

# Application Considerations for Distance Relays on Impedance-Grounded Systems

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**Abstract**—Widespread use of digital distance relays has increased the application of distance protection to lower voltages, including subtransmission and distribution circuits. Many systems may be impedance grounded. In this paper, we look at some unique problems that may arise on single-source, distribution systems, such as might occur at the 26-kV voltage level. A source of concern for distance relays on these systems is the inclusion of a current-limiting impedance in the neutral of the source transformer. The voltage drop across this impedance during fault conditions affects the voltages seen by the relay and may affect the polarizing voltage used by the distance relay. We will explain the problem and offer solutions that will allow the application of distance elements.

## I. INTRODUCTION

Microprocessor-based relays have made the installation and maintenance of protection schemes safer and more cost effective. The low-cost and multifunction capability of digital distance relays has broadened the use of distance-based schemes. Applications that would normally use directional-overcurrent relays now use distance relays for faster clearing times, improved security and better selectivity. The widespread use of digital distance relays has increased the application of distance protection to lower voltages, including distribution circuits. Many systems may be impedance grounded instead of solidly grounded. We look at some unique problems relative to single-source, distribution systems that might occur at the 26-kV voltage level.

Distance relays are normally applied in a step-distance scheme at this voltage level. A source of problems for distance relays on these systems is the inclusion of a current-limiting impedance in the neutral of the source transformer. The voltage drop across this impedance during fault conditions affects the voltages seen by the relay on the unfaulted phases. This may also affect the polarizing voltage used by the distance relay. In this paper, we will explain the problem and offer solutions that will allow the application of distance elements. Different polarizing voltages and techniques will be reviewed, such as self-polarized, memory voltage, and positive-sequence voltage.

## II. 26-KV DISTRIBUTION SYSTEM

A typical 26-kV distribution circuit is shown in Fig. 1. The only source on the 26-kV circuit is on the Bergen bus and consists of three wye-delta-wye 75 MVA, 138-kV-to-26-kV transformers with the three 26-kV transformer neutrals connected in parallel to an 8-ohm current-limiting grounding resistor. The 13.8-kV delta tertiary is unloaded. The resistors

are used primarily to limit the fault current to an acceptable  $I^2T$  level based on long-standing agreements with the phone company that shares the utility poles with the distribution circuits. One additional benefit is in the breaker interrupting duty. Public Service Electric and Gas Company (PSE&G) has been able to avoid large-scale breaker replacement programs because of the current-limiting resistors. Since the entire customer loading on the 26-kV system is connected phase-to-phase, the grounding resistor provides an additional benefit by reducing the voltage drop seen by the customers for single line-to-ground faults on the 26-kV system. This is shown in Fig. 2.

