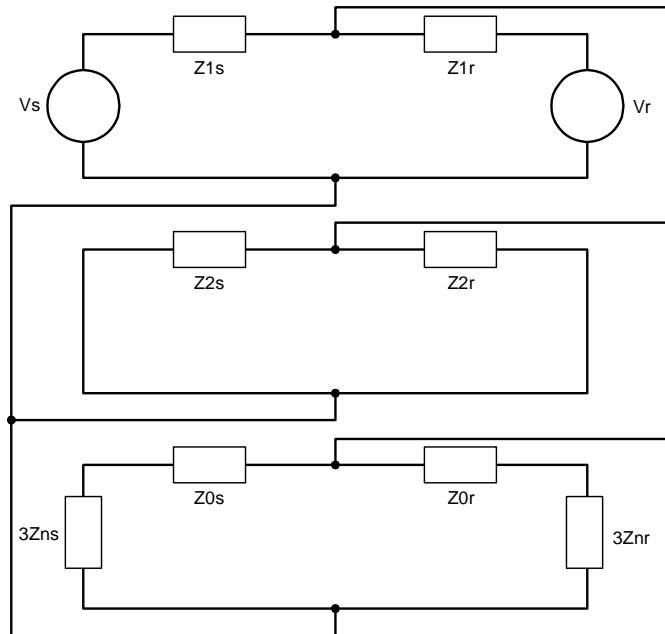
Figure 12   BC-to-Ground Fault

For a phase-to-phase-to-ground fault, the three networks are connected in parallel, as shown in Figure 12.

From this brief review of symmetrical component analysis, and by focusing on the negative-sequence quantities, we can conclude the following:

- Negative-sequence components are present in all fault types except the three-phase fault.
- Negative-sequence components indicate unbalances and faults.
- Negative-sequence impedances are the same as positive-sequence impedances (with the possible exception of impedances in generators), and they are more homogenous than the zero-sequence network impedances.
- Negative-sequence networks are basically equal to positive-sequence networks except for the absence of sources and different phase shifts in some connections of power transformers.

Faults and unbalances produce negative-sequence components. These components indicate the abnormal operation of a power system during faults. Protective relays can use negative-sequence quantities in a variety of techniques, following the symmetrical components theory, to provide the protection engineer with functions that are reliable in detecting unbalances and faults.

NEGATIVE-SEQUENCE QUANTITIES IN PROTECTIVE RELAYING

Positive-sequence quantities have been correctly associated with load and balanced conditions. Zero-sequence quantities are easy to measure and quantify. Negative-sequence quantities, on the other hand, have been a source of mystery to many protection engineers because they have not been readily measurable.

Numerical relays can now reliably measure negative-sequence quantity and also provide the tools for the relay engineer to analyze negative-sequence components. The relay engineer can now confidently use negative-sequence quantities because they are measured and reported by these devices.

Most manufacturers follow the same practices for protective relaying elements based on negative-sequence quantities; a few incorporate proprietary techniques using these quantities for protective relaying. Use of negative-sequence quantities in protective relaying is diverse; this paper illustrates some of these application techniques. This section is devoted to discussing negative-sequence and relay input sources, rotating machinery applications, overcurrent protection, directional elements, line current differential, phase selection, fault location, and power system unbalances.

Relay Input Sources

Negative-sequence and zero-sequence components are present during unbalanced faults. The measurement of these quantities by protective relays is not meaningful during normal operating conditions. Any presence of these quantities under load conditions is basically an indication of impedance unbalances in the power system.

Relay input sources are the set of three-phase CTs and VTs. They are meant to accurately reflect the primary values of the power system. Negative-sequence quantities are more forgiving than zero-sequence quantities when a secondary circuit failure occurs and remains unnoticed until a fault occurs; this is when the primary circuit negative-sequence and zero-sequence components are meaningful.

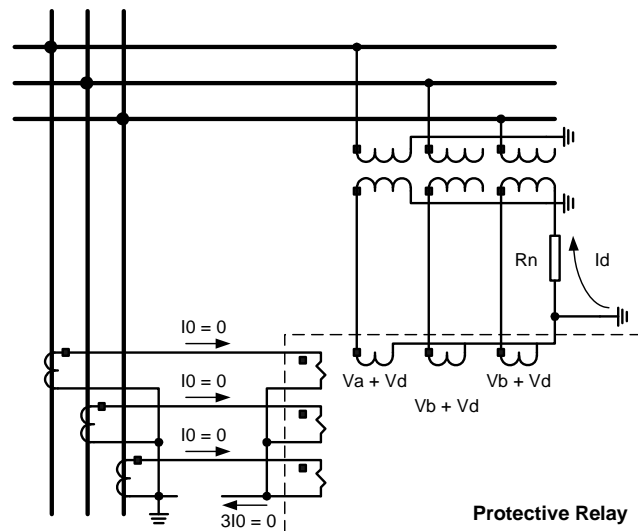**Figure 13** CT and VT Secondary Circuit Failures

A secondary circuit failure in a CT circuit is a broken neutral lead. Figure 13 illustrates the situation. During a ground fault, zero-sequence currents flow in the primary circuits; but because no zero-sequence currents flow in the secondary circuits, due to the broken ground return conductor, the protective relay is unable to measure zero-sequence currents.

Negative-sequence currents, on the other hand, utilize the same path as load flow currents and they do not need the broken ground return conductor. The relay will correctly measure negative-sequence currents.

A secondary circuit failure in a VT circuit is an unintended second ground in the neutral of the circuit, as shown in Figure 13. The two grounds are not necessarily at the same potential, and a voltage difference between the two induces a current (Id). The current and the lead impedance of the neutral wire yield a difference voltage (Vd) that shows up as an added quantity in the secondary measurements of the relay, as shown in Equations (5), (6), and (7).

$$Var = Va + Vd \tag{5}$$

$$Vbr = Vb + Vd \tag{6}$$

$$Vcr = Vc + Vd \tag{7}$$

Notice that when calculating the zero-sequence voltage, the relay uses the following relationship:

$$3V0r = 3V0 + 3Vd$$

On the other hand, when calculating the negative-sequence voltage, the relay will obtain:

$$3V2r = 3V2 + (1 + a + a^2)\, Vd = 3V2$$

This implies that an unintentional second ground in the neutral conductor of the VT circuit has no effect on the negative-sequence measurement. Negative-sequence quantities utilize the same circuit path as the normal positive-sequence quantities; therefore, any accidental modification of the return circuit has no effect on them.

Rotating Machinery

Three-phase rotating machinery is severely affected by the flow of negative-sequence currents. For both motors and generators, the stator is free from any damage due to the flow of negative-sequence currents. The rotor, on the other hand, is greatly affected and can suffer thermal structural damage from the induced double frequency currents due to the flow of negative-sequence currents.

Figure 14   Flow of Positive-Sequence (Left) and Negative-Sequence (Right) Currents in a Rotating Machine

Figure 14 illustrates the influence of the flow of positive-sequence and negative-sequence currents on a rotating machine. When positive-sequence currents flow in the stator of a rotating machine (left-hand side in Figure 14), the flux of the rotor (ϕ_R) and the flux of the stator (ϕ_S – sum of the phase fluxes) rotate in the same direction. For a generator, the two fluxes rotate basically

at synchronous speed (ω_S) with a small angle difference between the two. Ideally, there is no induction of currents in the rotor. For an induction motor, the two fluxes rotate normally at almost the same speed. The stator flux (ϕ_S) rotates at synchronous speed, but the rotor flux (ϕ_R) rotates at almost synchronous speed. The difference between the two speeds is the slip frequency. The difference between the stator and rotor fluxes induces current flow in the rotor. For the generator, this induction is negligible; for the motor, the induction is proportional to the slip frequency (s = (fs – fr)), which is a very small number [4].

