Selecting Directional Elements for Impedance-Grounded Distribution Systems

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Presented at the
34th Annual Western Protective Relay Conference
Spokane, Washington
October 16–18, 2007

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***Abstract*—This paper reviews general applications and future trends of impedance-grounded systems and summarizes available directional elements for ground fault detection in these systems. Later the paper describes improved directional elements that provide high fault detection sensitivity in resistance-grounded systems. The paper evaluates the performance of these elements using EMTP simulations of real utility systems. Finally, the paper provides application guidelines for selecting and setting directional elements to improve protection selectivity and sensitivity.**

I. Introduction

Impedance-grounded systems are popular in utility distribution systems, industrial plants, and commercial centers worldwide. In the United States, Southern California Edison, Omaha Public Power District, and other utilities have, or are introducing, impedance-grounded distribution systems. Impedance grounding reduces thermal stress on equipment and improves human safety by limiting fault current magnitudes. However, impedance-grounded systems pose challenges to the sensitivity and selectivity of protective relaying.

Effectively and low-impedance-grounded systems require line tripping to remove ground faults. Ground directional elements available for these systems include the zero-sequence current-polarized element (32I), negative-sequence voltage-polarized element (32Q), and zero-sequence voltage-polarized element (32V) [1]. A best choice ground directional element [2] selects the best element to use (32I, 32Q, or 32V) for ground faults according to system conditions. This element does not require user settings.

Ungrounded, high-resistance-grounded, and compensated systems may operate for some time during single-line-to-ground faults because the fault does not affect the phase voltage triangle. The system must have a phase-to-phase insulation level, and all loads must be connected phase-to-phase. Ground fault detection in these systems requires sensitive relays because the fault current is very low. Some directional elements available for these systems are the ground directional element for ungrounded systems (32U) [3][4], the wattmetric directional element (32W), and the incremental conductance element (32C) for high-resistance-grounded and compensated systems [3].

II. Review of Grounding Methods of Medium-Voltage Distribution Systems

For medium-voltage distribution systems, we choose a grounding method to achieve the following objectives [3]:

- Minimize equipment voltage stress
- Minimize equipment thermal stress
- Provide personnel safety
- Reduce interference to communications systems
- Assist quick detection and isolation of ground faults

No grounding method satisfies all these objectives. Utilities have to sacrifice some objectives in order to achieve those that they consider more important. For example, limiting ground fault current reduces equipment thermal stress and communications interference and also increases personnel safety, but impairs fault detection. Modern microprocessor-based relays provide high fault detection sensitivity and selectivity. Ground faults on ungrounded or high-impedance-grounded systems can be detected using newer relays.

In the following sections, we briefly review grounding methods for utility or industrial medium-voltage distribution systems [3].

A. Ungrounded or Isolated Neutral

Ungrounded or isolated neutral systems have no intentional connection to the ground. The distributed conductor capacitances indirectly connect the system to ground. All loads are phase-to-phase connected. Equipment must have phase-to-phase voltage insulation level to withstand overvoltages on the healthy phases during ground faults.

Single-line-to-ground faults shift the system neutral voltage but leave the phase-to-phase voltages intact. Hence, these systems can remain operational during sustained, low-magnitude faults.

Zero-sequence line-to-ground capacitance and fault resistance limit the single-line-to-ground fault current to a small magnitude. The concern of equipment thermal stress is minimal. However, the low fault current values require sensitive fault detection devices.

A large ungrounded system may have enough capacitance to support large fault currents. At higher magnitudes of fault current, faults are less likely to self-extinguish because of the high transient recovery voltage.

B. Effective Grounding

According to an IEEE standard [5], an effectively grounded system complies with $(X_0/X_1) \leq 3$ and $(R_0/X_1) \leq 1$, where X_0 and R_0 are the zero-sequence reactance and resistance, and X_1 is the positive-sequence reactance of the power system.

In North America, effectively grounded distribution systems are multigrounded systems. The neutral wire is connected to ground at the substation, at every distribution transformer, and every 1000 feet or so if there is no transformer ground throughout the feeders. Multigrounded systems provide the flexibility of connecting loads either phase-to-neutral or phase-to-phase. Equipment only needs a phase-to-neutral insulation level.

In multigrounded systems, both load unbalance and ground fault currents divide between the neutral conductor and earth. Detecting high-resistance ground faults on these systems is difficult because the protective relay measures the high-resistance ground fault current combined with the unbalance current [6].

Ground faults on effectively grounded systems may produce high-magnitude currents (higher than 60 percent of the three-phase fault current [5]) that require immediately tripping the entire circuit and interrupting load to many customers. About 80 percent of ground faults occurring on overhead distribution lines are transient. For these systems, automatic multiple-shot reclosing is widely used. The resulting interruption/restoration cycle can represent a problem to customers with large motor loads or those with loads intolerant of voltage sags and swells.

Effective grounding reduces the risk of overvoltages during ground faults.

C. Low-Impedance Grounding

In low-impedance grounding, the system is grounded through a low-value resistor or reactor with the objective of reducing equipment thermal stress. The ground fault current magnitude is in the order of hundreds of amperes and suitable for relaying purposes. Many medium-voltage industrial distribution systems use low-resistance grounding, with typical ground fault currents in the range of 100 to 1000 A.

Resistance grounding is preferred because it allows better reduction of the ground fault current than reactance grounding, without risk of transitory overvoltages [7]. For reactance grounding, the ground fault current must be above 25 percent of the three-phase fault current. Resistance grounding allows values below 25 percent without overvoltage problems.

D. High-Resistance Grounding

In high-resistance grounding, the system is grounded through a resistor with its resistance equal to or slightly less than $R_G = 1/3 \bullet XC_{0S}$, the total system capacitive reactance to ground, in order to limit transient overvoltages to safe values during ground faults [5]. The high-resistance grounding method limits transient overvoltages to less than 2.5 times the peak value of the nominal phase-to-ground voltage. Ground fault current is typically below 25 A.

As with isolated neutral systems, single-line-to-ground faults on these systems shift the system neutral voltage without modifying the phase-to-phase voltage triangle. This grounding method permits utilities or industrial plants to continue operating the system during sustained ground faults. The low-level ground fault currents on these systems require sensitive fault detection devices.

E. Resonant Grounding

In resonant grounding, the system is grounded through a high-impedance reactor. The reactor is ideally tuned to the overall system phase-to-ground capacitance [5]. The grounding reactor is called a Petersen coil after its inventor. It is also known as an arc-suppression coil or ground-fault neutralizer. Systems with this type of grounding are referred to as resonant-grounded or compensated systems. When the coil reactance matches the system capacitive reactance, the system is fully compensated or at 100 percent tuning. If the coil reactance is greater than the system capacitive reactance, the system is overcompensated. If the coil reactance is smaller than the system capacitive reactance, the system is undercompensated.

Older installations use a low-cost, fixed-value reactor. In these systems, the tuning condition (under- or overcompensated) changes with the configuration of the distribution network. Tap-changing reactors permit manual or automatic control of the tuning conditions. Modern installations include a moving-core (plunger) reactor equipped with a control system to provide almost 100 percent tuning for all system-operating conditions. These plunger systems also provide a smooth means of system tuning.

Resonant grounding systems can reduce the ground fault current to about 3 to 10 percent of that for an ungrounded system. The low fault current values require sensitive fault detection devices. For 100 percent tuning, the active coil losses, system harmonics, and system active leakage current determine the fault current magnitude [8].

Because ground faults in compensated systems do not affect the phase-to-phase voltage triangle, it is then possible to continue operating the system in the faulted condition. The system must have a phase-to-phase insulation level, and all loads must be connected phase-to-phase.

Resonant grounding provides self-extinction of the arc in overhead lines for about 80 percent of temporary ground faults [8]. Considering that about 80 percent of ground faults are temporary faults, we conclude that more than 60 percent of ground faults in overhead lines clear without breaker tripping. Ground faults represent more than 50 percent of all faults in overhead lines.

The arc self-extinction action depends not only on the fault current magnitude, but also on the transient recovery voltage rate after successful arc extinction at the current zero crossing. In compensated systems, this voltage recovery is much slower than in ungrounded systems.

F. *Other Grounding Choices*

Some legacy distribution systems do not follow today's typical grounding methods. Most of these systems developed from ungrounded systems. Later in this paper, we describe one of these systems.

III. System Grounding Survey

Throughout the world, utility and industrial distribution systems use one of the above grounding methods. Reference [3] provides an interesting insight into the locations of use and characteristics of each grounding method. To complement this information, a small survey was sent to users and representatives of the authors' company throughout the world requesting, per their experience, a description of the different grounding methods used in utility and industrial distribution systems. While this survey did not cover a large population and was not a very scientific process, it provided useful information about grounding methodologies in the world.

A. *Utility Systems*

The responses we received show that the most widely used grounding method in distribution networks is effective grounding. Larger population countries like the United States, Brazil, Mexico, India, Australia, and other Latin American and African countries show a very high percentage use of this grounding method.

Low-impedance grounding in utility systems seems to have certain localized applications in different regions. It is not a dominant grounding method. A large usage in Turkey and Greece is reported from the survey, and we may find some applications in other parts of Europe, the United States, Australia, Brazil, and Argentina, for example.

High-resistance grounding is perhaps the least popular grounding method. Very small usage in utility systems is reported in the survey. The percentage use of this grounding method is on the average around 1 percent in different parts of the world.

Resonant grounding has many applications in Europe. Compensated distribution networks are standard practice in countries like Italy, France, and Lithuania and are used in other European countries. Given the operational advantages of resonant grounding, other countries are considering its application. In Brazil for example, projects are underway to implement this technology and gain experience.