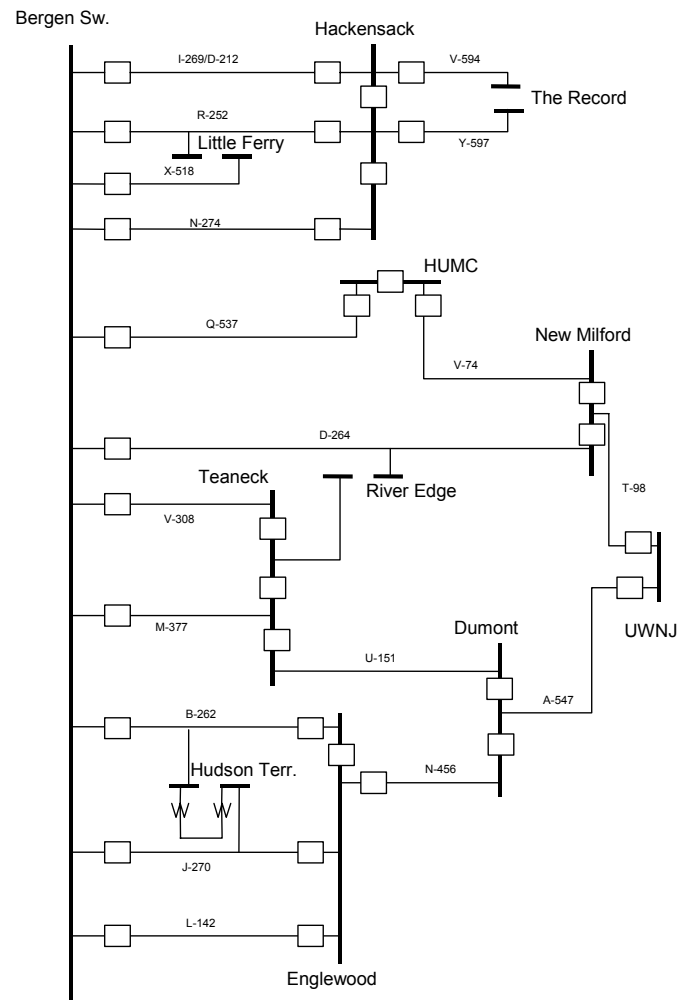


Fig. 1. Portion of the Bergen 26-kV Distribution Network

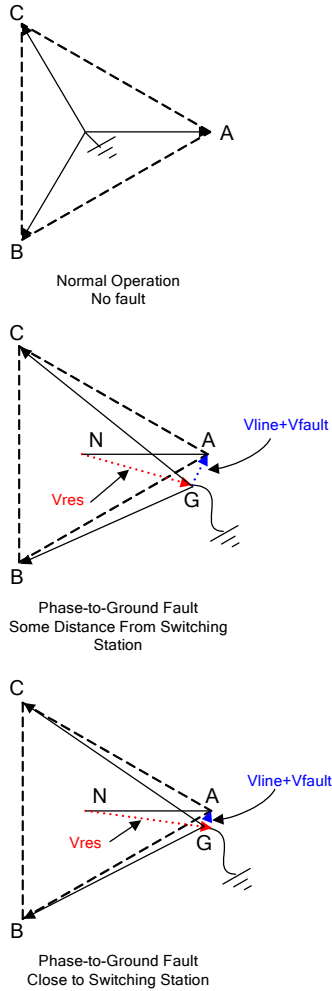


Fig. 2 Typical System Voltage

PSE&G will be operating the 26-kV system with a grounding resistor for the foreseeable future for the reasons cited above, plus the fact that the existing line relaying was selected for use with the ground resistor in place. Also, converting to a solidly grounded system would require a large-scale investment in relaying systems and circuits.

The original protection on this 26-kV system consisted of electromechanical relays employing phase distance and ground directional-overcurrent protection. The ground directional-overcurrent protection typically performs as designed. However, since the 26-kV networks contain many lines (see Fig. 1) that are fed from a single-source station, ground overcurrent relay coordination is challenging. To maintain good coordination, in some cases the relays might be set to trip with a delay as long as five seconds. In an effort to improve the overall speed of fault clearing, the existing protection systems are being augmented with microprocessor-based relays with ground impedance elements. Overall, about 75% of the protection is still electromechanical, but on the Bergen system (Fig. 1), about 75% has been upgraded to digital relaying.

### III. DISTANCE RELAY DESIGN

The design of distance relays has been discussed in numerous papers [1], [2]. These papers have concentrated on the application of distance relays to solidly grounded transmission and distribution systems. The techniques used to create and improve the phase- and ground-distance elements are similarly based on solidly grounded systems. Many improvements involve the design of the polarizing voltage used in the distance measurement [1]. In this paper, we will evaluate some of these choices with a specific view to a single-source system with resistance grounding. For the initial evaluation, we will use a generic phase angle comparator ground distance element.

The operating signal for the Phase A element is:

$$I \cdot Z - V = (I_A + 3 \cdot K_0 \cdot I_0) \cdot Z_G - V_A \quad (1)$$

where:

$I_A$  is the phase current

$I_0$  is the zero-sequence current

$V_A$  is the Phase A-to-ground voltage

$Z_G$  is the relay reach setting

$K_0$  is the zero-sequence current compensation factor equal to  $(Z_0 - Z_1) / (3 \cdot Z_1)$

Three possible polarizing voltages will be considered:

- $V_{mem}$  is the memory voltage equal to the pre-fault voltage
- $V_1$  is the measured positive-sequence voltage during the fault
- $V_A$  is the Phase A-to-ground voltage during the fault

The phase angle comparator distance element will operate when the angle between the operating and polarizing signals are within  $\pm 90$  degrees.

### IV. GROUND MHO DISTANCE EVALUATION

For the initial evaluation, the system of Fig. 1 was simplified, as shown in Fig. 3.

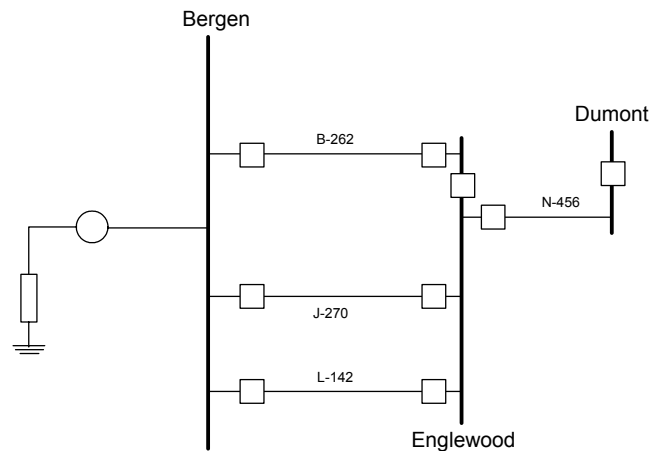


Fig. 3 Simplified System

An A-to-ground fault was applied on the Dumont bus of Fig. 3, and the response of the ground distance relay on the N-456 line at Englewood was analyzed. The results are shown in Table I.