When negative-sequence currents flow in the stator of a rotating machine, the stator flux (ϕ_S) rotates in a different direction and opposite to the rotor flux (ϕ_R), as illustrated in the right-hand side of Figure 14. The difference between the rotation for the generator is an equivalent induction of currents with twice the synchronous frequency: fs – (–fs) = 2fs. For the motor, the stator currents induce voltages in the rotor proportional to: (–fs – fr) = –(2fs – s), again, very close to twice the synchronous frequency.

The damaging effect of negative-sequence current flow in the rotor has been addressed for generators with K = $I2^2$t curves [1][5]. The generator manufacturer provides a curve for each K factor. Modern numerical generator protection relays have implemented $I2^2$t curves with greater sensitivity and accuracy than their electromechanical predecessors. These curves provide the adequate backup protection to the generator for unwanted negative-sequence current flow.

For induction motors (the great majority of the electrical motors), the $I2^2$t curves may be used if the motor manufacturer provides the information. A negative-sequence overcurrent relay may be applied [1].

Heating in the rotor of a motor is a process that depends on the motor sequence of operation. Starting a motor at ambient temperature when the motor has been inactive for a long time is different from starting the same motor after it has been interrupted from operation. Modern digital and numerical techniques allow for the implementation of thermal models [6]. It is, therefore, fitting for motor protection to include a thermal model that reflects the effect of the flow of negative-sequence currents in the stator.

A thermal model estimates the heating that stator currents cause in the rotor. More specifically, it is the heating of the rotor resistance (Rr). The rotor resistance is not a constant function; it is a function of the slip frequency in per unit (s = (fs – fr)/fs). Moreover, the rotor resistances to the flow of positive-sequence and negative-sequence currents, respectively, are:

$$Rr+ = (R1 – R0)s + R0$$

$$Rr– = (R1 – R0)(2 – s) + R0$$

Where R1 is the locked rotor resistance (the estimated resistance at s = 1, or locked rotor resistance), and R0 is the running rotor resistance (approximated when s ≈ 0).

When the motor starts (s = 1), the heating effect of the flow of positive-sequence or negative-sequence currents on the rotor is the same, because the rotor resistance is Rr = R1 when s = 1. On the other hand, when the motor is running (s ≈ 0), the positive-sequence rotor resistance is R0, but the negative-sequence resistance is 2R1 – R0. When the motor is running, the heating effect of negative-sequence currents is greater than that for positive-sequence currents.

A model that considers the effects of positive-sequence and negative-sequence currents under starting and running conditions proposes heating and cooling in an exponential manner [6], analogous to the charging and discharging of a capacitor.
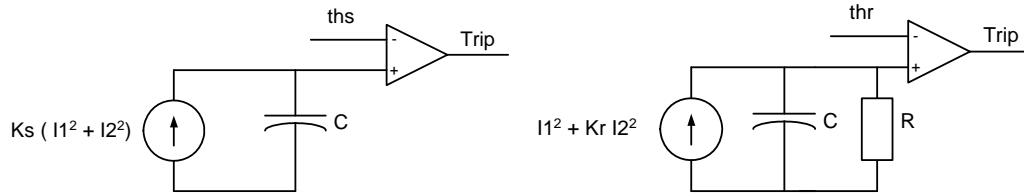
Figure 15   Starting and Running Motor Thermal Models

Figure 15 illustrates the idea of a two-state thermal model. The starting motor state makes a very conservative assumption that all the heat is going into heating the rotor and that both positive-sequence and negative-sequence currents heat the rotor in the same manner. The running motor state takes into account the greater heating effect of the negative-sequence currents. This running state allows for the dissipation of heat through an equivalent resistor and an RC time constant. All constants shown in Figure 15 are calculated from the motor nameplate data. The description of these constants can be found in Reference [6].

The important point to notice in the thermal model is the "charge" in the capacitor, C. This "charge," which emulates heating in the rotor, provides the memory to the model. The thermal model remembers the heating caused at the starting state and in the running state. During the transition from one state to the other, the capacitor remembers its "charge." The thermal model changes state to the starting state when motor currents exceed 2.5 pu. Below that level, the thermal model remains in the running state.

The differential equations necessary to model the thermal element described above can be implemented using programming methods in numerical relays. This thermal model is an elegant example of the use of microprocessors and the ease of calculating negative-sequence components.

Negative-Sequence Overcurrent Coordination

After having reviewed symmetrical components and the sequence networks for the different unbalanced faults, it is intriguing to wonder why negative-sequence current was not the quantity used to protect power system distribution feeders against phase-to-phase faults and ground faults. The main reason may have been that the theory of symmetrical components was not readily available when the art of overcurrent protection began. Another reason may have been that, as described above, the sequence filter hardware in the electromechanical technology was expensive and complicated. Another reason is that, for ground faults, depending on the grounding of the network, there is a need to increase the sensitivity provided by the phase CTs (information used to calculate I2) using a lower ratio neutral CT. The neutral CT with its lower ratio (used to calculate I0) provides greater sensitivity than higher ratio phase CTs.

In the case where it is possible to use only the phase CTs to calculate both the negative-sequence current and the zero-sequence current, both currents provide the same sensitivity. For example, this is possible in distribution systems that have the neutral solidly grounded. In ungrounded distribution networks, on the other hand, there is a demanding need to make the ground fault detection as sensitive as possible due to the insignificant and hard-to-measure ground fault current magnitude. A lower ratio neutral CT is required for this purpose. In these cases, the sensitivity of the zero-sequence current is greater than the one for the negative-sequence current.

It has become the practice of protection engineers to associate ground faults with zero-sequence currents, which is valid reasoning. Negative-sequence overcurrent coordination for ground fault protection is possible; however, it is generally considered as a backup quantity to zero-sequence

overcurrent coordination rather than the main ground fault detection method. Ground fault protection with zero-sequence components in distribution networks will remain the quantity of choice for the factors mentioned above. For the detection of phase-to-phase and phase-to-phase-to-ground faults, negative-sequence overcurrent protection is, however, a more sensitive and easier-to-apply alternative than traditional phase relays [7].

Overcurrent coordination of radial feeders for phase and ground relays is a well-known and described practice. Protection engineers are well versed in the subject, but there may be some concern about applying negative-sequence elements when coordinating overcurrent protection.
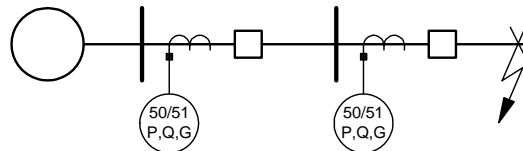

Figure 16   Radial Feeder Coordination

Figure 16 illustrates a typical radial feeder that requires the coordination of protective overcurrent devices. For the moment, we can assume that the source is solidly grounded since we will make a few considerations about grounding later in this section. Short-circuit studies or manual calculation will yield the corresponding fault magnitudes that the system will present to the relays. The most downstream overcurrent device will be set for the greatest sensitivity. The phase elements (P) are set as sensitively as possible while remaining always above the maximum load current expected. Unfortunately, this limits their sensitivity for phase-to-phase faults. The ground elements (G = 3I0) are set as sensitively as possible and above the highest expected unbalance. For phase faults, the phase elements operate. For single line-to-ground faults, the ground elements operate. For double line-to-ground faults, there is generally no miscoordination because ground relays are set from 3 to 10 times more sensitively than phase elements, and their time to operate is shorter. For negative-sequence overcurrent devices, denoted by the letter "Q," the concern is their coordination with phase and ground elements.
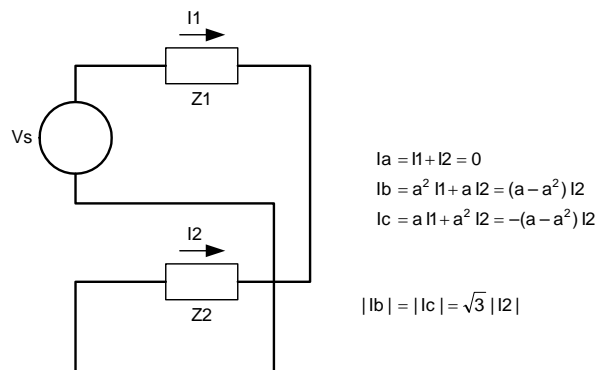