Ungrounded distribution networks are not used in many distribution companies, but there are relatively large users in Latin America and Europe. Distribution companies in Peru and El Salvador report a very large percentage use of ungrounded distribution networks. In some European countries like the Czech Republic, a 5 percent usage is reported.

Table I shows percentages of grounding method usage by utilities as estimated from the survey responses. These are examples of distribution system grounding methods used in certain countries around the world.

TABLE I
GROUNDING METHODS SURVEY RESULTS (UTILITY)

Country/ Region	Effective	Low Imp.	High Res.	Resonant	Ungrounded
United States	85%	10%	0%	0%	5%
Australia	95%	5%	0%	0%	0%
Brazil	97%	2%	0%	0%	<1%
Mexico	100%	0%	0%	0%	0%
Czech Republic	0%	20%	0%	75%	5%
Peru	20%	0%	0%	0%	80%
Turkey	5%	95%	0%	0%	0%

Note: The above percentages are estimates only.

The survey also shows that future distribution grounding will not change dramatically. Effectively grounded networks will still be used in a large number of installations. Resonant-grounded networks, preferred in large portions of Europe, will be increasingly used in future installations.

B. *Industrial Systems*

Grounding practices in medium-voltage industrial systems do not necessarily coincide with utility practices. Effectively grounded industrial distribution networks seem to be a smaller proportion in industrial systems than in utility networks.

Low-impedance grounding appears to have the larger percentage use in medium-voltage industrial systems. In Brazil, for example, some replies mention 90 percent usage; Mexico reports 70 percent, Greece 80 percent, Turkey 60 percent, and the United States 50 percent. On the average, low-impedance grounding seems to be around 55 percent.

High-resistance grounding in industry seems to have a better acceptance than in utilities. The survey reflects an average of 20 percent of use in Brazilian industrial installations and significant percentage use in the United States and other countries. However, high-resistance grounding seems to have around a 10 percent share in industrial installations.

Resonant-grounded industrial networks have found application in Europe, and no other region has reported their use. The Czech Republic reports a 35 percent share of industrial installations with resonant grounding.

Ungrounded networks represent a good percentage of industrial installations. Petroleum off-shore installations in Brazil are all ungrounded distribution systems. The estimated usage of ungrounded networks is 45 percent for the Czech Republic and 20 percent for Greece, for example.

TABLE II
GROUNDING METHODS SURVEY RESULTS (INDUSTRY)

Country/ Region	Effective	Low Imp.	High Res.	Resonant	Ungrounded
United States	35%	50%	13%	0%	2%
South Africa	100%	0%	0%	0%	0%
Brazil	15%	55%	20%	0%	10%
Mexico	30%	70%	0%	0%	0%
Czech Republic	0%	20%	0%	35%	45%
Greece	0%	80%	0%	0%	20%
Turkey	25%	60%	2%	0%	13%
Rest of Latin America	55%	0%	25%	0%	20%

Note: The above percentages are estimates only.

Europe reports a trend to building new ungrounded and resonant-grounded industrial distribution networks. The replies from other parts of the world show preference for low-impedance, high-resistance, or effective grounding methods.

C. Survey Overview

The survey, while not completely methodical, shows that utility distribution companies prefer effectively grounded networks, except in Europe where compensated networks are prevalent. There are also some applications of low-impedance-grounded and ungrounded systems.

In industry, low-impedance grounding is generally preferred, but effective grounding, high-resistance grounding, and ungrounded systems have found application. Compensated networks are practically not used.

D. Protection Practices for Systems With Low-Magnitude Ground Fault Currents

The survey requested additional information on the protection practices for high-resistance-grounded, compensated, and ungrounded networks. In these systems, a simple ground overvoltage relay may be used to indicate the presence of a ground fault. However, sensitive ground directional elements are required to identify the faulty feeder.

From the reports on high-resistance-grounded networks, the average use of appropriate ground directional overcurrent relays in industry is approximately 5 percent. The maximum torque angle of the relays varies from 45 degrees up to 80 degrees.

Some resonant-grounded networks have ground fault detection systems based on current injection. However, the wattmetric ground relay is the most widely used solution. The Czech Republic, for example, reports an approximate 95 percent use of this method.

Utility users of ungrounded networks in Latin America report 70 to 100 percent use of sensitive ground directional overcurrent relays. In Europe, the usage seems to be close to 100 percent. In industry, the reports are not uniform. Brazil and other Latin American countries report less than 10 percent of industries using directional elements. The Czech Republic, on the other hand, reports 60 percent.

IV. REVIEW OF GROUND DIRECTIONAL ELEMENTS FOR MEDIUM-VOLTAGE DISTRIBUTION SYSTEMS

A. Need for Directional Elements

In looped systems, the fault current direction depends on the fault location with respect to the relay location. These systems require directional elements. For ground faults, the system behaves as a looped system when there are zero-sequence sources at both line ends. A grounded-wye transformer or a grounding bank contribute to ground faults even without generation connected behind them.

Industrial or utility distribution systems are typically radial systems. In effectively and low-impedance-grounded radial systems, the current magnitude is sufficient indication of the fault location and the faulted feeder. Overcurrent elements are generally adequate for ground fault protection in these radial systems.

For higher grounding impedance values, even radial systems require ground directional elements, because the feeder protection can measure similar current magnitudes for feeder faults and out-of-feeder faults. As an example, Fig. 1 depicts a resistance-grounded radial distribution system with the loads connected phase-to-phase.

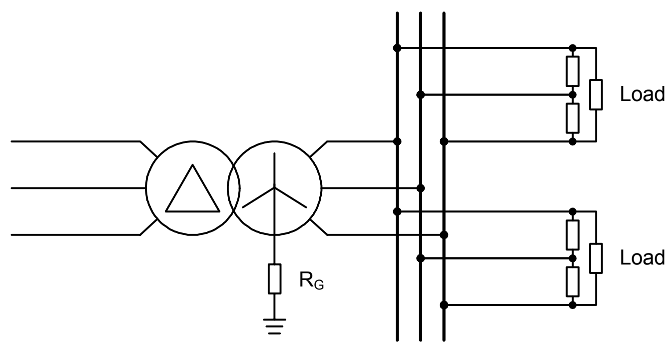

Fig. 1. A resistance-grounded distribution system

Fig. 2 shows the zero-sequence current magnitude (in secondary amperes) that a feeder relay measures in this system for a forward solid single-line-to-ground fault as a function of the grounding resistance (R_G) value. The fault current drops dramatically as the grounding resistance increases.

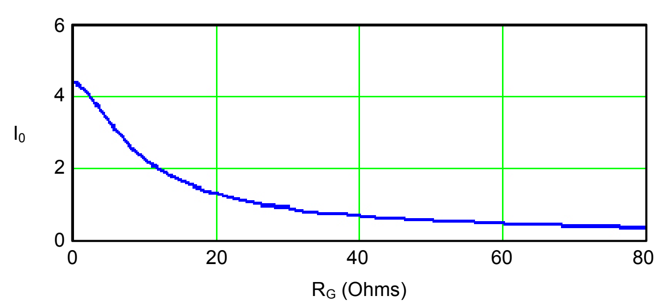

Fig. 2. A plot of the zero-sequence current magnitude (I_0) for a solid forward single-line-to-ground fault as a function of R_G in Fig. 1 system

For low R_G values, we could expect that the fault current magnitude for a forward fault is greater than that for a reverse fault, so we can simply use current magnitude to discriminate between forward and reverse faults. This assumption would be correct if the relay was only required to detect faults with low fault resistance (for example, $R_F < 10\ \Omega$). However, many users require the relay to detect higher resistance faults. For example, a utility in Australia requires the relay to detect faults with currents as low as 3 A primary. The main reason for this is that the utility supplies customers in the remote regions of Australia where the lines go through bush areas. Undetected high-resistance faults could cause bush fires and destroy large areas of vegetation.

Fig. 3 is a simulation of a forward fault with a fault resistance $R_F = 90\ \Omega$. Fig. 4 is a simulation of a reverse fault with a lower fault resistance ($R_F < 1\ \Omega$) on the same distribution system. From Fig. 3 and Fig. 4, we can see that the current magnitudes for the forward and reverse faults are almost the same. It is not possible to use current magnitude to discriminate between forward and reverse faults.

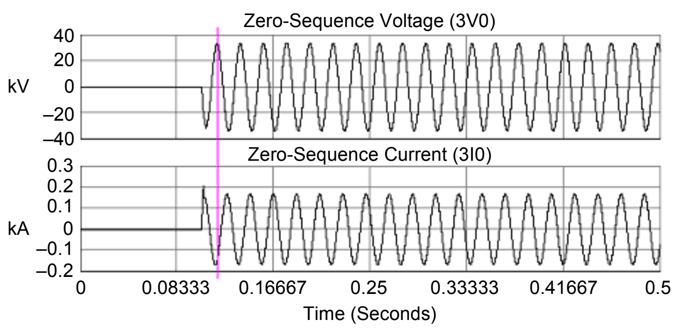

Fig. 3. RTDS plot for a forward ground fault in Fig. 1 system with 90 Ω fault resistance

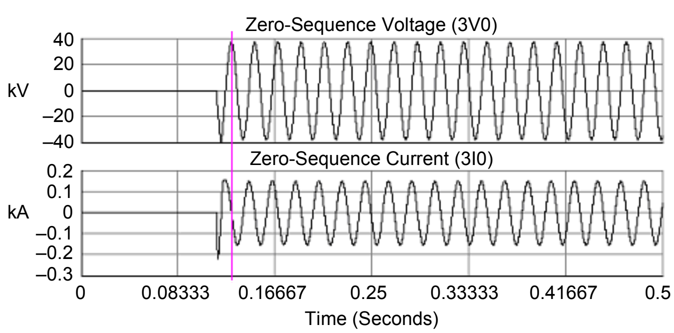

Fig. 4. RTDS plot for a reverse ground fault in Fig. 1 system with low fault resistance ($R_F < 1\ \Omega$)

B. Directional Elements for Effectively and Low-Impedance-Grounded Systems

Traditional ground directional elements make a phase angle comparison of an operating current with a polarizing quantity (either a voltage or a current). Digital designs offer better alternatives.