TABLE I  
AG FAULT ON DUMONT BUS—SIMPLIFIED SYSTEM

VA	6.2 kV @ 31.2°
VB	18.5 kV @ -151.9°
VC	24.1 kV @ 132.8°
IA	1180 A @ -34.7°
IB	0
IC	0
V1	14.6 kV @ -1.6°
V <sub>mem</sub>	15.2 kV @ 0°

The operating and polarizing signal angles for the simple distance element with a reach of 120% of the line impedance are shown in Table II.

TABLE II  
ZONE 2 GROUND MHO

IZ-V Angle	VPOL Signal	VPOL Angle	Difference Angle
33.5°	Prefault Memory	0°	33.5°
33.5°	Fault V1	-1.6°	35.1°
33.5°	Fault VA	31.2°	2.3°

The distance element will operate if the angular difference between the IZ-V and VPOL angles is  $\pm 90$  electrical degrees or less. Zone 2 would operate for all three polarizing voltage signals, but it can be seen that the memory and positive sequence polarizing signals are farther away from the operate than the faulted phase voltage. For comparison purposes, the same fault study was performed with the current limiting resistor shorted. The resulting operating and polarizing angles are shown in Table III.

TABLE III  
ZONE 2 GROUND MHO—WITHOUT RESISTOR

IZ-V Angle	VPOL Signal	VPOL Angle	Difference Angle
-2.3°	Prefault Memory	0°	2.3°
-2.3°	Fault V1	-0.7°	1.6°
-2.3°	Fault VA	-4.5°	2.2°

As expected, when the current limiting resistor was shorted, all three polarizing signals were essentially in phase with the operating signal.

An AG fault was also applied on the Dumont bus using the full system of Fig. 1. The results are shown in Table IV and Table V.

TABLE IV  
AG FAULT ON DUMONT BUS—FULL SYSTEM

VA	3.5 kV @ 51.8°
VB	22.1 kV @ -155.7°
VC	26.5 kV @ 139.3°
IA	671 A @ -15.5°
IB	18 A @ 114.2°
IC	18 A @ 114.2°
V1	15.0 kV @ -1.8°
V <sub>mem</sub>	15.2 kV @ 0°

TABLE V  
ZONE 2 GROUND MHO

IZ-V Angle	VPOL Signal	VPOL Angle	Difference Angle
54.4°	Prefault Memory	0°	54.4°
54.4°	Fault V1	-1.8°	56.2°
54.4°	Fault VA	51.8°	2.6°

When the fault was applied on the full system of Fig. 1, the angle between the operating and memory and V1 polarizing signals increased by approximately 20 degrees as compared to the simplified system results in Table I, which furthers the likelihood that the ground distance element may fail to operate for a fault that is theoretically within its reach setting.

A Phase A-to-ground fault was applied on the Englewood bus, and the response of the Zone 1 ground distance element with a reach of 85% of the line impedance on line N-456 at Dumont was evaluated. The results are shown in Table VI and Table VII.

TABLE VI  
AG FAULT ON ENGLEWOOD BUS—FULL SYSTEM

VA	1.6 kV @ 61.7°
VB	23.9 kV @ -154.7°
VC	27.0 kV @ 143.2°
IA	305 A @ -6.5°
IB	11 A @ 93°
IC	11 A @ 93°
V1	15.1 kV @ -2.0°
V <sub>mem</sub>	15.2 kV @ 0°

TABLE VII  
ZONE 1 GROUND MHO

IZ-V Angle	VPOL Signal	VPOL Angle	Difference Angle
-120.9°	Prefault Memory	0°	120.9°
-120.9°	Fault V1	-2.0°	118.9°
-120.9°	Fault VA	61.7°	182.6°

Note that the prefault memory voltage and the positive sequence voltage during the fault were shifted approximately 60 degrees from the IZ-V operate signal. An additional 30-degree shift would cause the Zone 1 to overreach for this fault. The faulted phase polarizing voltage is approximately

180 degrees out of phase with the operating signal and is very secure for this fault. The IZ-V angles in Table VIII are approximately 180 degrees from those in Table V because this was an external fault to the Zone 1, but internal for Zone 2.

#### V. GROUND QUADRILATERAL DISTANCE EVALUATION

The same faults were used to evaluate the operation of a ground quadrilateral element using  $I_A \cdot X$ ,  $I_2 \cdot X$ , and  $I_0 \cdot X$  as the polarizing signal, where  $X = 1 @ 90$  degrees. The results are shown in Table VIII–Table X.