$$Ia = I1 + I2 = 0$$
$$Ib = a^2\, I1 + a\, I2 = (a - a^2)\, I2$$
$$Ic = a\, I1 + a^2\, I2 = -(a - a^2)\, I2$$

$$|\, Ib\,| = |\, Ic\,| = \sqrt{3}\;|\, I2\,|$$

Figure 17   Phase-to-Phase Fault Current and Negative-Sequence Current Magnitude

Figure 17 is a simple yet descriptive illustration of the relationship between phase fault current and negative-sequence current. When coordinating a phase overcurrent element and negative-sequence overcurrent element, the equivalent phase current of a negative-sequence element is √3 of the measured I2. Therefore, when coordinating phase and negative-sequence overcurrent devices, the factor of √3 must be considered.
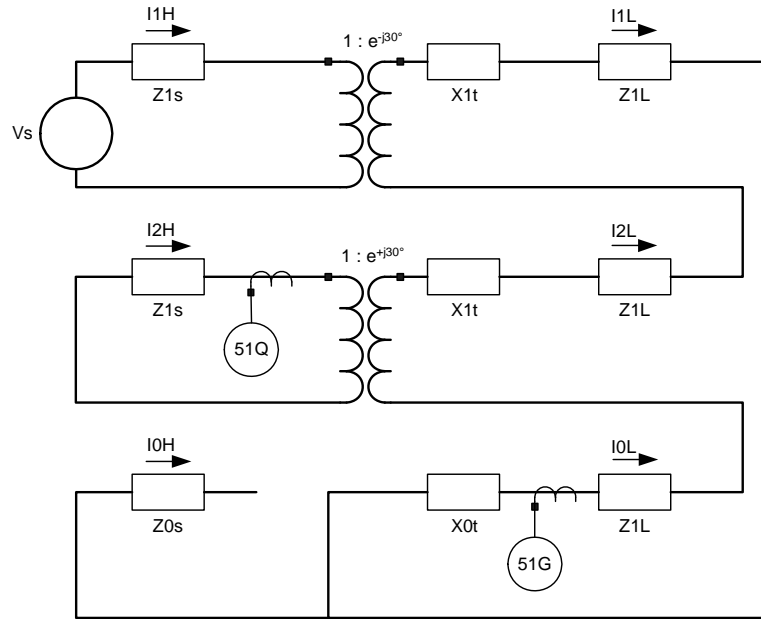
Figure 18 Radial Feeder Overcurrent Coordination

When a delta-wye transformer is in the coordination path, negative-sequence overcurrent elements can provide backup overcurrent coordination to ground overcurrent relays in the wye side of the transformer, as shown in Figure 18. The figure illustrates the sequence network connection for a ground fault in the low side of a delta-wye transformer. The ideal transformers are simply shifting the phase by 30° from one side to the other. The current magnitude, in per unit, does not change from the primary to the secondary side. The current in per unit at the 51Q relay is the same as that at the 51G relay. Moreover, the 51Q relay can also protect the transformer and the low voltage side of the system for unbalanced phase faults. Notice that a ground overcurrent relay in the high voltage side of the transformer does not provide any backup to the low voltage side. The delta connection on the high voltage side of the transformer does not allow the flow of zero-sequence currents, as denoted in Figure 18 with I0H = 0.

The discussion above focused on solidly grounded power systems, where there is plenty of ground fault current and the equivalent zero-sequence impedance of the source is small. Some distribution systems do not have a solidly grounded neutral. In fact, the practice in a large number of locations throughout the world is to leave the neutral ungrounded or use the distribution station transformer low voltage side connected in delta. These are called, for obvious reasons, ungrounded networks. There are also a large number of installations that intend to force the ground fault current magnitude to zero, utilizing a compensating reactor tuned to the zero-sequence capacitance of the system. These are Petersen Coil-grounded networks.

Ungrounded and Petersen Coil-grounded networks will present negligible ground fault current; it is the recommended practice to measure the zero-sequence current with a toroidal CT of much lower ratio than the phase CTs. Moreover, it is necessary to provide some directional methodology for ground fault detection. Unfortunately, for these networks, ground fault detection cannot rely on negative-sequence quantities. The magnitudes of both negative-sequence voltage and negative-sequence current are too small to be useful. Unbalanced phase fault detection, however, can benefit greatly from negative-sequence overcurrent. Phase-to-phase faults can be detected with a lower sensitivity than using just the phase overcurrent elements because negative-sequence overcurrent relays can be set below load current. For ungrounded and

Petersen Coil-grounded networks, the 50/51Q element coordinates only with phase fault detection devices. Because the negative-sequence filter uses phase CTs, sensitivity will be much less than for the sensitive ground fault elements.

Directional Elements

The purpose of a directional element is to indicate the direction of the power flow during a fault. These elements are not used to trip or alarm by themselves, but are used as supervising elements.
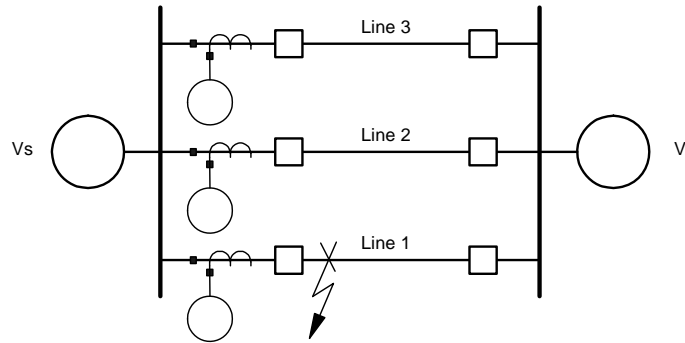

Figure 19   Example of Fault Direction

A simpler way to illustrate the concept of a directional element is through an example such as that shown in Figure 19. A fault in Line 1 is in the forward (FWD) direction for the relay in Line 1. The same fault is in the reverse (REV) direction for the relays in lines 2 and 3. Directional elements are required in most applications where the lines are not radial. If the lines (feeders) are radial, it may be possible to intelligently determine the fault direction by the magnitude of the current. Ungrounded and Petersen Coil-grounded radial feeders require directional elements for ground faults.

With negative-sequence quantities, it is possible to design reliable directional elements for all types of unbalanced faults. Three-phase faults do not contain negative-sequence components, so they require a different approach. The symmetrical components review showed that the negative-sequence network is present in all unbalanced faults. We use this network for proposing and analyzing a directional element [8].
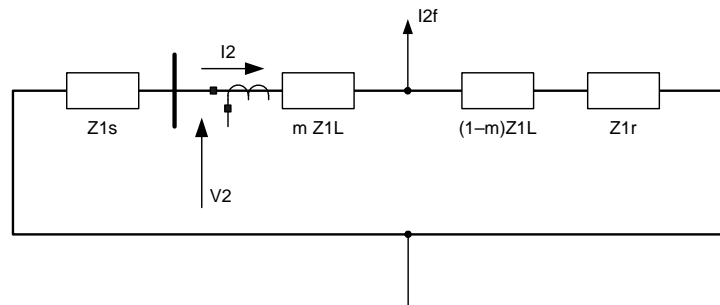

