Negative-Sequence Overcurrent Element Application and Coordination in Distribution Protection

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NEGATIVE-SEQUENCE OVERCURRENT ELEMENT APPLICATION AND COORDINATION IN DISTRIBUTION PROTECTION

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Negative-sequence overcurrent elements, Distribution protection, Protective device coordination, Open phase conductor

ABSTRACT

Negative-sequence overcurrent elements do not respond to balanced load and can thus be set to operate faster and more sensitively than phase overcurrent elements for phase-to-phase faults. This paper demonstrates that on a radial distribution system, negative-sequence overcurrent elements need only be coordinated with downstream phase overcurrent devices for phase-to-phase faults. Coordination for other fault types is then achieved with no further analysis required. The effects of negative-sequence load current and open phase conductors on negative-sequence overcurrent elements are also discussed.

INTRODUCTION

Because negative-sequence overcurrent elements do not respond to balanced load, they can be set to operate faster and more sensitively than phase overcurrent elements for phase-to-phase faults on distribution systems. Like ground overcurrent elements, negative-sequence overcurrent elements can be set below load levels. On the other hand, phase overcurrent elements must be set above maximum load levels.

Negative-sequence overcurrent elements with standard inverse-type characteristics are now available in microprocessor-based distribution protective relays as part of the complement of elements and functions provided [Reference 1]. These elements, provided at virtually no additional cost, can improve phase-to-phase fault protection with minimal coordination effort.

FAULT ANALYSES

I_2 = negative-sequence fault current

I_P = phase fault current

The following fault analyses are based on negative-sequence overcurrent elements that operate on $3I_2$ magnitude negative-sequence current. The coordination principles discussed also apply for I_2 responsive elements, with appropriate adjustment of the coordination factor. The analyses show that negative-sequence overcurrent elements need only be coordinated with downstream phase overcurrent devices for phase-to-phase faults. Coordination for other fault types is then achieved. All analyses in this paper are restricted to radial distribution systems only.

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Faults on a Radial Distribution System

Appendix I compares the ratio $|3I_2/I_P|$ for AG, BC, and BCG faults [equations (I-1), (I-2), and (I-4)]. The results are listed in Table I, below.

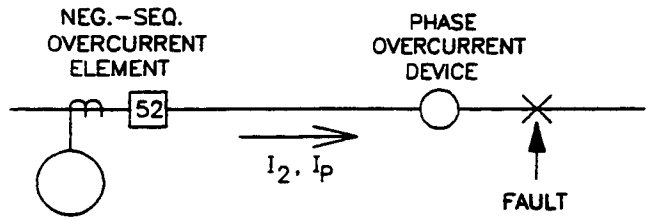


Figure 1 Fault on a Radial Distribution System

Table I Faults on a Radial Distribution System

Fault	$\lvert 3I_2/I_P \rvert$
AG	1
BC	$\sqrt{3}$
BCG	$\leq \sqrt{3}$

Faults on the Secondary of a Delta-Wye Transformer

Phase-to-ground and phase-to-phase faults on the wye secondary of a delta-wye transformer generate negative-sequence currents on the primary system [Reference 2]. Appendix II compares the ratio $|3I_2/I_P|$ on the primary for ag and bc faults on the secondary [equations (II-1) and (II-2)]. The results are listed in Table II.

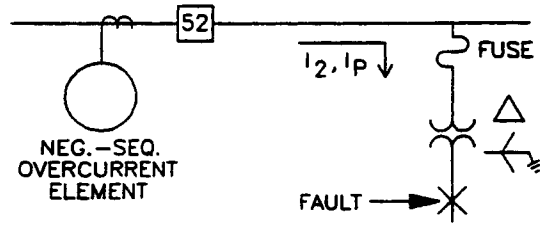


Figure 2 Fault on the Secondary of a Delta-Wye Transformer

Table II Faults on the Secondary of a Delta-Wye Transformer

Fault	$\lvert 3I_2/I_P \rvert$
ag	$\sqrt{3}$
bc	1.5

Fault Summary

From Tables I and II, the highest $\lvert 3I_2/I_P \rvert$ ratio is:

$$\lvert 3I_2/I_P \rvert = \sqrt{3} \quad (1)$$

Thus, a negative-sequence overcurrent element operating on $3I_2$ current with a pickup set to $\sqrt{3}$ times the pickup value of a phase overcurrent device has the same sensitivity for primary phase-to-phase faults and less or equal sensitivity to other fault types when compared to the same phase overcurrent device. The following guidelines apply for setting the negative-sequence overcurrent element.

GUIDELINES FOR COORDINATING NEGATIVE-SEQUENCE OVERCURRENT ELEMENTS WITH PHASE OVERCURRENT ELEMENTS

1. Start with the furthest downstream negative-sequence overcurrent element (e.g., distribution feeder relay in a substation).

2. Identify the phase overcurrent device (e.g., line recloser, fuse) downstream from the negative-sequence overcurrent element that is of greatest concern for coordination. This is usually the phase overcurrent device with the longest clearing time.

3. Consider the negative-sequence overcurrent element as an "equivalent" phase overcurrent element. Derive pickup, time dial (lever), curve type, or time-delay settings for this "equivalent" element to coordinate with the downstream phase overcurrent device, as any phase coordination would be performed. Load considerations can be disregarded when deriving the "equivalent" phase overcurrent element settings.

4. Multiply the "equivalent" phase overcurrent element pickup setting by $\sqrt{3}$ to convert it to the negative-sequence overcurrent element pickup setting in terms of $3I_2$ current.

   Negative-sequence overcurrent element pickup = $\sqrt{3}$ ("equivalent" phase overcurrent element pickup) (2)

   Any time dial (lever), curve type, or time-delay calculated for the "equivalent" phase overcurrent element is also used for the negative-sequence overcurrent element with no conversion factor applied.

5. Set the next upstream negative-sequence overcurrent element to coordinate with the first downstream negative-sequence overcurrent element and so on. Again, coordination is not influenced by load considerations.

EXAMPLE OF COORDINATING A NEGATIVE-SEQUENCE OVERCURRENT ELEMENT WITH A PHASE OVERCURRENT ELEMENT

In Figure 3 the phase and negative-sequence overcurrent elements of the feeder relay (51F and 51QF, respectively) must coordinate with the phase overcurrent element of the line recloser (51R).

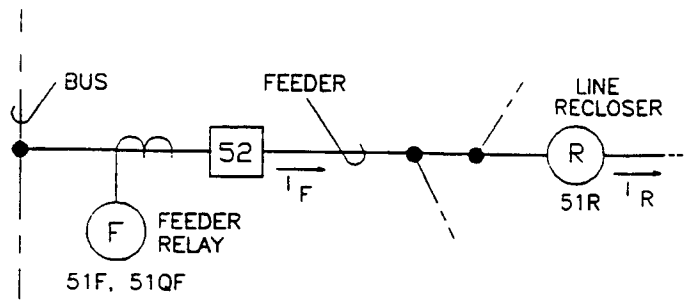


Figure 3 Distribution Feeder Protective Devices

I_F = Maximum load current through feeder relay = 450 A

I_R = Maximum load current through line recloser = 150 A

51F = Feeder relay phase time-overcurrent element

51QF = Feeder relay negative-sequence time-overcurrent element

51R = Line recloser phase time-overcurrent element (phase "slow curve")