1) Zero-Sequence Current-Polarized Directional Element (32I)

The 32I element is the digital version of the traditional current-polarized ground directional element. The analog input quantities to this element are the operating quantity $3\ \bar{I}_0$ (the sum of the phase currents) and the polarizing quantity $\bar{I}_{POL}$ [1]. We may use the neutral current of a delta-wye transformer as $\bar{I}_{POL}$, for example.

The 32I element [9] uses (1):

$$T = \mathrm{Re}\left[3\bar{I}_0 \cdot \bar{I}_{POL}^{\ *}\right] \tag{1}$$

where $3\,\bar{I}_0$ is the operating quantity, and $\bar{I}_{POL}^{\ *}$ is the complex conjugate of the polarizing quantity $\bar{I}_{POL}$. The 32I element compares the result of the torque calculation T against preset thresholds. When T is positive and above the positive threshold, the element asserts to declare a forward ground fault. When T is negative and below the negative threshold, the element asserts to declare a reverse ground fault.

2) Negative-Sequence Voltage-Polarized Directional Element (32Q)

The analog input quantities to the 32Q element [1][2] are the negative-sequence voltage V_2 and the negative-sequence current I_2. The 32Q element calculates the scalar quantity z_2 using (2):

$$z_2 = \frac{\mathrm{Re}\left[\bar{V}_2 \cdot \left(\bar{I}_2 \cdot 1\angle Z1L\right)^*\right]}{\left|\bar{I}_2\right|^2} \tag{2}$$

where $\bar{V}_2$ is the negative-sequence voltage, $\bar{I}_2$ is the negative-sequence current, and Z1L is the line positive-sequence impedance angle, which equals the line negative-sequence impedance angle (a relay setting).

The directional element compares z_2 with two thresholds. If z_2 is below a forward-fault threshold, the 32Q element declares a forward fault. If z_2 is above a reverse-fault threshold, the 32Q element declares a reverse fault.

3) Zero-Sequence Voltage-Polarized Directional Element (32V)

The 32V element is the zero-sequence analogy of the 32Q element. Equation (3) shows the algorithm used to calculate the scalar quantity z_0.

$$z_0 = \frac{\mathrm{Re}\left[3\bar{V}_0\left(3\bar{I}_0 \cdot 1\angle Z0MTA\right)^*\right]}{\left|3\bar{I}_0\right|^2} \tag{3}$$

where $\bar{V}_0$ is the zero-sequence voltage, $\bar{I}_0$ is the zero-sequence current, and Z0MTA is the maximum torque angle of the 32V element (a relay setting). The 32V element makes directional decisions in the same way as the 32Q element. The element compares z_0 against the forward-fault and reverse-fault thresholds to determine the direction of the ground fault.

4) 32Q and 32V Element Operation for Ground Faults

The 32Q and 32V elements declare forward and reverse ground faults similarly. Fig. 5 shows the 32Q element voltage V_2 and current I_2 for a ground fault at the remote terminal of the protected line in a two-source system. I_2 is the current contribution from the local end. At the relay location,

$\overline{V}_2 = -\overline{I}_2 \cdot \overline{Z}_{2S}$. If the negative-sequence impedance source angle $\angle\overline{Z}_{2S}$ equals the setting angle Z1L, the calculated scalar quantity is $z_2 = -\left|\overline{Z}_{2S}\right|$. For any location of the forward fault, the directional element measurement corresponds to the negative-sequence impedance of the equivalent system behind the relay. A similar analysis shows that for all reverse ground faults, the scalar quantity is $z_2 = \left|\overline{Z}_{2L} + \overline{Z}_{2R}\right|$, corresponding to the negative-sequence impedance of the equivalent system in front of the relay.

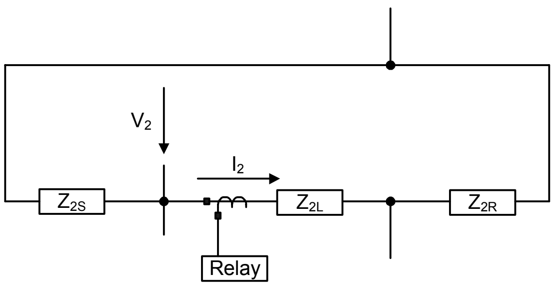

Fig. 5. Relay negative-sequence voltage V_2 and negative-sequence current I_2 for a ground fault at the end of the protected line

Fig. 6 shows the operating characteristic of the 32Q (Fig. 6a) and 32V (Fig. 6b) elements and also the calculated z_2 and z_0 values for forward and reverse faults. For simplicity, we consider the power system to be purely inductive and assume the line positive-sequence impedance angle and the maximum torque angle (Z1L and Z0MTA respectively) are set to 90 degrees. For the 32Q element, we use Z_{1L} instead of Z_{2L} in Fig. 6a. (Recall that $Z_{1L} = Z_{2L}$ for lines.)

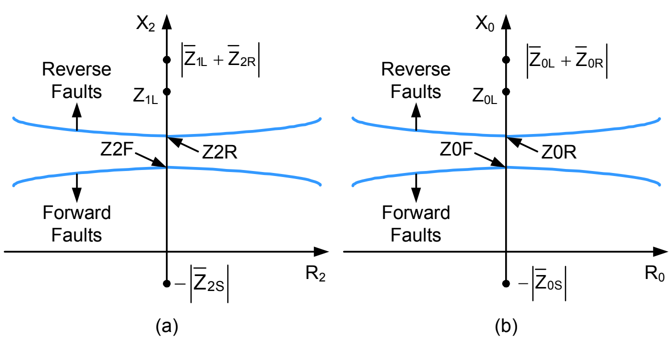

Fig. 6. Operating characteristics of 32Q (a) and 32V (b) directional elements

C. Directional Element for Ungrounded Systems

For ungrounded systems, the distributed capacitance of feeders and other system components provides the path for ground fault current. In a faulted ungrounded system, the currents of healthy feeders and the faulted feeder current are not significantly different. Overcurrent protection is not reliable to determine the faulted line. Traditional ground fault protection on ungrounded systems relies on a zero-sequence overvoltage indication plus a sequential manual opening of each feeder to locate the faulted line.

A zero-sequence voltage-polarized directional element (32U) for ungrounded systems [3][9] uses (3) with Z0MTA = –90° to calculate the scalar value z_0. This element compares z_0 against forward-fault and reverse-fault thresholds to determine the direction of the ground fault.

Fig. 7 shows an approximate zero-sequence representation of a forward ground fault in an ungrounded system, where XC_{0L} is the zero-sequence capacitive reactance of the protected line and XC_{0S} is the zero-sequence capacitive reactance of the remaining system. At the relay location, $\overline{V}_0 = -\overline{I}_0\left(-jXC_{0S}\right) = jXC_{0S}\overline{I}_0$. Therefore, the apparent zero-sequence impedance (the $\overline{V}_0/\overline{I}_0$ ratio) equals the equivalent capacitive reactance behind the relay $-(-jXC_{0S}) = jXC_{0S}$. A similar analysis shows that the apparent impedance value for a reverse fault is the protected line capacitive reactance $-jXC_{0L}$.

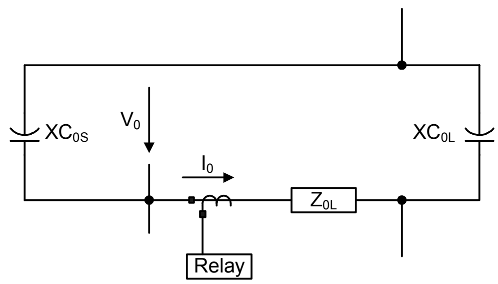

Fig. 7. Zero-sequence network for a forward ground fault in an ungrounded system

Fig. 8a shows the phasor diagram for forward and reverse faults. Fig. 8b shows the 32U element operating characteristic. The setting Z0MTA = –90° results in the forward-fault region being on the first and second quadrants of the impedance plane and the reverse-fault region being on the third and fourth quadrants of the impedance plane. The forward-fault and reverse-fault thresholds are set for $+jXC_{0S}$ to fall in the forward-fault region and $-jXC_{0L}$ to fall in the reverse-fault region.

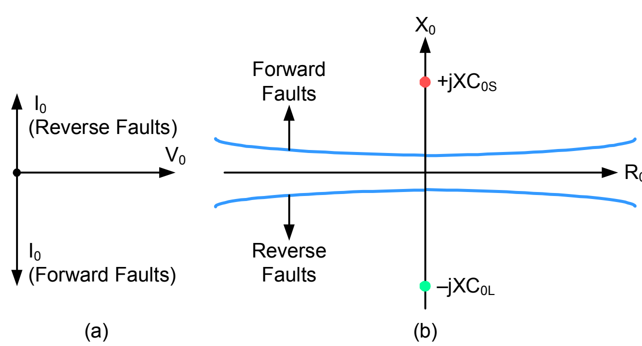

Fig. 8. Ground directional element for ungrounded systems (32U). Phasor diagram for ground faults (a) and element operating characteristic (b)

D. Directional Elements for Compensated Systems

A zero-sequence overvoltage condition is a valid ground fault indication for resonant grounding systems. The system operator has to disconnect each feeder of the bus to find the faulted line. The lengthy fault location time and service interruptions of healthy lines are unacceptable for present day distribution systems.