Figure 20   Fault in Front of the Relay

Figure 20 shows the negative-sequence network for a fault in front of the relay with the relationship of V2/I2 = –Z1s. If the impedances are reactive, the measurement plots on the negative reactive axis, as shown in Figure 22.
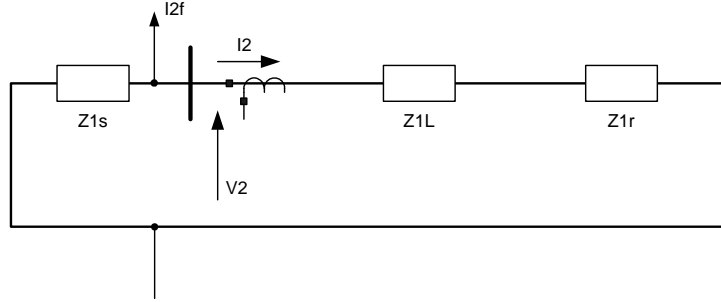
Figure 21 Fault Behind the Relay

Figure 21 shows the negative-sequence network for a fault behind the relay. The relationship of $V2/I2 = + (Z1L + Z1r)$. The measurement is the sum of all the impedances in front of the relay and has a positive sign. If the impedances are reactive, the measurement plots on the positive reactive axis, as shown in Figure 22.
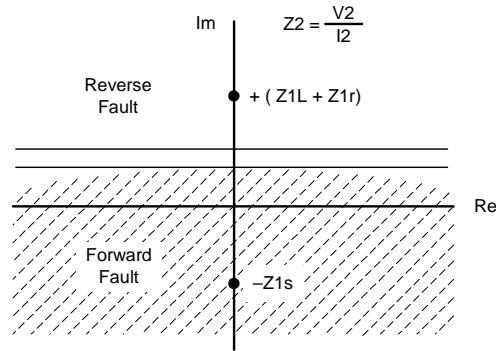

Figure 22 Impedance Plane for a Negative-Sequence Impedance-Based Directional Element

Using the sign of the V2/I2 measurement (an impedance), a directional element can be formulated [8]. Figure 22 shows a directional element with two thresholds indicating a forward fault and a reverse fault condition. The criterion for adjustment is based on the known line impedance (Z1L). For a reverse fault, the relay measures at least the line impedance. If the forward and reverse thresholds are taken close to Z1L/2 (a very conservative assumption), then thresholds for the directional element are defined. Figure 22 shows these two thresholds.

The negative-sequence directional element, as with other elements in a protective relay, does not operate alone; it is part of a scheme with other elements that detects faults reliably. These other elements could be overcurrent or distance elements, for example. The negative-sequence directional element reliably determines the direction of all fault types in the power system, except the three-phase fault. This makes the element highly attractive for modern relays that need to provide phase fault protection and ground fault protection.

In the negative-sequence network, the angles of the impedance are highly predictable; they are basically reactances. This makes the negative-sequence directional element application simpler for all networks as opposed to zero-sequence directional elements that may need to consider the grounding of the system for their operation.

A ground directional element can be designed with zero-sequence quantities. It can be based on impedance or on the traditional phasor comparison of the zero-sequence voltage and the zero-sequence current.
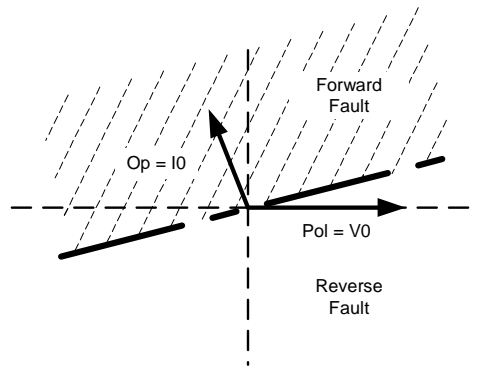
Figure 23   Traditional Zero-Sequence Directional Element

Figure 23 illustrates a traditional zero-sequence voltage-polarized ground directional element. The zero-sequence voltage (V0) is the polarizing quantity, and the zero-sequence current is the operating quantity. The presence of V0 is required and necessary for the element to be "polarized" (have a reference). Without a reliable V0, this element does not have the proper polarization.
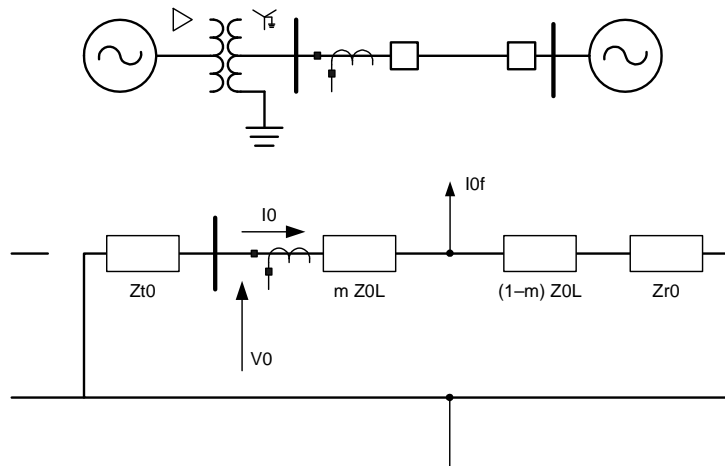

Figure 24   When V0 Is Small, There Is No "Polarizing" Quantity

The zero-sequence voltage is very small in certain situations. One typical case is illustrated in Figure 24. A solidly grounded wye side of the transformer with very small zero-sequence impedance presents very small zero-sequence voltage. The magnitude of the voltage does not "polarize" the zero-sequence voltage-polarized ground directional element. A traditional solution has involved using another zero-sequence quantity to polarize the ground directional element. The neutral of the power transformer is a good polarizing source [9].
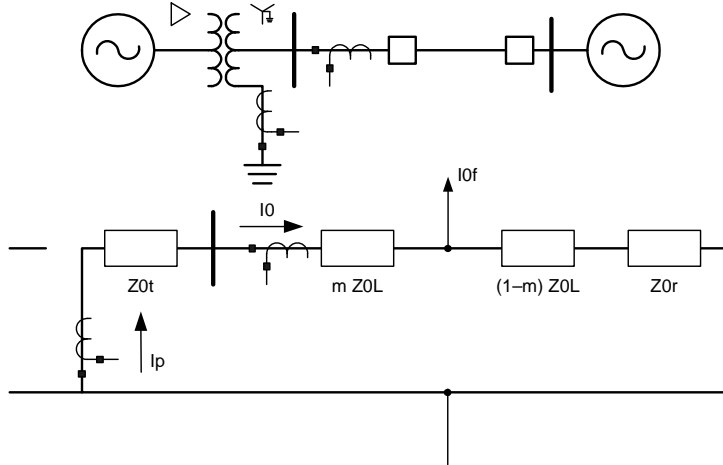
Figure 25 Ground Directional Element Polarized With a Zero-Sequence Current

As can be seen in Figure 25, the neutral of the transformer will provide a polarizing current that is always in the same direction for ground faults. The zero-sequence current, measured at the relay location, will be compared to this polarizing current for a forward or reverse direction determination.

Even with the proper polarizing quantity, zero-sequence ground directional elements face a difficult task when protecting a line with a parallel path. It is well established that the zero-sequence mutual impedance between the parallel lines can cause ground directional problems. The flow of zero-sequence currents in a parallel line induces current in the other line. The zero-sequence mutual effect could be such that the direction of the fault is not properly determined.
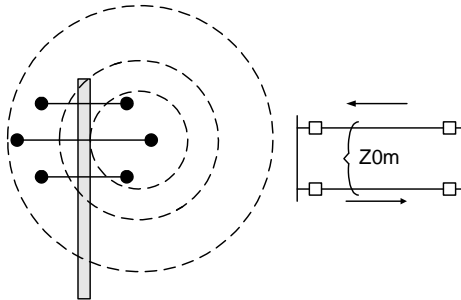

Figure 26 Mutual Effects Resulting From Zero-Sequence Mutual Impedance

Figure 26 helps analyze this situation without resorting to complex impedance calculations. If we consider the flux linkages of one circuit to the other, the negative-sequence and positive-sequence linkages are very small because $Ia + Ib + Ic = 0$. The zero-sequence flux linkage, however, is significant because $\sum I \neq 0$. As shown in Figure 26, the zero-sequence mutual, $Z0m$, induces zero-sequence currents in the other line. This may lead to incorrect directional determination.