Traditional Phase Coordination

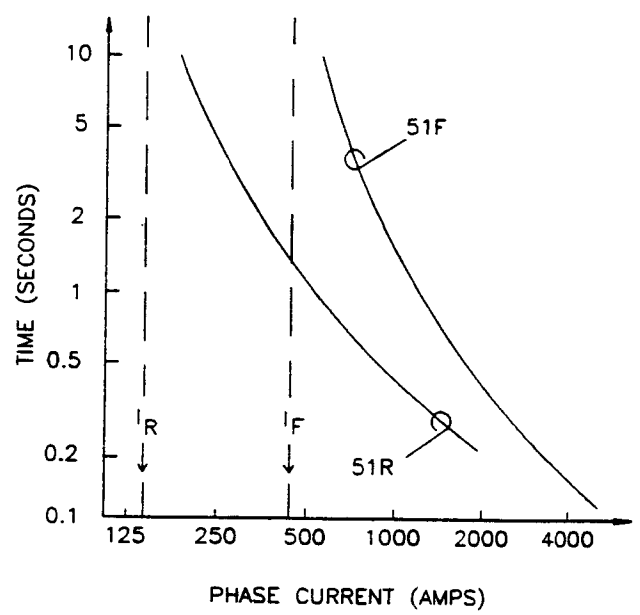


Figure 4 Traditional Phase Coordination

51F: pickup = 600 A (above max. feeder load, I_F)

51R: pickup = 200 A (above max. line recloser load, I_R)

Figure 4 shows traditional phase overcurrent element coordination between the feeder relay and line recloser phase overcurrent elements. Phase overcurrent elements must accommodate load and cold load pickup current. The 450 A maximum feeder load current limits the sensitivity of the feeder phase overcurrent element, 51F, to a pickup of 600 A. The feeder relay cannot back up the line recloser for phase faults below 600 A.

Apply the Feeder Relay Negative-Sequence Overcurrent Element (Guidelines 1 to 3)

Applying negative-sequence overcurrent element coordination guidelines 1 to 3 results in the feeder relay "equivalent" phase overcurrent element (51EP) in Figure 5. Curve for 51F is shown for comparison only.

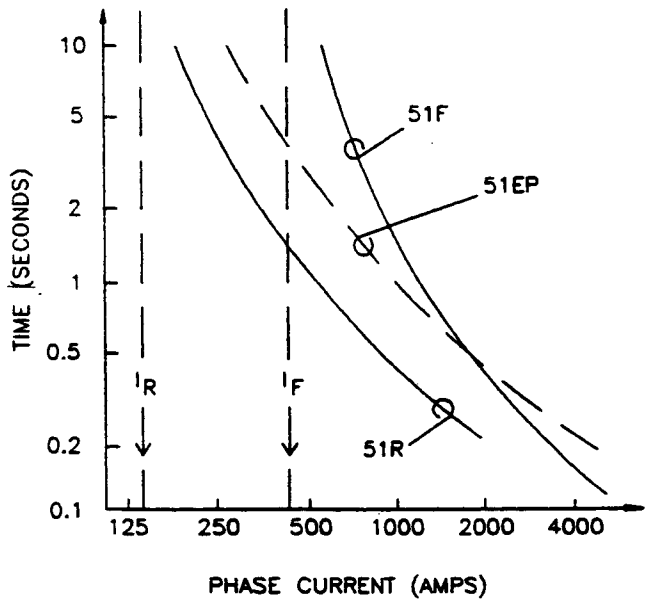


Figure 5 Phase-to-Phase Fault Coordination

51EP: pickup = 300 A (below max. feeder load, I_F)

Considerable improvement in sensitivity and speed of operation for phase-to-phase faults is achieved with the 51EP element. The 51EP element pickup of 300 A has twice the sensitivity of the 51F element pickup of 600 A. The 51EP element speed of operation for phase-to-phase faults below about 2000 A is faster than that for the 51F element.

Convert "Equivalent" Phase Overcurrent Element Settings to Negative-Sequence Overcurrent Element Settings (Guideline 4)

The "equivalent" phase overcurrent element (51EP element in Figure 5) converts to true negative-sequence overcurrent element settings (51QF in Figure 6) by applying equation (2). The time dial (lever) and curve type of the element remain the same.