1) Wattmetric Directional Element (32W)

The 32W element [3][9] has the following output quantity:

$$W_0 = \mathrm{Re}\left[3\overline{V}_0 \cdot 3\overline{I}_0^{\,*}\right] \quad (4)$$

where $\overline{I}_0^{\,*}$ is the complex conjugate of $\overline{I}_0$.

The 32W element compares W_0 with forward-fault (negative) and reverse-fault (positive) thresholds to make the fault direction declaration. Fig. 9a shows the phasor diagram for ground faults in compensated networks. The sign of the in-phase (active) component of $\overline{I}_0$ is always positive for reverse faults and negative for forward faults. Fig. 9b shows the directional element operating characteristic in the complex power plane. If W_0 is below (to the left of) the forward-fault threshold, the 32W element declares a forward fault. If W_0 is above (to the right of) the reverse-fault threshold, the element declares a reverse fault.

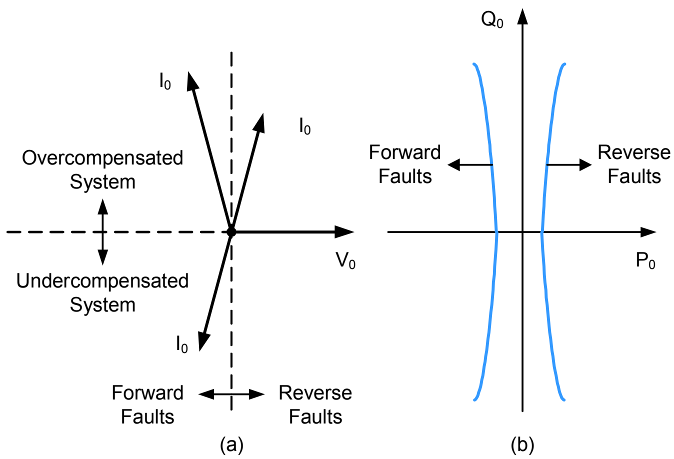

Fig. 9. Wattmetric directional element (32W). Phasor diagram for ground faults (a) and element operating characteristic (b)

The active component of $\overline{I}_0$ is very low during ground faults, so the relay should be very sensitive. To avoid relay misoperations during normal system conditions, it is necessary to add a starting element responding to the magnitude of $\overline{V}_0$. Then wattmetric element sensitivity is determined by the V_0 element sensitivity. The threshold V_0 value should be greater than the value of V_0 for normal system unbalances. A typical setting is 20 percent of the nominal system voltage.

We may apply the wattmetric element for ground fault detection in all types of distribution systems having low ground fault current values. This includes isolated neutral, high-resistance-grounded, and compensated systems. Flux-summing CTs are strongly recommended for wattmetric relays.

2) Incremental Conductance Directional Element (32C)

The 32C element [3][9] compares the measured incremental conductance (real part of the incremental current/incremental voltage ratio) with positive and negative thresholds to discriminate forward faults from reverse faults. We can use this element as a complement to the 32W element for detecting high-resistance ground faults.

E. Directional Elements for High-Resistance-Grounded Systems

Fig. 10 shows the zero-sequence network of a resistance-grounded system during a forward single-phase-to-ground fault. R_G is the grounding resistance. $\overline{Z}_{0T}$ is the transformer or grounding bank zero-sequence impedance. The system zero-sequence impedance $\overline{Z}_{0S}$, behind the relay in this case, is the parallel of the series combination of $3R_G$ and $\overline{Z}_{0T}$ with the total capacitive reactance XC_{0S} of the remaining system. For this forward fault, the measured zero-sequence impedance (the $\overline{V}_0/\overline{I}_0$ ratio) equals the equivalent source impedance behind the relay $-\overline{Z}_{0S}$. A similar analysis shows that for reverse faults, the measured impedance equals the protected line capacitive reactance $-jXC_{0L}$ (assuming that $XC_{0L} >> Z_{0L}$).

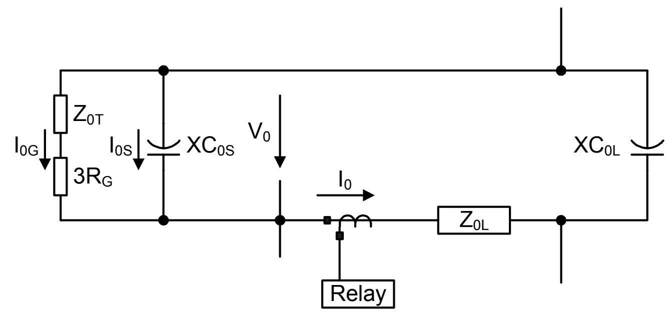

Fig. 10. Zero-sequence network for a forward ground fault on a resistance-grounded system

In a high-resistance-grounded system, the grounding resistance has a typical value of $3R_G = XC_{0S}$. We may disregard the transformer impedance in this case ($3R_G >> Z_{0T}$). The system zero-sequence impedance $\overline{Z}_{0S}$ has an angle of –45 degrees, and the angle of $-\overline{Z}_{0S}$ is 135 degrees. Therefore, during a forward fault, the zero-sequence current $\overline{I}_0$ of the faulted feeder roughly lags the system zero-sequence voltage $\overline{V}_0$ by 135 degrees as shown in Fig. 11a. The measured zero-sequence impedance $-\overline{Z}_{0S}$ plots in the second quadrant of the impedance plane (see Fig. 11b).

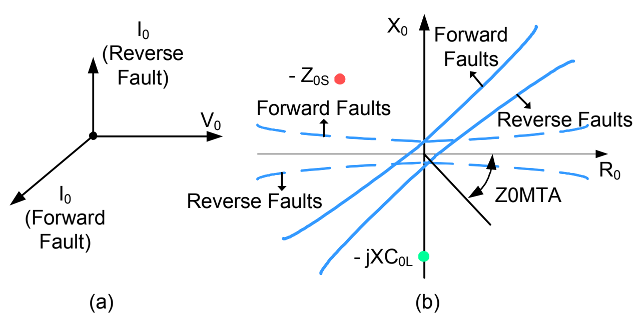

Fig. 11. Application of zero-sequence voltage-polarized directional elements to a resistance-grounded system. Phasor diagram for ground faults (a) and element operating characteristics (b)

High-resistance-grounded systems require flux-summing CTs and very sensitive ground directional elements. The 32U element characteristic, represented by the dotted lines in Fig. 11b, works well for this case. However, a better solution is a combination of wattmetric (32W) and conductance (32C) directional elements as in compensated networks.

V. Modified Directional Elements for Low-Impedance-Grounded Systems With High Charging Capacitances

Distribution systems with underground cables or long overhead feeders have high charging capacitances. Ground fault currents may be detected using phase CTs. Traditional directional elements, such as 32V and 32I, are available for these systems. However, we will show in this section that 32V and 32I elements require modifications for application in these systems.

A. Modified 32V Element

In the previous section, we showed that in a high-resistance-grounded system, the measured zero-sequence impedance plots in the second quadrant of the impedance plane.

However, for systems with $3R_G < XC_{0S}$, the angle of $\overline{Z}_{0S}$ may be between –45 degrees and 0 degrees, causing the angle of the apparent impedance $-\overline{Z}_{0S}$ to be between 135 degrees and 180 degrees. The apparent impedance could fall below the forward-fault operating characteristic. Furthermore, for low-resistance-grounded systems, the zero-sequence reactance $\overline{Z}_{0T}$ of the transformer or grounding bank may cause the angle of $\overline{Z}_{0S}$ to become positive and the angle of the apparent impedance to be above 180 degrees (third quadrant of the impedance plane). We may disregard the effect of XC_{0S} in this case. Fig. 12 shows the variation of the measured zero-sequence impedance $-\overline{Z}_{0S}$ as the grounding resistance varies from zero to $3R_G = XC_{0S}$. We find a similar behavior in low-reactance-grounded systems.

The solution to this problem is to modify the 32V element. In the traditional 32V element, the maximum torque angle Z0MTA was implicitly set equal to the line zero-sequence impedance. The modification consists of converting Z0MTA into an independent relay setting. The maximum torque angle Z0MTA should be set between 0 degrees and –90 degrees. The forward and reverse thresholds Z0F and Z0R (see Fig. 6) should be set at 0.1 and –0.1 secondary ohms to bring the characteristic down to the origin of coordinates. The resulting characteristic (represented by the solid lines in Fig. 11b) is tilted to accommodate $-\overline{Z}_{0S}$ values corresponding to forward faults in systems with different R_G values.

Setting Z0MTA for a low-impedance-grounded system requires considering the effect of the transformer or grounding bank impedance $\overline{Z}_{0T}$. Later in this paper, we provide the methodology to set Z0MTA for the modified 32V element.

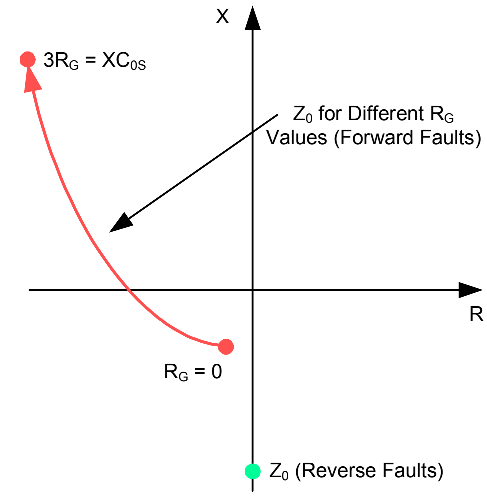

Fig. 12. The measured zero-sequence impedance $-\overline{Z}_{0S}$ moves from the third to the second quadrant of the impedance plane as the grounding resistance varies from zero to $3R_G = XC_{0S}$

B. Modified 32I Element

We may use a 32I element to detect ground faults in low-resistance-grounded systems. We select the grounding resistance current I_{0G} (see Fig. 10) as the polarizing current and the protected feeder current I_0 as the operating current for the 32I element. The torque calculation of the 32I element, as shown in (1), is positive when the angle difference between the polarizing and operating currents is less than 90 degrees. The torque is negative when this angle difference is greater than 90 degrees.