Negative-sequence ground directional elements do not suffer from this limitation. It is widely recognized that negative-sequence-based directional elements are most appropriate for protecting parallel transmission lines.

Line Current Differential

Line current differential relays are an excellent choice for line protection when adequate communications facilities are available to accommodate the bandwidth demand for information exchange. These relays have simpler settings and involve applying the differential algorithm to the transmission line. Phase comparison systems compare the phases of currents at both terminals and the result is similar to that of line differential relays. Relays with the alpha plane characteristic combine phase and magnitude comparison of the currents to make the appropriate decision.

Original line protection current-only systems considered phase and zero-sequence information. Very few electromechanical relays provided negative-sequence quantities for line differential relaying. Due to limitations of the channel, the negative-sequence information was used in a composite way; relays used the sum of the weighted sequence components.

The alpha plane line differential relay exchanges negative-sequence information independently from the phase or ground comparison elements [10]. The alpha plane is a magnitude and phase comparison of the remote and local currents (Iremote/Ilocal) on a complex plane. Modern filtering techniques and digital communications are used to determine the presence of internal or external faults in a transmission line.
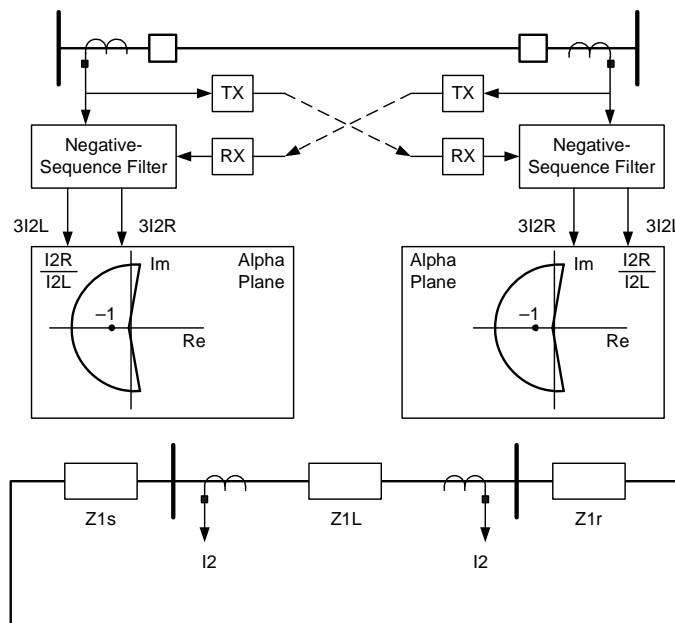

Figure 27   Alpha Plane Line Current Differential With Negative-Sequence Components

Figure 27 illustrates the process of negative-sequence comparison in an alpha-plane relay. The local three-phase currents (Ia, Ib, and Ic) are used to calculate the magnitude and angle of the local negative-sequence components, as described in a previous section of this paper. The three-phase currents are sent to the remote end using the communications channel. The local relay receives currents from the remote end and uses these currents to calculate the remote end negative-sequence component.

The alpha plane provides a very generous and secure restraint characteristic as well as a reliable operating area capable of accommodating severe outfeed conditions.

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Although an alpha plane relay performs comparisons of phase and zero-sequence quantities, the simplicity of calculating negative-sequence components in numerical relays allows the scheme to also make negative-sequence comparisons. As shown in Figure 27, the relay supervises the current flow in the negative-sequence network. An external fault will map on the negative unity (–1) on the alpha plane, as shown in Figure 27. For an internal fault, the currents will change; the magnitudes will most likely be different at both ends, and the angles of the two currents will be nearly equal. This will map on the right-hand side of the alpha plane.

Negative-sequence comparison in a line differential relay adds sensitivity to the detection of high-resistance ground faults and phase-to-phase faults. During an internal fault with high resistance, the phase current does not change much. The negative-sequence and zero-sequence differential comparison, however, will provide a higher degree of sensitivity capable of detecting these faults. The negative-sequence differential is as sensitive as, if not more sensitive than, the zero-sequence differential for ground faults. Moreover, it provides additional coverage to high resistance phase-to-phase faults.

The negative-sequence alpha-plane comparison is considered more secure than the zero-sequence alpha-plane comparison during CT saturation. One of the usual concerns when considering a line current differential is the ability to tolerate a certain degree of CT saturation. CT saturation produces a current phasor that is smaller in magnitude and more leading than the ideal phasor without CT saturation. The phase shifts (the a and a^2) in the negative-sequence equation make it more secure to phase reversals (not magnitude) than zero-sequence components due to the saturation of one phase CT [10].

Phase Selection Algorithm

Phase selection is an algorithm used extensively in single-pole trip schemes. During ground faults, the idea is to trip the pole that has the faulted phase. Different algorithms are used to select the proper pole during a ground fault. Operation of the individual ground distance elements is not sufficient to select the pole to trip.

Modern numerical relays use a very elegant and effective solution based on the comparison of the terminal zero-sequence current and the measured negative-sequence components. Remember that for most cases the calculation of the A-phase negative-sequence component (I2a) is sufficient for most negative-sequence component applications. However, for phase selection, the sequence components for phases B and C are needed (I2b and I2c). This requires a simple phase shift (a^2 and a) from the A-phase component.
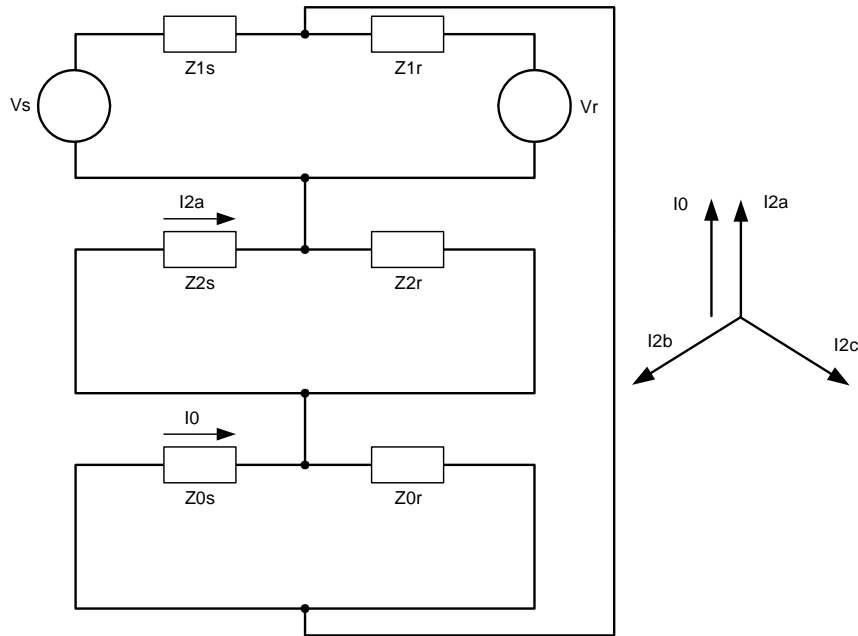
Figure 28   Faulted Phase Selection Using Negative-Sequence Components

Figure 28 illustrates the phase selection of an A-to-ground fault. For the ideal case shown above, the A-phase negative-sequence component aligns with the zero-sequence component. The assumption is that the negative-sequence and zero-sequence distribution factors yield current components that are nearly in phase, although a small angle variation is expected.

If the B-phase negative-sequence component aligns with the zero-sequence component, then the fault is a B-to-ground fault. The same can be thought for the C-to-ground fault. Phase selection in this algorithm selects the proper faulted phase for single line-to-ground faults. The phase selection logic in the protective device should also consider that a BC-to-ground fault will also have the I2a and I0 components in phase. Fortunately, there are other indicators in the power system that can determine whether it is an A-to-ground or a BC-to-ground fault, and the relaying scheme will make the appropriate phase selection.