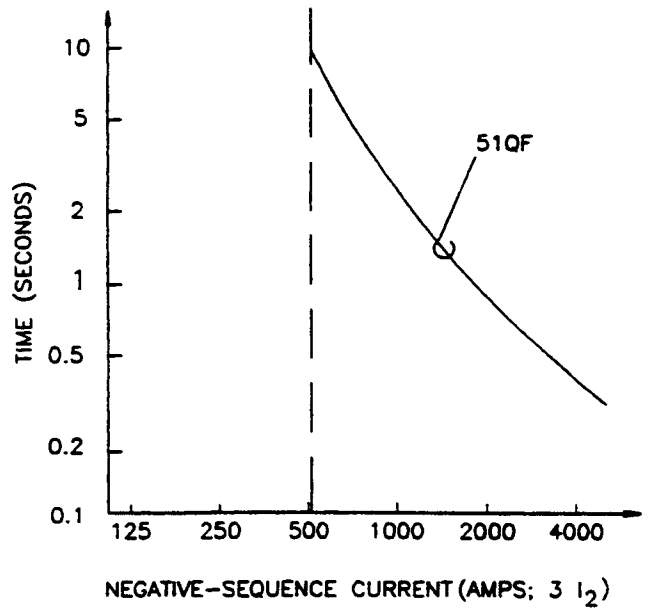


Figure 6 Negative-Sequence Overcurrent Element Derived from "Equivalent" Phase Overcurrent Element, 51EP

51QF: pickup = $\sqrt{3}$(300 A) = 520 A

Having achieved coordination between the feeder relay negative-sequence overcurrent element (51QF) and the downstream line recloser phase overcurrent element (51R) for phase-to-phase faults, coordination between the two devices for other fault types is also achieved.

Negative-Sequence Overcurrent Element Applied at a Distribution Bus (Guideline 5)

The preceding example was for a distribution feeder. A negative-sequence overcurrent element protecting a distribution bus provides an even more dramatic improvement in phase-to-phase fault sensitivity.

The distribution bus phase overcurrent element pickup must be set above the combined load of all the feeders on the bus, plus any emergency load conditions. The bus phase overcurrent element pickup is often set at least four times greater than the pickup of the feeder phase overcurrent element it backs up. Thus, sensitivity to both bus and feeder phase faults is greatly reduced. Feeder relay backup by the bus relay is limited.

Negative-sequence overcurrent elements at the distribution bus can be set significantly below distribution bus load levels and provide dramatically increased sensitivity to phase-to-phase faults. It is coordinated with the distribution feeder phase or negative-sequence overcurrent elements and provides more-sensitive and faster phase-to-phase fault backup.

OTHER POSSIBLE CONCERNS FOR NEGATIVE-SEQUENCE OVERCURRENT ELEMENT APPLICATION

Ground Coordination

If the downstream protective device includes ground overcurrent elements, in addition to phase overcurrent elements, there should be no need to check the coordination between the ground overcurrent elements and the upstream negative-sequence overcurrent elements. The downstream phase overcurrent element, whether it operates faster or slower than its complementary ground overcurrent element, will operate faster than the upstream negative-sequence overcurrent element for all faults, including those that involve ground.

Negative-Sequence Load Current

An unbalanced feeder fault generates negative-sequence voltage on the distribution bus which in turn generates negative-sequence load current on the unfaulted feeders connected to the bus. The effect of the negative-sequence load current of unfaulted feeders is to reduce the negative-sequence current to the bus relay [Reference 3]. This desensitizes the bus relay negative-sequence overcurrent elements and aids these elements in coordinating with downstream feeder relay overcurrent elements.

Figure 7 and Table III show how this desensitization of the bus relay negative-sequence overcurrent elements takes place. Table III lists the ratio $|I_{2B}/I_2|$ for varying load/source impedance ratios ($|Z_{2L}/Z_{2S}|$) for an example distribution station. As Z_{2S} decreases (stronger source) or Z_{2L} increases (lower load), the desensitization effect on the bus relay negative-sequence overcurrent elements is reduced ($|I_{2B}/I_2|$ approaches unity).