TABLE VIII  
ZONE 2 QUADRILATERAL, AG ON DUMONT BUS—SIMPLIFIED SYSTEM

IZ-V Angle	POL Signal	POL Angle	Difference Angle
33.5°	$I_A \cdot X$	55.3°	21.8°
33.5°	$I_2 \cdot X$	55.3°	21.8°
33.5°	$I_0 \cdot X$	55.3°	21.8°

TABLE IX  
ZONE 2 QUADRILATERAL, AG ON DUMONT BUS—SIMPLIFIED SYSTEM  
RESISTOR SHORTED

IZ-V Angle	POL Signal	POL Angle	Difference Angle
-2.3°	$I_A \cdot X$	19.6°	21.8°
-2.3°	$I_2 \cdot X$	19.6°	21.8°
-2.3°	$I_0 \cdot X$	19.6°	21.8°

TABLE X  
ZONE 2 QUADRILATERAL, AG ON DUMONT BUS—FULL SYSTEM

IZ-V Angle	POL Signal	POL Angle	Difference Angle
54.4°	$I_A \cdot X$	74.5°	20.0°
54.4°	$I_2 \cdot X$	76.9°	18.9°
54.4°	$I_0 \cdot X$	73.3°	22.5°

These results show that the ground quadrilateral element was virtually unaffected by the presence of the current-limiting grounding resistor. While many older electromechanical relays use the phase current to polarize the reactance characteristic, this has been shown to be problematic [2]. Many modern microprocessor-based relays offer either zero- or negative-sequence polarizing, or in some cases allow a user selection.

The response of the Zone 1 ground reactance element at Dumont for the AG fault on the Englewood bus is shown in Table XI.

TABLE XI  
ZONE 1 GROUND QUADRILATERAL

IZ-V Angle	POL Signal	POL Angle	Difference Angle
-120.9°	$I_A \cdot X$	83.5°	155.6°
-120.9°	$I_2 \cdot X$	81.5°	157.6°
-120.9°	$I_0 \cdot X$	87.5°	151.6°

The Zone 1 ground reactance element was secure for the external fault on the remote bus. This was an improvement over the ground mho elements previously evaluated.

#### VI. RELAY PERFORMANCE ON SYSTEM FAULTS

On June 24, 2005, a Phase C-to-ground fault occurred on line J-270 close to the Bergen bus. A simplified diagram of this area of the 26.4 kV system is shown in Fig. 4. During this fault, the relay at the Dumont terminal of the Dumont–Englewood line N-456 unexpectedly tripped via Zone 1 ground distance element.

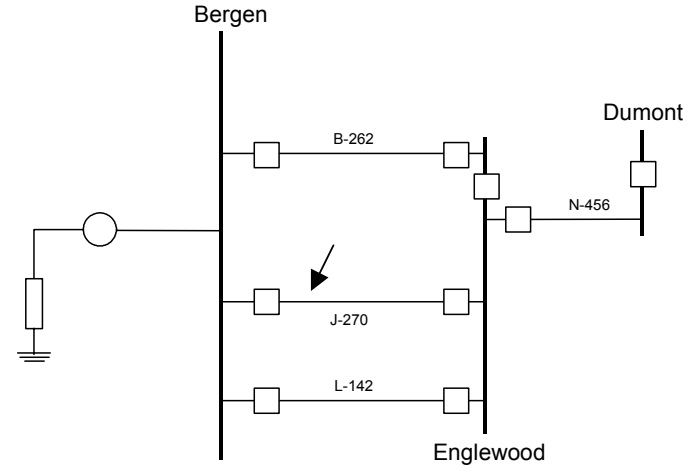


Fig. 4 Fault Location on Simplified 26.4-kV System Diagram

The oscillographic data captured by the DFR at Bergen is shown in Fig. 5.

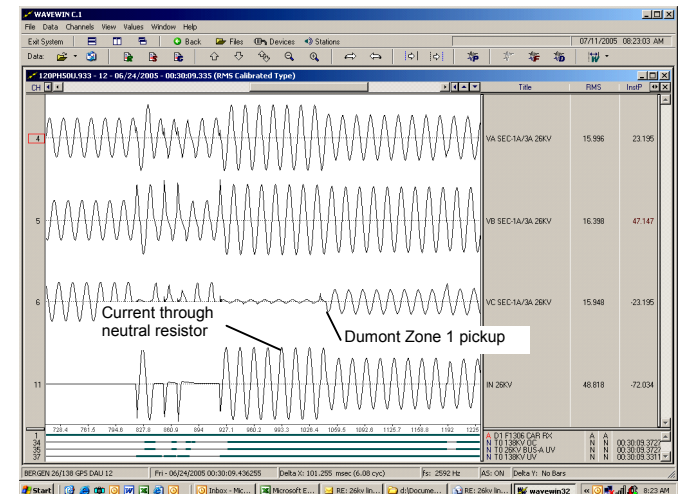


Fig. 5 Bergen DFR Record

Initially there was arcing on Phase C. This was followed by a Phase C-to-ground fault on line J-270 close to Bergen. When the Bergen breaker opened, the Phase C voltage increased. After the breaker opened, the Zone 1 ground distance relay at the Dumont terminal of the Englewood–Dumont line tripped.

The oscillographic data captured by the relay at Dumont is shown in Fig. 6.