Fault Location

Modern numerical relays provide fault location as a standard feature—an idea that in earlier days was inconceivable. Besides the many other functions packaged in a numerical relay, fault location is a very important and expected function of the device.

Fault location differs from the impedance calculation algorithm in the sense that the fault location output is supposed to be accurate, and the relay, therefore, has more than enough time to issue the calculation. Distance elements are instantaneous and their function is to detect the power system faults. Application of distance elements in protective relaying schemes is such that output errors are tolerated and expected.

This paper limits discussion on this topic to the use of negative-sequence components in fault location algorithms. This topic has deserved a great deal of attention and several techniques have been proposed. No attempt is made in this paper to qualify these techniques.

A simple fault location methodology uses the calculation of the apparent positive-sequence impedance of the transmission line. The result is an impedance, (R + jX), that indicates the distance to a fault. Assuming that the reactive part of this impedance is the most accurate information, the distance to the fault is calculated as a percentage of the total line reactance. The described method is the reactance fault location algorithm. The main drawback of the algorithm is the effect of high load flow with high resistance in the impedance calculation. The calculation will yield a positive or negative reactive component that adversely affects the fault location calculation.

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 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 one has to catch our attention in this paper. This method, a modified Takagi algorithm, utilizes negative-sequence quantities [11][12].
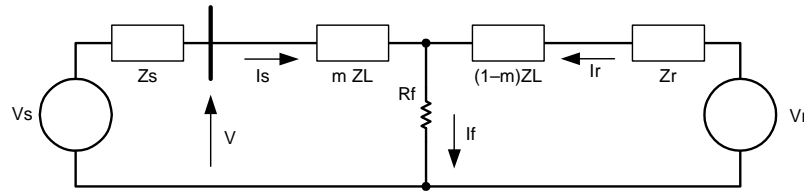

Figure 29   Single-Phase Development of the Takagi Algorithm

To simplify the derivation, we use a single-phase arrangement of the impedances shown in Figure 29. The derivation can be extended to the different loop impedances for phase-to-ground and phase-to-phase faults. Equation (8) describes Figure 29:

$$V = Is(mZL) + (If)(Rf) \tag{8}$$

Where:
- "Is" is the fault current measured in the terminal where the fault location algorithm is performed.
- "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 pre-fault (Ispf) terminal current, as shown in Equation (9):

$$Ifs = Is - Ispf \tag{9}$$

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 Ifs to get Equation (10):

$$V \, Ifs^* = m(ZL \, Is \, Ifs^*) + Rf(Ifs + Ifr)Ifs^* \tag{10}$$

Note that Ifs and Ifr have nearly the same phase, and if we accept any small error resulting from this assumption, then 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):

$$m = \text{Im}\{ZL \text{ Is Ifs}^*\}/\text{Im}\{V \text{ Ifs}^*\} \tag{11}$$

Equation (11) indicates the need to know the pre-fault current at the terminal. A modified version of this algorithm recognizes that negative-sequence currents are incremental quantities, similar to Ifs, where the pre-fault value is zero.

$$m = \text{Im}\{ZL \text{ Is I2}^*\}/\text{Im}\{V \text{ I2}^*\}$$

Using negative-sequence components in fault location allows for some mitigation of the zero-sequence mutual effects of transmission lines, as described previously.

The method we have just discussed is a single-ended algorithm present in modern numerical relays. The methodology is affected by mutual coupling from parallel lines. To overcome this difficulty, some researchers have proposed two-ended methodologies with a variety of requirements. One of the more important requirements is the need for a communications channel to send information from both ends to a central location or local information to the remote end. Some methods propose exact synchronization of data at both ends of the line.

A two-ended fault location algorithm uses negative-sequence quantities to overcome difficulties associated with the needs of any pre-fault data, zero-sequence mutual effects, and any zero-sequence infeed to the line [13]. As with any two-ended method, it requires the transmission of data, but the amount of data transferred is minimum, consisting of the I2 magnitude and the negative-sequence source impedance (Z2) with its magnitude and angle.
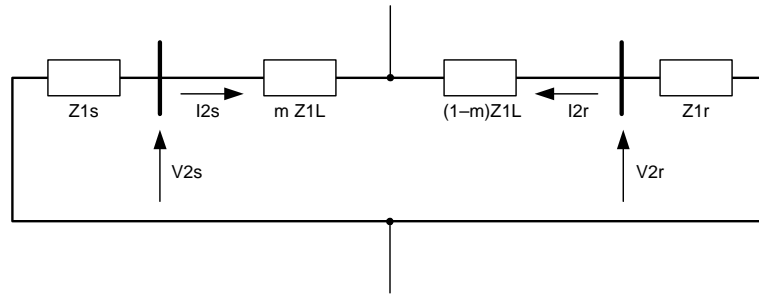

Figure 30   Negative-Sequence Network for Fault Location

Figure 30 illustrates the negative-sequence network for any unbalanced series fault (three-phase faults do not show negative-sequence components). The algorithm takes advantage of this fact, proposing a single equation for all unbalanced faults.

Both ends can easily measure the magnitude and angle of the source impedance as shown in Equations (12) and (13):

$$Z1s = -(V2s/I2s) \tag{12}$$

and

$$Z1r = -(V2r/I2r) \tag{13}$$

At the fault location, Equation (14) is true, where all the variables are known or measured except "m," the distance to the fault.

$$Is(Z1s + m \text{ Z1L}) = Ir(Z1r + (1 - m)Z1L) \tag{14}$$

Because Equation (14) is a vectorial equation, we can solve for "m" using appropriate mathematical techniques.

The important aspect of the above fault location technique, in the scope of this paper, is the use of all negative-sequence quantities. These line negative-sequence parameters are easily calculated and are equivalent to the positive-sequence impedance. The negative-sequence source impedances are easy to measure (V2/I2) because there is no equivalent source behind them. As this paper noted earlier, this method provides an excellent estimate of fault location.

Power System Unbalances

Symmetry in power systems is desired for all the phases. The A-phase conductor should be the same as for the other phases; otherwise, the symmetry will be broken. Power systems rely on the symmetry of the phases. The geometry of transmission lines, however, does not allow for the symmetry of the phases. The distances among the phases and ground can never be the same so there will be unbalances in the flow of load current.

Consider a transmission line with self-impedances of the phases Zaa, Zbb, Zcc, and mutual impedances among the phases Zab, Zbc, and Zca. The voltage drop in the line can be calculated as:

$$\begin{bmatrix} \Delta Va \\ \Delta Vb \\ \Delta Vc \end{bmatrix} = \begin{bmatrix} Zaa & Zab & Zca \\ Zab & Zbb & Zbc \\ Zca & Zbc & Zcc \end{bmatrix} \begin{bmatrix} Ia \\ Ib \\ Ic \end{bmatrix}$$

The impedances depend on the geometry of the transmission line. The ground return consideration is included in them; therefore, if the currents are not balanced, then the equation includes the ground return influence. The only time that Zab, Zbc, and Zca are equal is when the line is completely transposed. In this situation, a different geometric arrangement exists every 1/3rd of the line [14].