Fig. 13 shows the phasor diagram for the forward-fault condition represented in Fig. 10. In a low-resistance-grounded system, the angle between I_{0G} and I_0 is close to zero because the system capacitive current I_{0S} is very small as compared to I_{0G}. The 32I element torque calculation is positive for this forward fault.

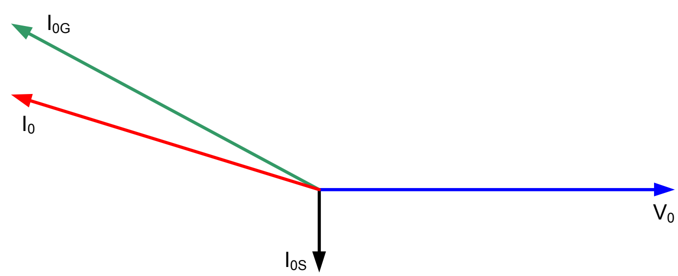

Fig. 13. Phasor diagram for the forward-fault condition in a low-resistance-grounded system (see Fig. 10)

Fig. 14 is the zero-sequence impedance diagram for a reverse ground fault on a resistance-grounded system. Fig. 15 shows the phasor diagram. The angle between I_{0G} and I_0 is less than 90 degrees, resulting in a positive torque value for this reverse fault. The 32I element fails to discriminate the out-of-section fault.

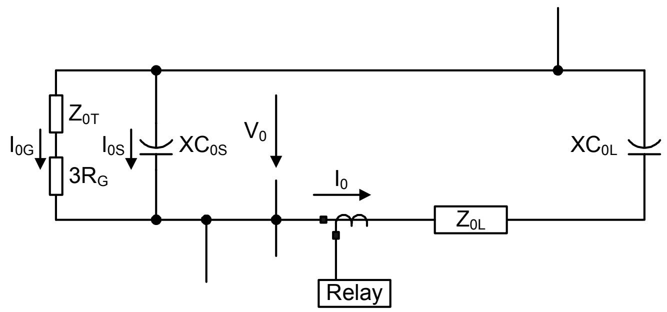

Fig. 14. Zero-sequence network for a reverse ground fault on a resistance-grounded system

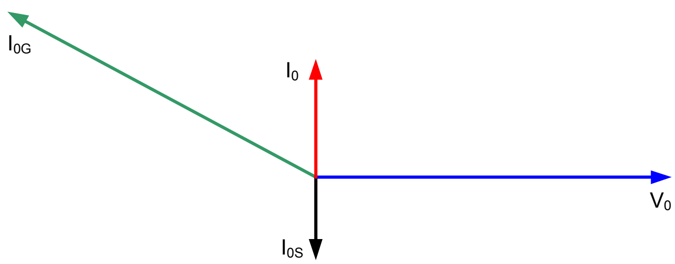

Fig. 15. Phasor diagram for the reverse-fault condition in a low-resistance-grounded system (see Fig. 14)

The solution to this problem is to use a modified 32I element. The modification consists of rotating the polarizing current counterclockwise in order to obtain an angle greater than 90 degrees for reverse faults. A new relay setting IMTA defines the angle rotation. Later in this paper, we provide the methodology to set IMTA for the modified 32I element.

VI. Analysis of a Practical Resistance-Grounded System

A. System Description

An Australian distribution utility (Powercor) uses a neutral resistor connected as shown in Fig. 1 on some 22 kV networks. An 8 Ω resistor limits the ground fault current to approximately 1600 A. Let us examine the behavior of the 32V and 32W elements in these low-resistance-grounded networks.

B. Modified 32V Element Setting and Operation

Fig. 16 and Fig. 17 are plots of the zero-sequence impedance measured by a feeder relay of the Powercor system for a forward fault obtained from digital simulation. To get more general results, we varied the grounding resistance R_G from 0 to 160 Ω. These figures show that the measured impedance moves from the third quadrant into the second quadrant as the grounding resistance increases. Fig. 17 shows that when R_G = 0, the 32V element measures the negative of the transformer impedance $-\overline{Z}_{0T}$.

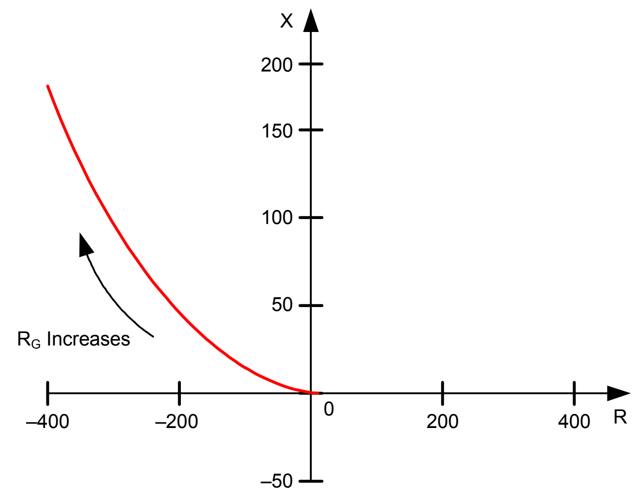

Fig. 16. Plot of the zero-sequence impedance for forward faults as the grounding resistance R_G varies from 0 to 160 Ω

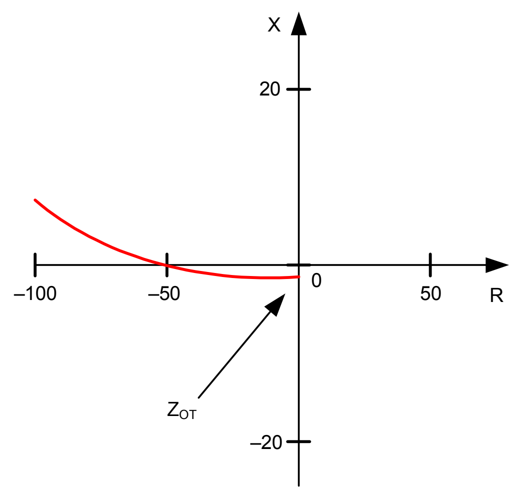

Fig. 17. Zoomed-in view of zero-sequence impedance plot to show that $Z_0 = Z_{0T}$ when $R_G = 0$

Superimposing on Fig. 17 a conventional 32V element characteristic with a Z0MTA setting of 45 degrees, we obtain Fig. 18. This figure shows that the conventional 32V element declares a reverse fault as a forward fault. The element correctly discriminates forward faults, except for very low R_G values, for which the measured impedance falls between both element characteristics.

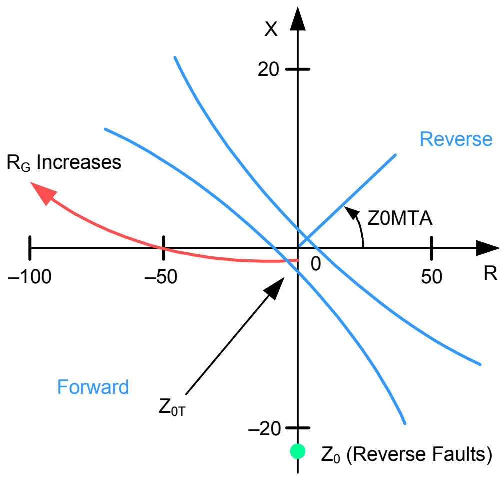

Fig. 18. The conventional 32V element fails to discriminate forward from reverse faults in low-impedance-grounded systems

As mentioned before, the solution to this problem is to rotate the characteristic clockwise, as shown in Fig. 19. This will lead to a correct directional element decision by this modified directional element polarized by zero-sequence voltage.

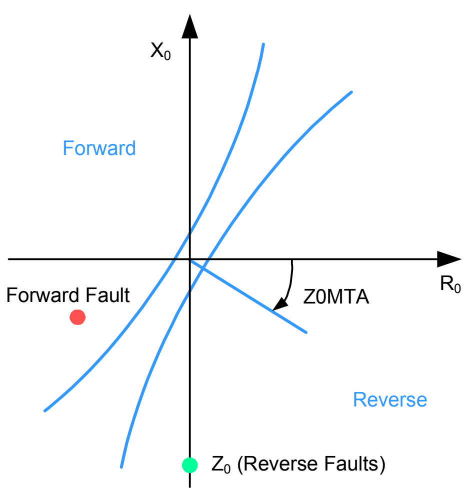

Fig. 19. Rotating the 32V element characteristic provides directional ground fault discrimination in low-impedance-grounded systems

Fig. 19 serves to illustrate the Z0MTA calculation methodology. The modified 32V element characteristic must lie between the $\overline{Z}_0$ values measured for forward and reverse faults. The forward fault is the critical condition to set the characteristic. In low-resistance-grounded systems, the angle of $\overline{Z}_0$ for forward faults depends on the values of R_G and $\overline{Z}_{0T}$. Considering the transformer or grounding bank to be purely inductive ($\overline{Z}_{0T} = X_{0T}$), the Z0MTA setting value is:

$$Z0MTA = \left(acot\left(\frac{3R_G}{X_{0T}} \right) + SFA \right) - 90° \quad (5)$$

where Z0MTA is the 32V element angle setting, R_G is the grounding resistance, X_{0T} is the transformer or grounding bank reactance, and SFA is an angle security factor with a typical value of 30 degrees.