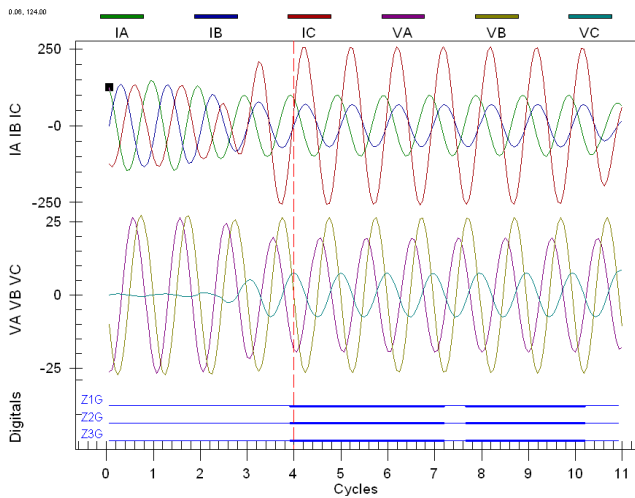


Fig. 6 Oscillographic Data

Initial analysis of the current and voltage shown in Fig. 6 reveals some anomalies. In the initial cycles of the event file, the currents were essentially balanced, but Phase C voltage was very low. A plot of the voltage and current phasors at 1.5 cycles into the event is shown in Fig. 7. This shows that the Phases A and B-to-ground voltages were approximately equal to the rated phase-to-phase system voltage. The initial data in the event file is not pre-fault data, but rather the current and voltage seen by the Dumont N-456 relay for the remote Phase C-to-ground fault. The neutral grounding resistor performed its intended function of reducing the effect of the single line-to-ground fault on the delta-connected customer loads by providing generally balanced phase-to-phase voltages.

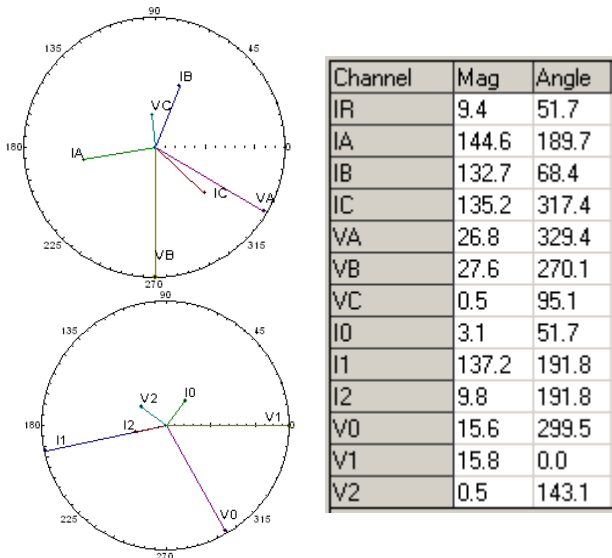


Fig. 7 Phasors at cycle 1.5

However, even though the magnitude of the phase-to-phase voltages was essentially maintained during the fault, there were angular shifts. For a zero voltage fault, one would expect VA and VA1 to remain in phase, and to be at approximately zero degrees. During the fault, VA shifted, lagging by 30 degrees.

The angles shown in Fig. 6 and Fig. 7 are referenced to the initial VA1 angle of Fig. 6. The angle of VA1 during the initial fault should be approximately the same as the pre-fault angle. There was substantial zero-sequence voltage, but minimum negative. The Dumont relay used positive-sequence voltage with memory to polarize the distance elements. It did not record the sampled polarizing voltage with the oscillographic data. The relay recorded a reference angle for the pre-fault polarizing memory that was used for analysis.

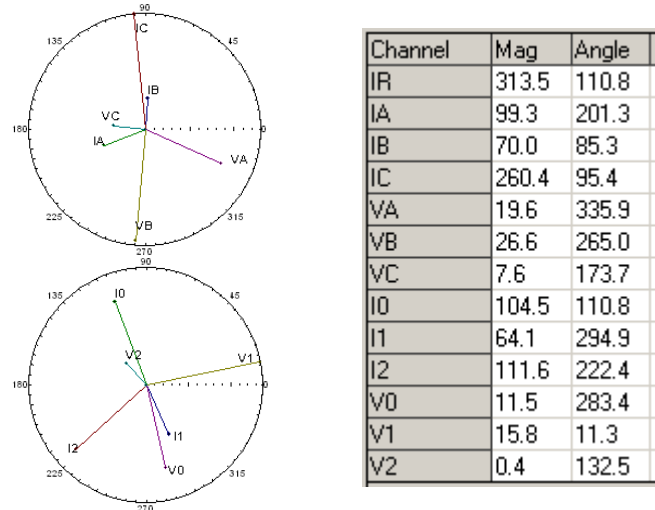


Fig. 8 Phasors at cycle 4.5

Fig. 8 shows the measured quantities after the Bergen breaker on line J-270 opens. The angle between the fault VC and the positive sequence referenced to Phase C (VC1) was over 40 degrees. According to the memory voltage reference recorded by the relay, the fault VC was 90 degrees out of phase with the memory voltage. We assumed that this large phase shift contributed to the misoperation of the relay. The generic phase angle comparator used the currents and voltages from Fig. 8 and the pre-fault memory recorded in the event record for the initial studies. The results are shown in Table XII.