Using the following identity based on the matrix in Equation (4), the symmetrical components can be found:

$$\begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} \Delta V0 \\ \Delta V1 \\ \Delta V2 \end{bmatrix} = \begin{bmatrix} Zaa & Zab & Zca \\ Zab & Zbb & Zbc \\ Zca & Zbc & Zcc \end{bmatrix} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} I0 \\ I1 \\ I2 \end{bmatrix}$$

and

$$\begin{bmatrix} \Delta V0 \\ \Delta V1 \\ \Delta V2 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix}^{-1} \begin{bmatrix} Zaa & Zab & Zca \\ Zab & Zbb & Zbc \\ Zca & Zbc & Zcc \end{bmatrix} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} I0 \\ I1 \\ I2 \end{bmatrix}$$

In simpler terms:

$$
\begin{bmatrix} \Delta V0 \\ \Delta V1 \\ \Delta V2 \end{bmatrix} = \begin{bmatrix} Z00 & Z01 & Z02 \\ Z01 & Z11 & Z12 \\ Z02 & Z12 & Z22 \end{bmatrix} \begin{bmatrix} I0 \\ I1 \\ I2 \end{bmatrix}
$$

If Zab, Zbc, and Zca are equal (a transposed line), the off-diagonal terms are zero and we have:

Z00 = Z0L = the zero-sequence line impedance; and

Z11 = Z22 = Z1L = the positive-sequence and negative-sequence line impedance
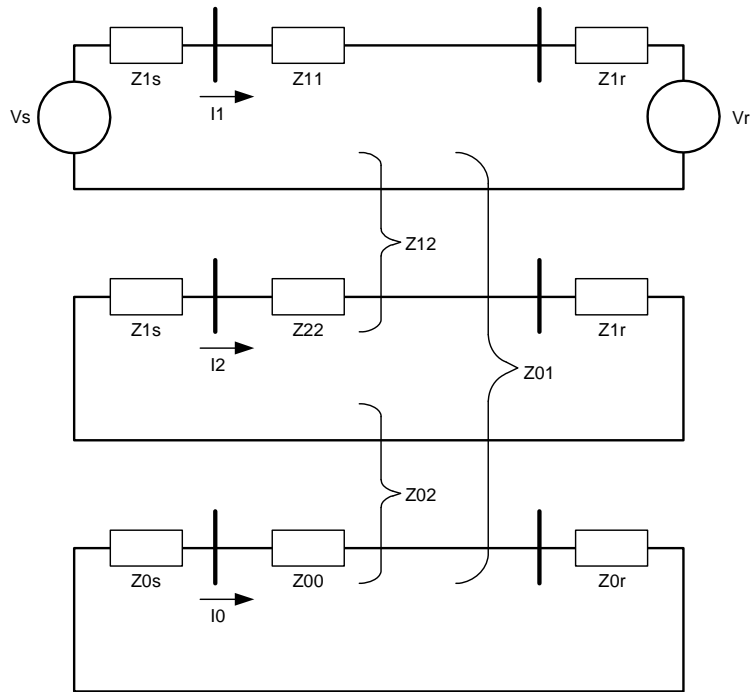

Figure 31   Unbalance as a Result of Asymmetry in a Transmission Line

The fact is that transmission lines are not generally transposed and unbalances are created. Figure 31 illustrates the effect of balanced voltages (such as those generated in power plants) in the sequence networks. There will be negative-sequence current and zero-sequence current induced in the transmission line as a result of asymmetries in the geometry of the line.

In protective relaying, relay sensitivities are generally set at a level high enough that relays are unaffected by these unbalances. Modern numerical relays are designed to supervise their protective elements (negative-sequence directional elements, for example) with fault detectors. These fault detectors require that the measured negative-sequence current be greater than the content of the positive-sequence current.
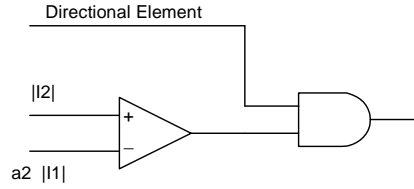
Figure 32   Fault Detector

Figure 32 shows a typical use of the fault detector supervising a relaying element: a directional element, for example. The flow of positive-sequence current in a transmission line induces negative-sequence currents, as shown before, but the ratio is constant and defined by the symmetrical components mutual impedances, Z12 in this case. The supervision shown in the figure secures the operation of protective relaying elements and ensures that they will operate for a real power system fault. For an unsymmetrical fault, the ratio of negative-sequence current to positive-sequence current is greater than the "a2" factor. Not only is negative-sequence supervision possible, but the same idea applies to zero-sequence currents.

IMPEDANCE ANGLE HOMOGENEITY IN THE NEGATIVE-SEQUENCE NETWORK

A set of power system impedances is said to be homogenous when the angles are equal. For example, if we assume that all the power system impedances are inductors (all with an angle of 90°) then the power system is homogenous. On the other hand, introducing impedances with different angles in the set of power system impedances implies some degree of non-homogeneity.

In most academic environments, it is always assumed that power system impedances are reactive, except in the zero-sequence network. This is a good assumption that facilitates the mathematics and, at the same time, shows that the zero-sequence network is the least homogenous. In reality, positive-sequence and negative-sequence impedance angles are predictable and very similar to each other. The zero-sequence impedances are influenced by the ground return that may be resistance (for example, grounding a generator), a rocky terrain with high resistivity (for a transmission line), or an infinite magnitude impedance (for a delta-connected transformer). In summary, the positive-sequence and negative-sequence networks tend to show the most homogenous impedances.

Non-homogeneity is a cause of error in the calculation of fault reactance and fault location. Assuming, for example, the single-phase system shown in Figure 29, the fault impedance measured from Source Vs is

$$Zfs = V/Is = (mZL) + (If/Is)Rf$$

Modern numerical relays offer a quadrilateral characteristic that estimates the reactive component of the fault impedance (mXL). If the angles of If and Is are equal, then

$$mXm = Im\{V/Is\} \quad (If \angle If = \angle Is)$$

Reference [15] describes the implementation of a reactive line for a quadrilateral distance relay. The idea is to estimate the reactive component of the line drop calculation, V – Zc I (Zc is the relay setting) with a polarizing current, Ip. A current generally polarizes reactance components of quadrilateral elements. Phase currents or the positive-sequence current component are affected by load flow (another source of error). The zero-sequence and negative-sequence current components are not affected by load.

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The polarizing current is just a reference; its angle is the important information. As described above, if a reactive line is to be implemented for a quadrilateral distance element for the single-phase network in Figure 29, we would have

$$V Ip^* = m ZL Is Ip^* + Rf If Ip^*$$

and

$$\frac{Im\{V Ip^*\}}{Im\{ZL Is Ip^*\}} = m + Rf \frac{Im\{If Ip^*\}}{Im\{ZL Is Ip^*\}}$$

A distance relay calculates "m," which is the per unit magnitude of the line impedance. The right-hand side of the above equation is the error term due to the fault resistance. It is the choice of a good polarizing current that will make the error term zero. In fact, if the polarizing current is Ip = If, then the error term is zero. It is the angle between If and Ip that makes the error term zero:

$$\frac{If}{Ip} = A \ \angle T \tag{15}$$

since

$$Im\{If Ip^*\} = |If| \ |Ip| \ Sin \ T$$

The simple single-phase network of Figure 29 and the above discussion has allowed the illustration of the error caused by the fault resistance (Rf). Traditionally, quadrilateral elements are associated with the ground distance elements of modern numerical relays.
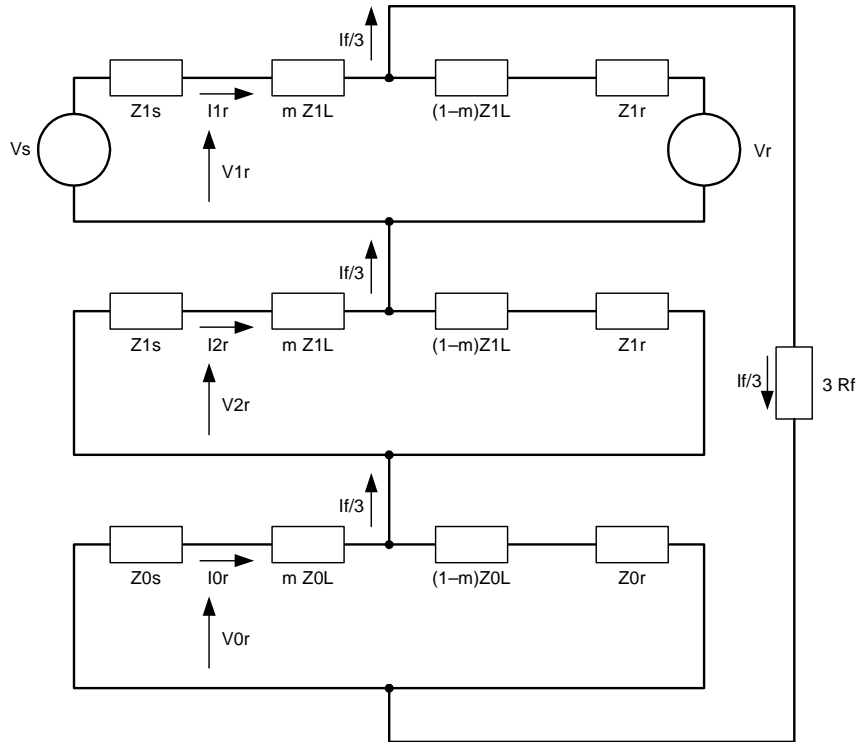