As an example, the Powercor system has the following data:

Transformer:

$MVA_{TR} = 20$ MVA
$V_{TR} = 69/22$ kV
$X_{0T} = 10\%$

Grounding resistor:

$R_G = 8\ \Omega$

The X_{0T} value in ohms is:

$$X_{0T} = \frac{22^2}{20} \cdot 0.1 = j2.42\ \Omega$$

Hence:

$$\frac{3R_G}{X_{0T}} = \frac{24}{2.42} \approx 10$$

$$acot(10) = 5.7°$$

Taking SFA = 30°, from Equation (5) we get:

$$Z0MTA = (5.7° + 30°) - 90° = -55°$$

C. *Wattmetric Element Operation*

Another element to consider for directional discrimination in this system is the wattmetric element. This element uses (4) for the torque calculation.

Fig. 20 shows a plot of the zero-sequence active power as a function of the grounding resistance R_G for forward faults in the Australian system. After starting at zero for R_G = 0, the active power takes negative values indicating a forward fault as R_G grows to approximately 8 Ω. For higher R_G values, the reduction of the fault current makes the active power start reducing its value.

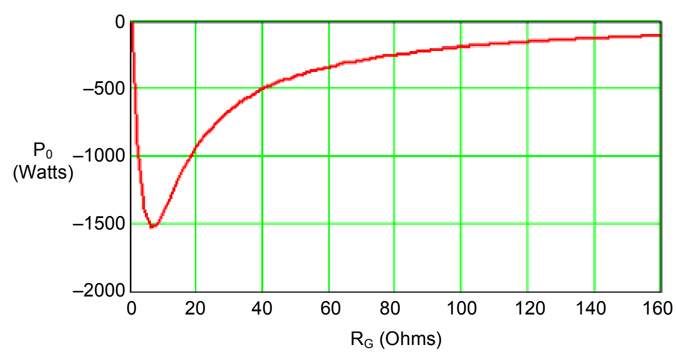

Fig. 20. Plot of the zero-sequence active power as a function of the grounding resistance R_G

Fig. 21 shows the wattmetric element torque calculation as a function of the grounding resistance. The torque is negative for all the simulated R_G values. The wattmetric element correctly discriminates forward faults.

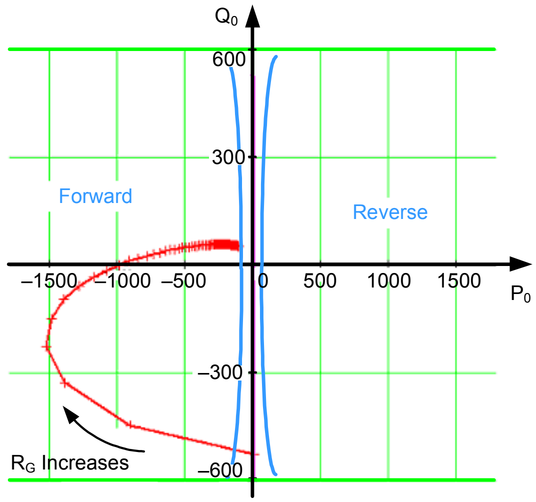

Fig. 21. Plot of the wattmetric element torque as a function of the grounding resistance R_G in the power plane

For reverse faults, the value of R_G does not affect the wattmetric calculation. For reverse faults, the zero-sequence current in the protected line is purely capacitive (if we ignore line insulation conductance). Hence, the calculated wattmetric element torque would be zero or a very small positive value resulting from the line conductance.

Fig. 22 is a plot of the zero-sequence current (in secondary amperes) for a reverse fault. This figure shows that R_G has very low effect on the zero-sequence current flowing in the feeder for reverse faults. We can conclude that the wattmetric element is reliable for detecting forward faults, but it may fail to detect reverse faults.

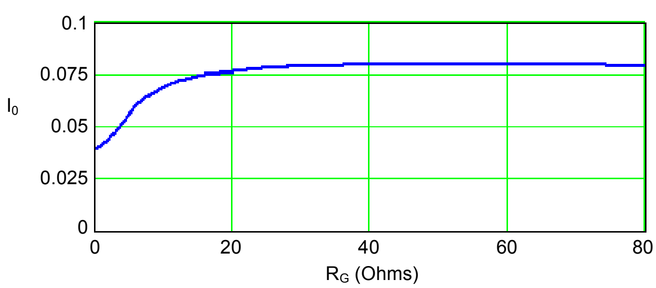

Fig. 22. Plot of zero-sequence current magnitude for a solid reverse fault as a function of the grounding resistance R_G

VII. Analysis of a System That Uses Grounding Transformers

For impedance-grounded systems, the current-polarized directional element 32I is also available. The 32I element is simple and reliable when the polarizing current comes from a reliable source and has a healthy magnitude. In this section, we study the Southern California Edison (SCE) distribution systems and outline the methodology to set IMTA for the modified 32I element.

A. SCE Distribution Systems

SCE had many 12 and 16 kV ungrounded networks [10], where grounding transformers were installed to facilitate ground fault detection. These networks are now impedance-grounded systems with impedance selected to satisfy ground fault detection requirements. Fig. 23 shows one type of SCE impedance-grounded distribution system. The grounding resistance R_G is inserted in the corner of the delta formed by the grounding bank secondary windings. A 600 V circuit breaker in series with the grounding resistor interrupts the ground current in the event of a sustained ground fault on a distribution line.

Traditional ground fault detection uses a voltage relay connected in parallel with the grounding resistor. At stations with only one line, the voltage relay trips the line. At stations with multiple lines, the voltage relay only alarms. Isolation of the faulted line is accomplished by manually opening each line until the fault disappears. Looped lines have to be opened at the receiving station to facilitate the fault-finding process. Some stations are equipped with a voltmeter calibrated to provide an indication of the fault resistance.

Small grounding banks are potentially susceptible of ferroresonance with the delta circuit breaker open due to the magnetizing reactance of the grounding transformers in parallel with the system line-to-ground capacitance. De-energizing a grounded line or a piece of equipment while the delta circuit breaker is open can trigger ferroresonance. The resistor R_F on the delta circuit damps out ferroresonance. During a ferroresonant condition, the grounding bank secondary voltage is approximately the same as the voltage during a ground fault. The frequency, however, is approximately 30 Hz. An underfrequency relay (not shown in Fig. 23) is used to detect a ferroresonant condition and close the delta breaker.

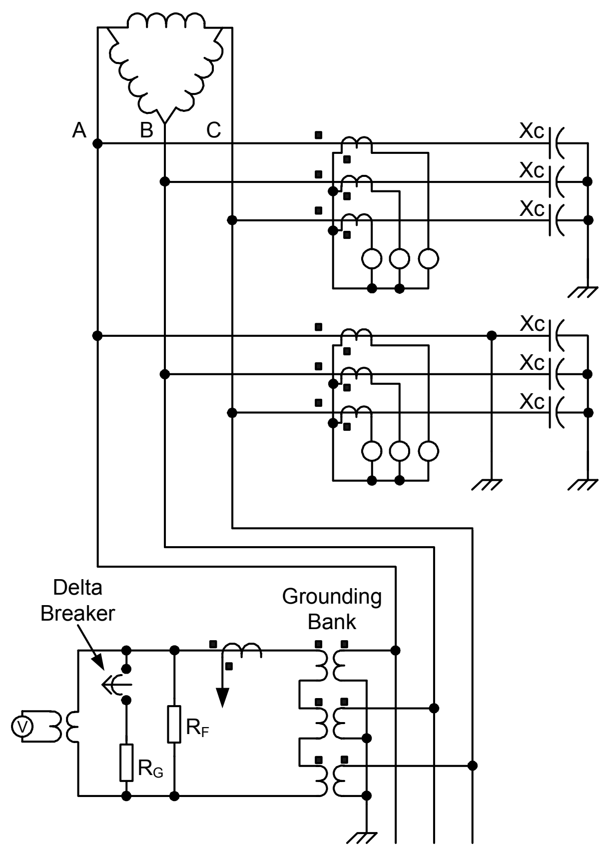

Fig. 23. One type of SCE impedance-grounded distribution system

SCE uses two sizes of grounding transformers. In the "Sensitive Ground System" configuration, a grounding bank consisting of three 5 or 10 kVA distribution transformers provides system grounding. A neutral grounding transformer may also be provided instead of the grounding bank. This type of grounding provides a maximum fault current of 30 to 60 A to a ground fault without fault resistance. The Sensitive Ground System configuration uses the grounding resistor R_G in the corner of the secondary delta as shown in Fig. 23. In these systems, the primary grounding bank current for a ground fault will lag the faulted phase voltage by about 30 to 45 degrees.

In the "Standard Low Ground System" configuration, a grounding bank of three 37.5 kVA distribution transformers is applied to the station bus and provides up to 150 A of primary ground fault current. There is no grounding resistor ($R_G = 0$), so the system is grounded through the grounding bank zero-sequence impedance. During a single-line-to-ground fault, the grounding bank current is at a lagging angle of about 75 degrees.

B. Ground Fault Protection With 32I Element

SCE distribution systems use directional ground relays to detect and trip the faulted line. Polarizing current is derived from the delta current during a fault, and operating current is derived from the line CT residual current. The installations do not have voltage transformers.

Fig. 24 shows the zero-sequence network for a ground fault on the system of Fig. 23. In the diagram, we assume only two feeders are connected to the station bus. For systems having more than two feeders, we can lump all unfaulted lines into the one shown in Fig. 24 without affecting our analysis otherwise. The zero-sequence network neglects the line impedance because the line capacitive charging reactance is much larger than the line impedance. In Fig. 24, I_0 is the zero-sequence current measured by the relay on the faulted feeder, I_{0S} is the line charging current of all unfaulted lines, and I_{0G} is the grounding bank current.