TABLE XII  
PHASE C ZONE 1 GROUND MHO

IZ-V Angle	VPOL Signal	VPOL Angle	Difference Angle
-5.3°	Prefault Memory	84	89.2
-5.3°	Fault VIC	131	136.5
-5.3°	Fault VC	174	179.3

With the pre-fault memory voltage shown in the event file, the phase angle is within the operate range. The unit would operate with the memory voltage, but not with the VIC or VC polarizing voltages.

A computer simulation of the relay was also used to process the data from the event file. Fig. 9 shows the Zone 1 ground distance calculation.

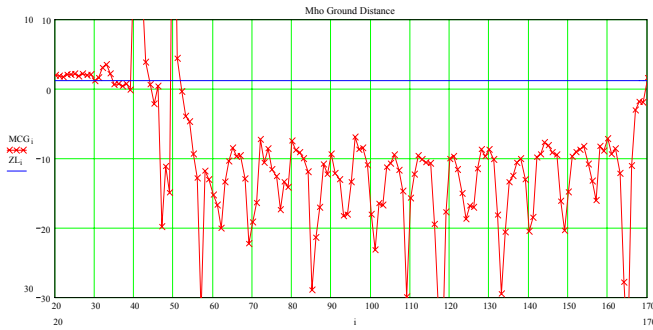


Fig. 9 Phase C Ground Distance Calculation

The horizontal line is the reach of the Zone 1 relay. The reach calculated by this algorithm is negative, which is typical for a reverse fault. This negative-impedance result is due to the large phase shift between the Phase C fault voltage and the memory polarizing voltage. A directional measurement is part of the ground distance algorithm to prevent operation on reverse faults. The directional calculation is shown in Fig. 10.

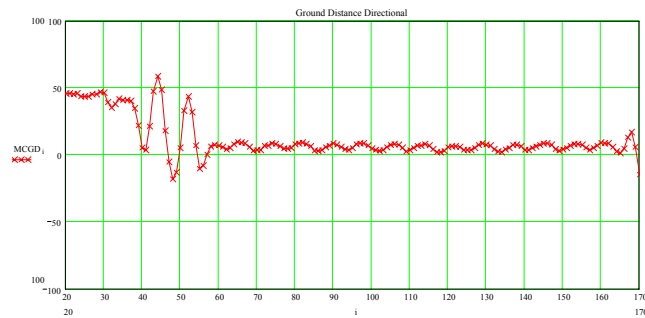


Fig. 10 Phase C Ground Directional Calculation

The positive result of the directional calculation indicates that the fault was in the forward direction. This is correct for this fault. However, the forward directional decision combined with the negative reach calculation resulted in an operation of the Zone 1, Phase C, ground distance element.

The relay at Dumont had both mho ground distance and quadrilateral ground distance elements in service at the time of this misoperation. Only the mho ground distance operated. The ground quadrilateral was secure. Fig. 11 and Fig. 12 show the results of a computer simulation of a negative-sequence current polarized quadrilateral and a zero-sequence current polarized quadrilateral. Both characteristics show a fault of almost six ohms, well beyond the reach of the Zone 1 element. Both characteristics are secure, as predicted by the previous analysis. Since the quadrilateral does not use memory voltage, it is unaffected by the large phase shifts that affect the operation of the ground mho characteristic.

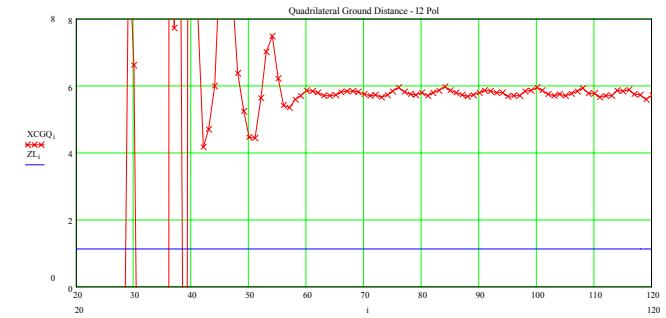


Fig. 11 12 Polarized Ground Quadrilateral Calculation

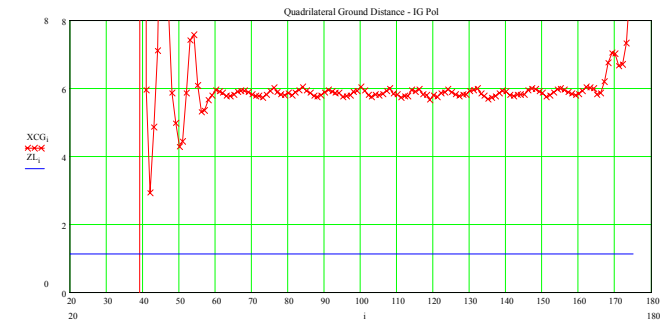


Fig. 12 10 Polarized Ground Quadrilateral Calculation

On June 25, 2005, a Phase A-to-ground fault occurred on Line J-270 at virtually the same location as the prior Phase C-to-ground fault. The relay at Dumont performed correctly for this incident. The ground distance calculation for this event is shown in Fig. 13.