Figure 33 Sequence Network Connection for an A-to-Ground Fault

The proper polarizing current for a reactive component of a ground quadrilateral distance element should be obtained by analyzing the network in Figure 33. The single-phase analysis for Figure 29 can be easily extended to that of Figure 33 and it can be easily shown that

$$VA = mZ1L\ (IA + 3I0\ K0) + If\ Rf \tag{16}$$

Where K0 is the zero-sequence compensation factor (K0 = (Z0L – Z1L)/3Z1L). The polarizing current's phase should be as close to the fault current's angle as possible. The two currents available to the measurement for this purpose are the negative-sequence (I2r) and zero-sequence (I0r) currents. The positive-sequence current is affected by load (the angle between Vr and Vs) and, therefore, is not an appropriate quantity.

The proper polarizing choice comes from the analysis of the homogeneity of the sequence impedances. The negative-sequence and zero-sequence currents are adequate quantities for polarizing the reactance line of a quadrilateral ground element. Equation (15), when viewed in the negative-sequence network in Figure 33, is a simple current divider:

$$I2r = \frac{(1-m)\,Z1L + Z1r}{Z1s + Z1L + Z1r}\ If$$

and

$$\frac{If}{I2r} = \frac{Z1s + Z1L + Z1r}{(1-m)\,Z1L + Z1r} = A_2\ \angle T_2$$

The same can be done for the zero-sequence network:

$$\frac{If}{I0r} = \frac{Z0s + Z0L + Z0r}{(1-m)\,Z0L + Z0r} = A_0\ \angle T_0$$

The angles (T_2 or T_0) are a good indication of the polarizing current to use. In most of the cases, the negative-sequence impedances are the most homogenous; therefore, T_2 is smaller than T_0. Modern numerical relays account for the non-homogenous calculated in the above equations and include an adjustment for the angle difference.

Equation (16) and a compensated polarizing current ($Ip\ e^{jT}$) allow for the correct calculation of the reactive reach of the quadrilateral ground element:

$$\frac{Im\{VA\ (Ip\ e^{jT})^*\}}{Im\{Z1L\ (IA + 3I0\ K0)\ (Ip\ e^{jT})^*\}} = m + Rf\ \frac{Im\{If\ (Ip\ e^{jT})^*\}}{Im\{Z1L\ (IA + 3I0\ K0)\ (Ip\ e^{jT})^*\}}$$

We can eliminate the Rf term of the right-hand side of the equation by including the T factor in the calculation. Ip will most likely be I2 due to the expected more homogenous negative-sequence network.

SUMMARY

Negative-sequence quantities indicate unbalanced power system operation, and measurement of these quantities yields important information for protective relaying. To illustrate the increased use of these quantities in modern protective relaying schemes, this paper presents a few examples of the use of negative-sequence components in numerical relays.

Negative-sequence component calculation and other features now standard in numerical relays were difficult to implement in earlier relay technologies. Modern numerical relays make it relatively simple to calculate negative-sequence components.

This paper discusses how negative-sequence relaying functions can be implemented in numerical relays. A thermal motor model is described for motor protection. Overcurrent coordination provides sensitive backup protection against phase faults and overcurrent backup protection through use of a delta-wye transformer. Negative-sequence directional elements can provide the necessary sensitivity and direction for all unbalanced faults. An alpha-plane relay with negative-sequence comparison increases the sensitivity of line differential relays in detecting unbalanced faults. An efficient phase-selection algorithm based on negative-sequence and zero-sequence currents allows for implementation of sophisticated single-pole tripping relays. Fault-location algorithms using negative-sequence components provide elegant and accurate solutions relatively unaffected by mutual coupling in parallel lines. The use of fault detectors can compensate for natural unbalance resulting from negative-sequence currents in transmission lines. The use of negative-sequence polarizing current for quadrilateral ground distance elements is due to the more homogenous negative-sequence network.

BIBLIOGRAPHY

[1] W. Elmore, "Protective Relaying Theory and Applications," Marcel Dekker, Inc., New York, NY, 1994.

[2] A.G. Padke, J.S. Thorp, "Computer Relaying for Power Systems," Research Study Press Ltd. John Wiley & Sons Inc., 1988.

[3] C.F. Wagner, R.D. Evans, "Symmetrical Components," Robert E. Krieger Publishing, Malabar, FL, 1982.

[4] M.S. Sarma, "Electric Machines – Steady-State Theory and Dynamic Performance," West Publishing Company, 1986.

[5] "IEEE Tutorial on the Protection of Synchronous Generators," IEEE 95TP102.

[6] S.E. Zocholl, "AC Motor Protection," published by SEL, ISBN 0-9725026-0-2, February 2003.

[7] A.F. Elneweihi, E.O. Schweitzer III, M.W. Feltis, "Negative-Sequence Overcurrent Element Application and Coordination in Distribution Protection," IEEE /PES Summer Meeting, Seattle, WA, July 1992.

[8] J.B. Roberts, A. Guzman, "Directional Element Design and Evaluation," Proceedings of the 21st Annual Western Protective Relay Conference, Spokane, WA, October 1994.

[9] J.L. Blackburn, "Protective Relaying: Principles and Applications," Second Edition, Marcel Dekker, Inc., New York, NY, 1998.

[10] J.B. Roberts, D.A. Tziouvaras, G. Benmouyal, H. Altuve, "The Effect of Multi-Principle Line Protection on Dependability and Security," Proceedings of the 54th Annual Conference for Protective Relay Engineers, College Station, TX, April 2001.

[11] T. Takagi, Y. Yamakoshi, M. Yamaura, R. Kondow, T. Matsushima," Development of a New Type Fault Locator Using the One-Terminal Voltage and Current Data," IEEE Transactions on Power Apparatus and Systems, Vol. PAS-101, No 8, August 1982.

[12] E.O. Schweitzer III, "Evaluation and Development of Transmission Line Fault Locating Techniques Which Use Sinusoidal Steady-State Information," Proceedings of the 9th Annual Western Protective Relay Conference, Spokane, WA, October 1982.

[13] D.A. Tziouvaras, J.B. Roberts, G. Benmouyal, "New Multi-Ended Fault Location Design for Two or Three Terminal Lines," CIGRE, 1999.

[14] P.M. Anderson, "Analysis of Faulted Power Systems," IEEE Press – Power System Engineering Series, 1995.

[15] E.O. Schweitzer III, J.B. Roberts, "Distance Relay Element Design," Proceedings of the 46th Annual Conference for Protective Relay Engineers, College Station, TX, April 1993.

[16] J. Mooney, J. Peer, "Application Guidelines for Ground Fault Protection," Proceedings of the 24th Annual Western Protective Relay Conference, Spokane, WA, October 1997.

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