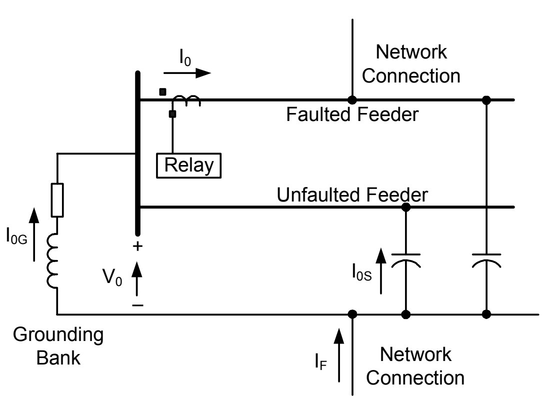

Fig. 24. Zero-sequence network for a ground fault on SCE systems

Given that $\bar{I}_{0S}$ lags the zero-sequence voltage $\bar{V}_0$ by 90 degrees, $\bar{I}_{0G}$ lags the faulted phase voltage, and $\bar{I}_0 = \left(\bar{I}_{0G} + \bar{I}_{0S}\right)$, we can draw the phasor diagram shown in Fig. 25 for an A-phase-to-ground fault.

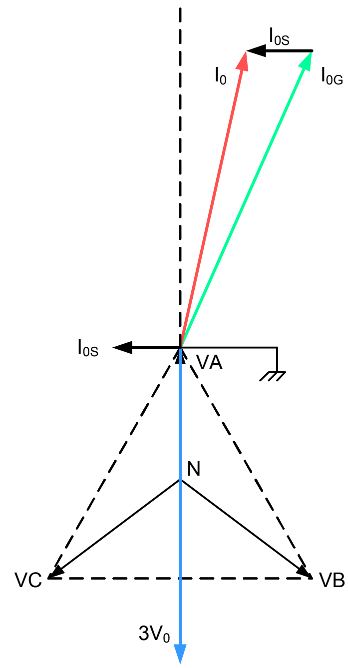

Fig. 25. Phasor diagram for a ground fault on SCE systems

Fig. 26 shows the torque calculations according to (1) for the 32I elements of the faulted and unfaulted lines. The elements use $\bar{I}_{0G}$ as the polarizing current, and the measured line zero-sequence current ($\bar{I}_0$ or $\bar{I}_{0S}$) as the operating current. We use $\bar{I}_{0G}$ current as the reference phasor in Fig. 26. Notice that the unfaulted line relay measures $\bar{I}_{0S}$ as a negative current because it flows towards the bus for this reverse fault. Since the operating currents $\bar{I}_0$ and $-\bar{I}_{0S}$ are less than 90 degrees with respect to the reference current $\bar{I}_{0G}$, the 32I torques for the faulted line ($T32I_F$) and for the unfaulted line ($T32I_U$) are positive. The sign of the 32I element calculation does not differentiate the fault direction for this system. It may seem that the magnitudes of calculated torques may provide indication of the fault direction. However, as the fault resistance increases, the torque magnitude for unfaulted feeders can become larger than that of the faulted feeder.

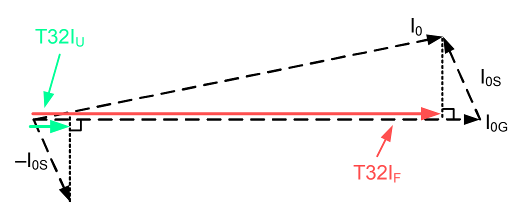

Fig. 26. Torque calculations of the traditional 32I element

A solution to this problem is to add an angle adjustment to the polarizing current. Fig. 27 shows that the polarizing current $\bar{I}_{0G}$ is rotated counterclockwise by a torque adjustment angle, IMTA. Using the rotated $\bar{I}_{0G}$ as a reference, the torque calculation for the faulted feeder is positive, and negative for the unfaulted feeders.

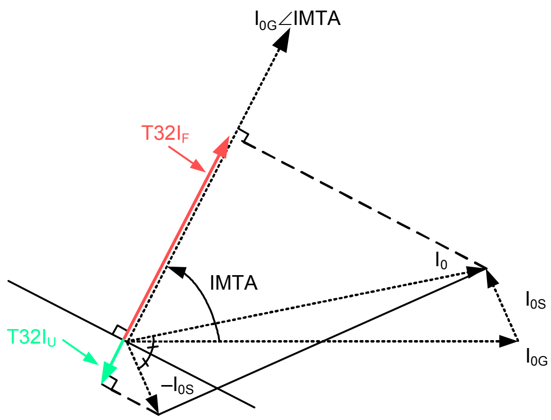

Fig. 27. Torque calculations of the modified 32I element

Fig. 27 shows that selecting the torque adjustment angle, IMTA, requires first determining the line that bisects the angle between $\bar{I}_0$ and $-\bar{I}_{0S}$. The perpendicular to the bisecting line is the desired position for the rotated $\bar{I}_{0G}$. Hence, IMTA is the angle between this perpendicular line and $\bar{I}_{0G}$, and is given by:

$$\text{IMTA} = 90° + \frac{\angle I_0 + \angle -I_{0S}}{2} - \angle I_{0G} \tag{6}$$

Equation (6) depends on two major factors, the total charging current from all unfaulted lines, $\bar{I}_{0S}$, and the zero-sequence current in the grounding bank, $\bar{I}_{0G}$. While $\bar{I}_{0S}$ is constant for a given system, the fault resistance affects $\bar{I}_{0G}$.

Fig. 28 is a simplified logic diagram for the modified 32I directional element. In addition to the torque adjustment angle IMTA discussed previously, there is a magnitude relationship check between the operating and polarizing currents. The logic shows that $3I_0$ has to be K_0 percentage of the polarizing current I_{0G} before the 32I element is allowed to operate. The current condition check assists in discriminating faults from error currents caused by mismatched phase CTs and therefore adds another level of security to the directional element.

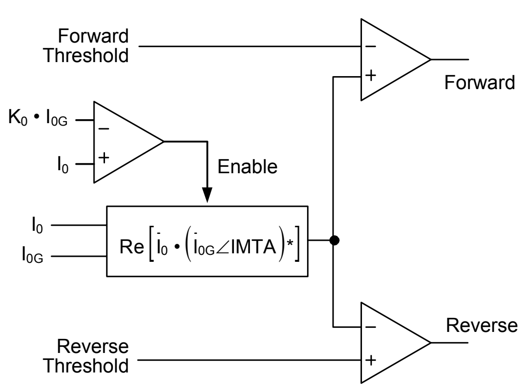

Fig. 28. Simplified logic diagram of the modified 32I directional element

In the following example, we use the parameters of a typical SCE Sensitive Ground System to illustrate how to determine the IMTA value.

Grounding transformer data:

MVA_{TR} = 0.01 MVA
V_{TR} = 12000/120 V
Z_{TR} = 2.5%
X/R ratio = 0.7
Grounding resistor: $R_G = 0$
Ferroresonance resistor: $R_F = 9.6\ \Omega$

Feeder data:

Total unfaulted-feeder length = 40 miles
Total unfaulted-feeder ground charging current = 4 A
Feeder leakage conductance = one tenth of feeder charging susceptance
Positive- and negative-sequence line impedance: $Z_1 = Z_2 = 0.8\ \angle 80°\ \Omega$ per mile
Zero-sequence line impedance: $Z_0 = 2.8\ \angle 70°\ \Omega$ per mile

Determining IMTA angle setting:

Grounding bank impedance = 360 $\angle 35°\ \Omega$
Grounding bank I_{0G} for a close-in fault:

$$I_{0G} = \frac{12000/\sqrt{3}}{360\angle 35°} = 19.25\angle -35°$$

$$I_{0S} = \frac{4}{3}\angle 90°$$

$$I_0 = I_{0G} + I_{0S} = 18.51\angle -31.62°$$

$$\text{IMTA} = 90° + \frac{-90° - 31.62°}{2} - (-35°) = 64.19°$$

C. Modified 32V Element Operation

When polarizing zero-sequence voltage is available, the modified 32V element is applicable for the SCE systems. Without a direct broken-delta residual voltage measurement, we can use a current-to-voltage transducer to convert the secondary delta current of the grounding bank into the required polarizing voltage. The traditional 32V element needs a phase shifter circuit to compensate the angle of the polarizing voltage for the grounding bank angle shift. With the modified 32V element introduced in Section V, we can set the Z0MTA to compensate the angle shift introduced by the grounding bank.

Fig. 29 shows the z_0 calculation of the traditional 32V element of (3), with Z0MTA set equal to the zero-sequence line impedance angle, which is close to 90 degrees. We see that both faulted and unfaulted feeders declare this fault as a forward fault because of the negative value of z_0. After the delta breaker opens, the system is close to an ungrounded system, and the traditional 32V element at the faulted feeder also makes an incorrect declaration of a reverse fault.

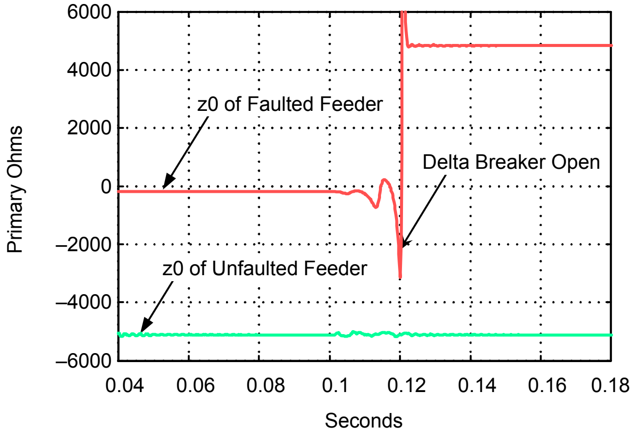

Fig. 29. Traditional 32V performance on SCE systems

Using the previous system parameters, we calculate the Z0MTA angle for the SCE system as follows:

$$\text{Z0MTA} = (35° + 30°) - 90° = -25°$$

Fig. 30 shows the behavior of the modified 32V element with Z0MTA = –25°. The modified 32V element is reliable both before and after the delta breaker is opened.