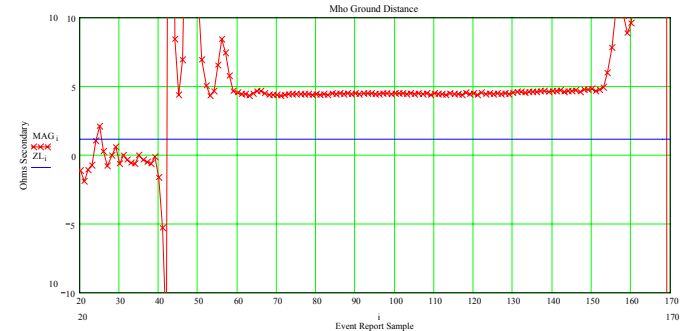


Fig. 13 Phase C Ground Distance Calculation

The calculated impedance to the fault in this case is positive and well beyond the set reach of the relay. For this fault, the phase shift between the Phase A voltage during the fault and the memory polarizing voltage is about 50 degrees, not the previously observed 90 degrees. The lower phase shift prevented the overreach that resulted from the prior Phase C fault.

## VII. CROSS-COUNTRY FAULTS

Cross-country faults are very common on resistive grounded networks. As shown in Fig. 2, the phase-to-ground voltages on the unfaulted phases during a phase ground fault rise to a level approaching the nominal phase-to-phase magnitude. This will often trigger a second phase-to-ground fault somewhere else in the network. From the source perspective, the measurements during simultaneous faults

resemble phase-to-phase-to-ground faults. From the perspective of the line terminal, depending on the fault locations, the faults will also look like phase-to-phase-to-ground faults but may only have the current from one faulted phase available. Assuming the neutral resistor has significantly higher impedance than the impedance between the two faults, a possible current flow is depicted in Fig. 14.

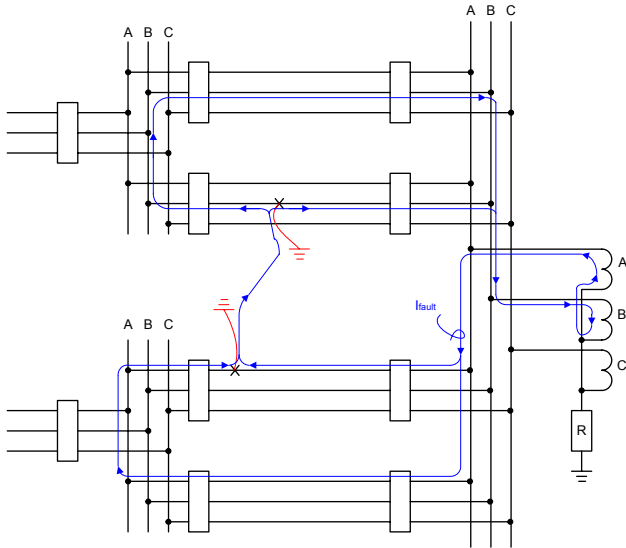


Fig. 14 Cross-Country Fault Currents

A detailed analysis of the relay performance during cross-country faults is beyond the scope of this paper, but significant attention must be paid to the performance of the directional characteristic chosen by the user. Depending on fault location and fault type, the performance of traditional ground directional elements cannot properly indicate direction. Additionally, cross-country faults do not usually occur at the same time. Rather, the presence of the first fault on the system for some time will then cause the second fault to occur. It is the duration between these faults that also makes the ground mho element undesirable on resistive grounded systems. Depending on the memory characteristic, the measured voltages of the first fault will act as the memory voltage for the second fault. This will cause the mho comparators to respond unfavorably. The quadrilateral characteristics are not susceptible to the prefault voltage and have performed well during simultaneous fault conditions.

VIII. MEASUREMENT ACCURACY

As shown in Fig. 2, for single line-to-ground faults the fault voltage becomes very low, even for end of line faults. This has an affect on the capacitive voltage transformer transients as well as the accuracy of voltages when wire-wound potential devices are used. The accuracy of voltage transformers is specified at voltage values near the nominal rating of the device. However, when a fault occurs on the system, the voltage will often be outside those limits. Any errors in the voltage will result in errors in the impedance measured by the relay. Accurate measurements are required

for an impedance-based element to perform well on a resistive grounded system.

In addition, accurate representation of the zero-sequence line impedance is critical to good relay performance. PSE&G recently implemented a program to physically measure the zero-sequence impedance of the 26-kV lines. These measurements show that the impedance calculated with traditional methods is often much higher than the measured value. This has caused overreaches in some cases. The PSE&G 26-kV system is comprised of lines of varying length, and the shorter lines always pose a challenge when setting the resistive and reactive reaches. The graph below shows the effect of measurement accuracy and k0 factor accuracy on a short cable circuit for end of line faults with varying fault resistance. The upper trace is the desired measurement of the relay. The lower trace represents the relay measurements with a k0 factor of 1.2 · actual (20 % error) and a current phase angle of three degrees plus the actual. The effect of these measurements on short lines is dramatic. If we want to obtain a 2-ohm resistive coverage, then the Xreach must be pulled back to prevent overreach.