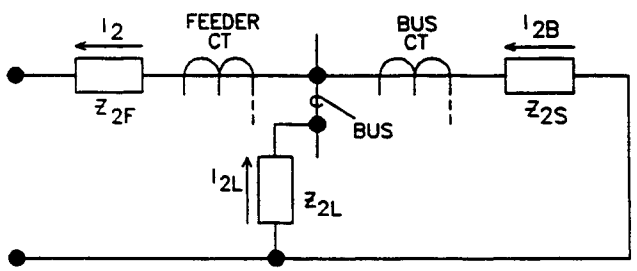


Figure 7 Negative-Sequence Network for Unbalanced Distribution Feeder Faults

Z_{2S} = negative-sequence source impedance

Z_{2F} = negative-sequence feeder line impedance to the fault

Z_{2L} = combined effective negative-sequence load impedance of unfaulted feeders

I_{2B} = magnitude of negative-sequence current to the bus relay

I_2 = magnitude of negative-sequence current to the feeder relay

I_{2L} = magnitude of negative-sequence load current of unfaulted feeders

$$I_{2B}/I_2 = Z_{2L}/(Z_{2L} + Z_{2S}) \quad (3)$$

Table III Bus Relay Negative-Sequence Element Desensitization for Varying Load/Source Impedance Ratios

$\lvert Z_{2L}/Z_{2S}\rvert$	3	4	5	6	8	12
$\lvert I_{2B}/I_2\rvert$ for:						
$\angle Z_{2S}$ = 80°	.83	.87	.90	.91	.94	.96
$\angle Z_{2S}$ = 85°	.85	.89	.91	.93	.94	.96

$\angle Z_{2L}$ (= 20°) is constant for all cases.

Typically the low end of the $|Z_{2L}/Z_{2S}|$ ratios in Table III are valid at peak load times only (small Z_{2L}). Most of the time, load levels are much lower and the high end of the ratios in Table III applies.

Open Phase Conductor

The following analyses for open phase conductor conditions assume an open phase conductor near the location of the negative-sequence overcurrent element (e.g., open phase where the distribution feeder exits the substation, just downstream from the feeder relay). Open phase conditions at points farther out on the distribution system (e.g., tap fuse operation) generally cause less unbalance.

The open phase conductor analyses assume no phase conductor is contacting ground or other phases conductors.

The purpose of the analyses is to show the levels of negative-sequence current generated for the outlined open phase conductor conditions and how negative-sequence overcurrent element settings relate to these current levels.

Four-Wire Distribution System:

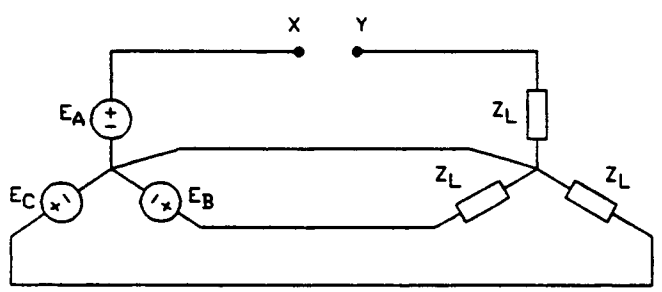


Figure 8 Open Phase Conductor on a Four-Wire Distribution System

Z_L = feeder load impedance

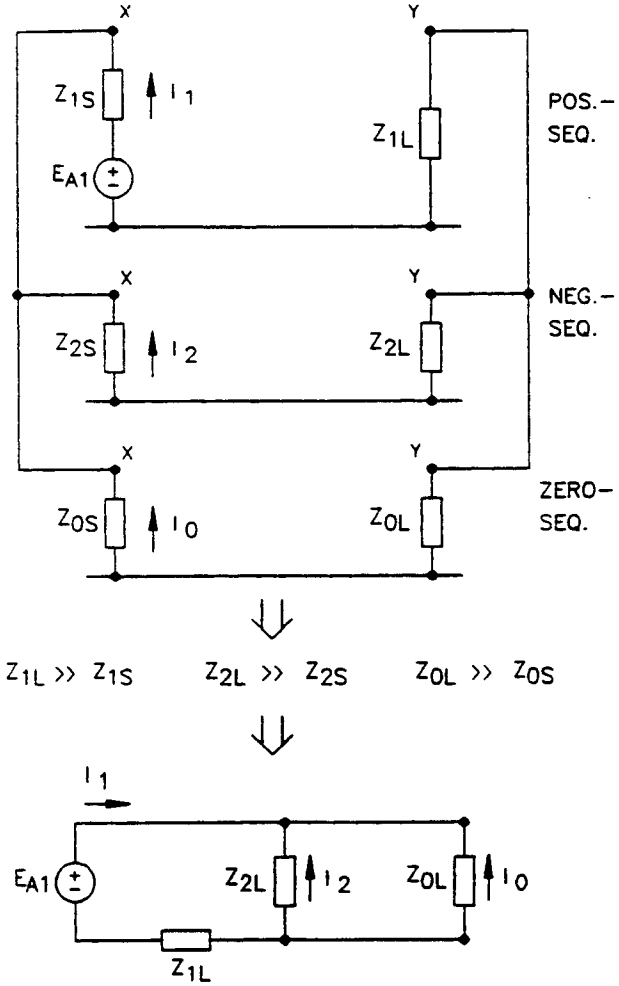


Figure 9 Sequence Network for Open Phase Conductor on a Four-Wire Distribution System

Z_{1L} = feeder positive-sequence load impedance

Z_{2L} = feeder negative-sequence load impedance

Z_{0L} = feeder zero-sequence load impedance

Z_{1S} = positive-sequence source impedance

Z_{2S} = negative-sequence source impedance

Z_{0S} = zero-sequence source impedance

I_1 = positive-sequence current

I_2 = negative-sequence current

I_0 = zero-sequence current

From the reduced network in Figure 9:

$$I_1 = E_{A1}/\{Z_{1L} + [Z_{2L}Z_{0L}/(Z_{2L} + Z_{0L})]\}$$

$$= E_{A1}(Z_{2L} + Z_{0L})/[Z_{1L}(Z_{2L} + Z_{0L}) + Z_{2L}Z_{0L}] \quad (4)$$

$$-I_2 = I_1 Z_{0L}/(Z_{2L} + Z_{0L})$$

$$= E_{A1}Z_{0L}/[Z_{1L}(Z_{2L} + Z_{0L}) + Z_{2L}Z_{0L}] \quad (5)$$

Before the "A" phase conductor opened, the following equation held true for the balanced four-wire system:

$$I_L = E_{A1}/Z_{1L} = \text{load current} \quad (6)$$

Combining equation (6) into equation (5) results in:

$$-I_2 = I_L Z_{1L} Z_{0L}/[Z_{1L}(Z_{2L} + Z_{0L}) + Z_{2L}Z_{0L}] \quad (7)$$

$$|3I_2| = |3I_L Z_{1L} Z_{0L}/[Z_{1L}(Z_{2L} + Z_{0L}) + Z_{2L}Z_{0L}]| \quad (8)$$

For example purposes, let $Z_{1L} = Z_{2L} = Z_{0L}$

then,

$$|3I_2| = |I_L| \quad (9)$$

Equation (9) indicates that the negative-sequence overcurrent element (operating on $3I_2$) detects the negative-sequence current generated by the open phase conductor condition if its pickup magnitude is set equal to I_L (I_L continually varies within minimum and maximum load current levels). Restating this relationship in terms of the "equivalent" phase overcurrent element pickup [see equation (2)]:

$$\text{"equivalent" phase element pickup} = |I_L/\sqrt{3}| = 0.577 I_L \quad (10)$$