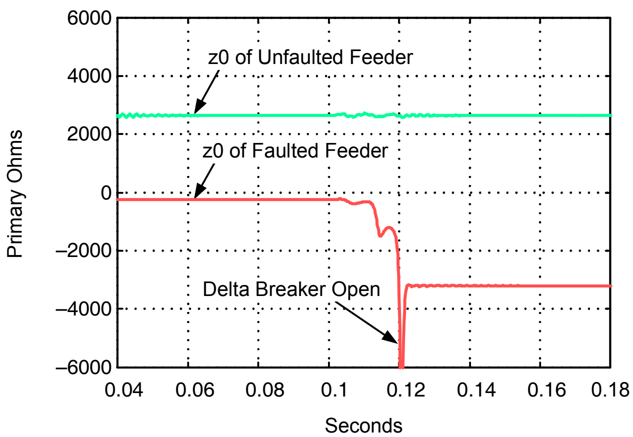

Fig. 30. Modified 32V performance on SCE systems

D. Wattmetric Element Operation

The wattmetric element also applies to the SCE distribution systems. Fig. 31 shows the wattmetric element calculation for the system parameters given previously. Before the delta breaker is opened, the faulted feeder element has a large negative wattmetric calculation indicating a forward fault. The system is close to an ungrounded system after the delta breaker opens. The sign of the wattmetric calculation as shown in Fig. 31 still indicates correct fault direction discrimination for both faulted and healthy feeders. However, phase CT mismatch errors (not included in this simulation) may affect the wattmetric element calculation, and a flux-summing CT is strongly recommended for a reliable result from the wattmetric directional element.

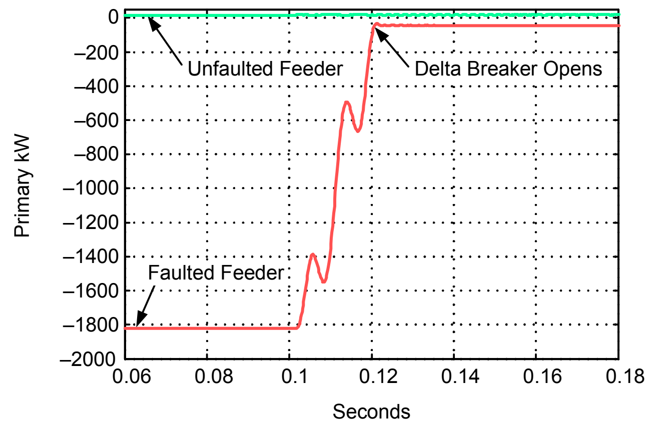

Fig. 31. Wattmetric element performance on SCE systems

VIII. Recommendation of Directional Elements for Impedance-Grounded Systems

Table III summarizes available and recommended ground directional elements for systems with various grounding methods. For effectively and low-impedance-grounded systems, use the best choice ground directional element, which automatically selects the optimal directional element, 32I, 32Q, or 32V, for each particular system configuration and ground fault condition.

For low-impedance-grounded systems with high charging capacitance, use the modified 32V or 32I elements, depending upon the availability of either zero-sequence voltage or current for element polarization.

For compensated systems and high-resistance-grounded systems, use a combination of the wattmetric (32W) and the incremental conductance (32C) elements. The 32W element provides reliable detection of low-resistance faults up to about 10 kΩ. The 32C element adds the sensitivity required to detect very high-resistance faults [3].

Finally, for isolated neutral systems, use the 32U element.

TABLE III
SUMMARY OF GROUND DIRECTIONAL ELEMENTS

System Grounding Method	Sensitive Current Input Required	Available Directional Elements	Recommended Directional Element
Effective and Low-Impedance Grounding	No	32I, 32Q, 32V	Best Choice Ground Directional Element
Low-Impedance Grounding With High Charging Capacitance	No	32V, 32I	32V or 32I
High-Resistance Grounding	Yes	32I, 32V, 32W, 32C	Combination of 32W and 32C
Resonant Grounding	Yes	32W, 32C	Combination of 32W and 32C
Isolated Neutral	Yes	32U, 32W, 32C	32U

Legend:
32I: Zero-Sequence Current-Polarized Directional Element
32Q: Negative-Sequence Voltage-Polarized Directional Element
32V: Zero-Sequence Voltage-Polarized Directional Element
32U: Zero-Sequence Element for Ungrounded Systems
32W: Wattmetric Directional Element
32C: Incremental Conductance Element

Table IV, adapted from [3], shows the basic CT and VT requirements for ground directional elements. Carefully select phase CTs to avoid false negative- and zero-sequence currents for three-phase faults [11] in the application of 32I, 32Q, and 32V elements. Use flux-summing CTs to provide zero-sequence current information to 32U, 32W, and 32C elements. Use Class 2 VTs or better in all ground directional element applications [11].

TABLE IV
CT AND VT REQUIREMENTS FOR GROUND DIRECTIONAL ELEMENTS FOR DISTRIBUTION SYSTEMS

Element	CT Requirements	VT Requirements
32I, 32Q, 32V	Select phase CTs to minimize saturation	Class 2 VTs or better recommended
32U, 32W, 32C	Flux-summing CTs recommended	Class 2 VTs or better recommended

IX. CONCLUSIONS

Utility distribution companies prefer effectively grounded systems, except in Europe, where compensated networks are widely used. There are also applications of low-impedance grounding and isolated neutral in utility networks.

Low-impedance grounding is generally preferred in industrial medium-voltage systems. There are also systems with effective grounding, high-resistance grounding, and isolated neutral.

Ground directional elements are required in looped systems and also in impedance-grounded radial systems. Detecting high-resistance faults requires ground directional elements even in low-impedance-grounded systems.

Modified zero-sequence voltage-polarized (32V) and current-polarized (32I) directional elements provide selective ground fault detection in low-impedance-grounded radial systems with high charging capacitance. The modification consists of having a settable maximum torque angle.

We recommend the following application guidelines for ground directional elements:

- For effectively and low-impedance-grounded systems, use the best choice directional element, which automatically selects the best directional element for each system configuration and fault condition.
- For low-impedance-grounded systems with high charging capacitance, use the modified 32V or 32I elements, depending on the availability of voltage or current for polarization.
- For compensated and high-resistance-grounded systems, use a combination of the wattmetric (32W) and incremental conductance (32C) elements.
- For ungrounded systems, use the 32U element.

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XI. Biographies

Ronald A. Lavorin received an MSEE from California State University at Los Angeles. He joined Southern California Edison (SCE) in 1970. He has managed several groups at SCE including Relay Technicians and Maintenance Electricians, Transmission Engineering, Civil Engineering, Apparatus Engineering, and recently Protection and Automation Engineering. He has served as Chair of the IEEE Metro Los Angeles chapter from 2005 to 2007. He has been a registered professional engineer in the state of California since 1975.

Daqing Hou received B.S. and M.S. degrees in Electrical Engineering at the Northeast University, China, in 1981 and 1984, respectively. He received his Ph.D. in Electrical and Computer Engineering at Washington State University in 1991. Since 1990, he has been with Schweitzer Engineering Laboratories, Inc., Pullman, Washington, USA, where he has held numerous positions including development engineer, application engineer, and R&D manager. He is currently a principal research engineer. His work includes system modeling, simulation, and signal processing for power systems and digital protective relays. His research interests include multivariable linear systems, system identification, and signal processing. He holds multiple patents and has authored or coauthored many technical papers. He is a Senior Member of IEEE.

Héctor J. Altuve received his BSEE degree in 1969 from the Central University of Las Villas, Santa Clara, Cuba, and his Ph.D. in 1981 from Kiev Polytechnic Institute, Kiev, Ukraine. From 1969 until 1993, Dr. Altuve served on the faculty of the Electrical Engineering School, at the Central University of Las Villas. He served as professor, Graduate Doctoral Program, Mechanical and Electrical Engineering School, at the Autonomous University of Nuevo León, Monterrey, Mexico, from 1993 to 2000. In 1999–2000, he was the Schweitzer Visiting Professor at Washington State University's Department of Electrical Engineering. In January 2001, Dr. Altuve joined Schweitzer Engineering Laboratories, Inc., where he is currently a Distinguished Engineer and Director of Technology for Latin America. He has authored and coauthored more than 100 technical papers and holds three patents. His main research interests are in power system protection, control and monitoring. Dr. Altuve is an IEEE Senior Member, and a PES Distinguished Lecturer.

Normann Fischer received a Higher Diploma in Technology, with honors, from Witwatersrand Technikon, Johannesburg in 1988, a BSc in Electrical Engineering, with honors, from the University of Cape Town in 1993, and an MSEE from the University of Idaho in 2005. He joined Eskom as a protection technician in 1984 and was a senior design engineer in Eskom's Protection Design Department for three years. He then joined IST Energy as a senior design engineer in 1996. In 1999, he joined Schweitzer Engineering Laboratories, Inc. as a power engineer in the Research and Development Division. He was a registered professional engineer in South Africa and a member of the South Africa Institute of Electrical Engineers.

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 Schweitzer Engineering Laboratories, Inc. as an International Field Application Engineer. Mr. Calero has authored technical papers for IEEE and protective relay conferences and has authored four patents in the field of protective relaying. Mr. Calero is a registered professional engineer in the state of Florida.

20070905 • TP6290-01