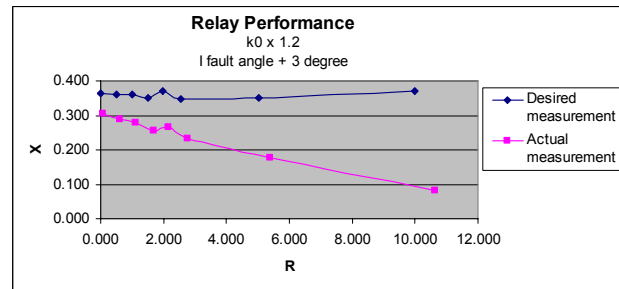


Fig. 15 Effect of Errors on Reach Measurement

Fig. 16 shows a graph of allowable resistive-to-reactive-reach ratio for angle measurement error of 1/20 radians (3°). The dashed line in this figure shows an example where an R/XL ratio of 8 (for a 1-ohm line and an 8-ohm resistive reach) permits setting m = 0.6 per-unit of the line. In other words, if you wish to set the resistive reach to 8 ohms, the maximum reactance reach that can be set is 0.6 ohm, given the CT, VT, and relay measurement errors assumed in this example.

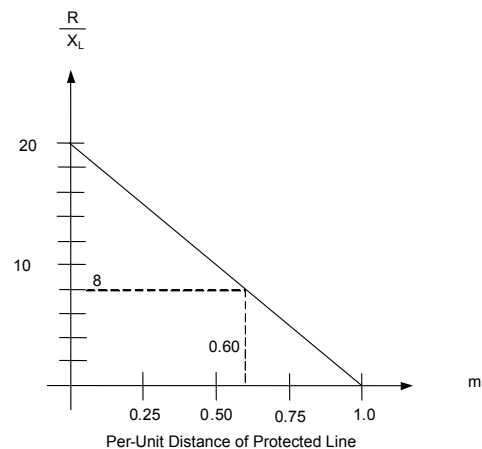


Fig. 16 Allowable Resistive-to-Reactive Reach Ratio

## IX. CONCLUSIONS

Modern distance relays have been optimized for use on solidly grounded transmission systems. The multiple advantages of advanced microprocessor-based relays have increased the use of distance relays in non-traditional applications. However, the features that produce optimal performance in traditional applications may have unanticipated results in non-traditional applications, such as systems with ground current-limiting impedances.

In the system studied, the loop nature of the system, in conjunction with the ground current-limiting impedances created weak infeed conditions unique to traditional applications on solidly grounded systems.

The zero-sequence voltage-induced phase shift in the phase-to-ground voltages on the system can drastically affect the performance of the typical cross-polarized ground distance mho element. We recommend that careful analysis be performed before applying such ground distance mho elements on impedance-grounded systems. However, the studies have shown that zero- and negative-sequence current polarized quadrilateral ground distance elements are not affected by the introduction of the current-limiting impedance. Where the relay offers a choice between mho and quadrilateral characteristics, the quadrilateral is preferred in these applications.

## X. REFERENCES

- [1] E. O. Schweitzer III, and J. Roberts, "Distance Relay Element Design," presented at the 46th Annual Conference for Protective Relay Engineers, 1993
- [2] J. Mooney and J. Peer, "Application Guidelines for Ground Fault Protection," presented at the 24th Annual Western Protective Relay Conference, Spokane, WA, October 1997.

## XI. BIOGRAPHIES

**James Hubertus, P.E.** received his B.S. in Electrical Engineering from Lafayette College in 1990, and his M.S. in Electrical Engineering from the New Jersey Institute of Technology in 1995. He joined Jersey Central Power and Light as a Relay and Controls Engineer in 1990. In 1996 he left JCP&L and joined ABB as an application engineer. In 1997, he joined Public Service Electric and Gas as a relay engineer. Currently, he works for Public Service Electric and Gas Company as the manager of System Protection. He is pursuing his Ph.D. in Electrical Engineering at the New Jersey Institute of Technology. Mr. Hubertus has more than 15 years experience in the design and analysis of power system protection schemes and in the study of power systems. He is a registered professional engineer in the State of New Jersey.

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

**George E. Alexander** holds a B.S. in Electrical Engineering from Villanova University and an M.S. in Electrical Engineering from Drexel University. He is a registered professional engineer in the State of Pennsylvania. He has over 30 years experience in the design and application of transmission line relaying, and holds several U.S. patents in this area. Mr. Alexander has been involved in the development and Model Power System testing of solid state, hybrid analog/digital and fully digital protective relaying systems. He joined SEL in 1999, and is currently regional service manager for the Northeast U.S. and Eastern Canada.

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