<u>Three-Wire Distribution System</u>:

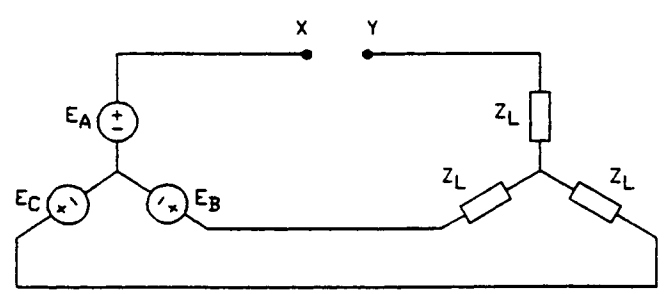


Figure 10 Open Phase Conductor on a Three-Wire Distribution System

Z_L = feeder load impedance

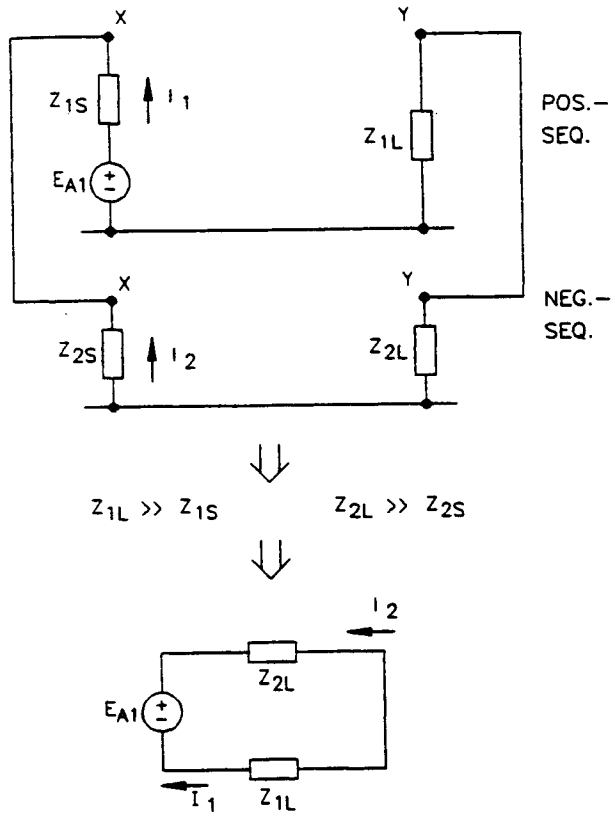


Figure 11 Sequence Network for Open Phase Conductor on a Three-Wire Distribution System

Z_{1L} = feeder positive-sequence load impedance

Z_{2L} = feeder negative-sequence load impedance

Z_{1S} = positive-sequence source impedance

Z_{2S} = negative-sequence source impedance

I_1 = positive-sequence current

I_2 = negative-sequence current

From the reduced sequence network in Figure 11:

$$I_1 = -I_2 = E_{A1}/(Z_{1L} + Z_{2L}) \quad (11)$$

Before the "A" phase conductor opened, the following equation held true for the balanced three-wire system:

$$I_L = E_{A1}/Z_{1L} = \text{load current} \quad (12)$$

Combining equation (12) into equation (11) results in:

$$-I_2 = I_L Z_{1L}/(Z_{1L} + Z_{2L}) \quad (13)$$

$$|3I_2| = |3I_L Z_{1L}/(Z_{1L} + Z_{2L})| \quad (14)$$

For example purposes, let $Z_{1L} = Z_{2L}$

then,

$$|3I_2| = |3I_L/2| = |1.5I_L| \quad (15)$$

Equation (15) indicates that the negative-sequence overcurrent element (operating on $3I_2$) detects the negative-sequence current generated by the open phase conductor condition if its pickup magnitude is set equal to $1.5I_L$ (I_L continually varies within minimum and maximum load current levels). Restating this relationship in terms of the "equivalent" phase overcurrent element pickup [see equation (2)]:

$$\text{"equivalent" phase element pickup} = |1.5I_L/\sqrt{3}|$$

$$= 0.866I_L \quad (16)$$

CONCLUSIONS

Negative-sequence overcurrent elements are now available in microprocessor-based distribution relays. These elements can be set below load levels to operate faster and more sensitively than phase overcurrent elements for phase-to-phase faults on the distribution system.

A possible hindrance to their application is a lack of guidelines on how to coordinate negative-sequence overcurrent elements with other distribution system protective devices that operate on different electric quantities (i.e., phase and zero-sequence currents).

This paper introduced simple setting guidelines to coordinate negative-sequence overcurrent elements with downstream phase overcurrent elements for phase-to-phase faults on a radial distribution system. Coordination for other faults and with ground overcurrent elements is then achieved, with no further analysis required.

The effect of negative-sequence load current was shown to be minimal and actually helps in coordinating negative-sequence overcurrent elements with downstream devices.

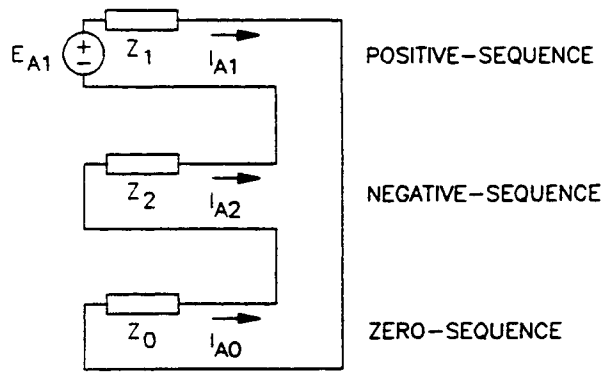
Open phase conductor conditions (phase conductor not contacting ground or other phase conductors) were analyzed. Correlations between load and negative-sequence current generated for these unbalance conditions were established.

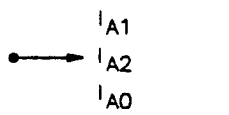
APPENDIX I

FAULTS ON A RADIAL DISTRIBUTION SYSTEM

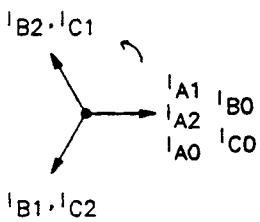
Refer to Figure 1.

Phase-to-Ground (AG) Fault

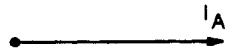




$$I_{A1} = I_{A2} = I_{A0}$$

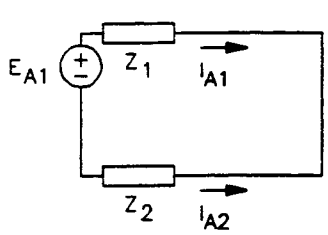


$$I_A = I_{A1} + I_{A2} + I_{A0}$$
$$I_B = I_{B1} + I_{B2} + I_{B0} = 0$$
$$I_C = I_{C1} + I_{C2} + I_{C0} = 0$$

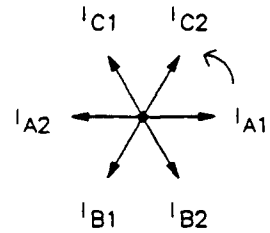


$$3\, I_{A2} = I_A$$
$$|3\, I_2| = |I_P|$$
$$\left|\frac{3\, I_2}{I_P}\right| = 1 \qquad (I-1)$$

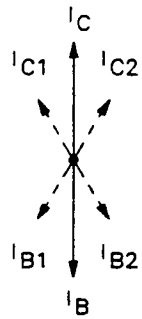
Phase-to-Phase (BC) Fault



$$I_{A2} = -I_{A1}$$

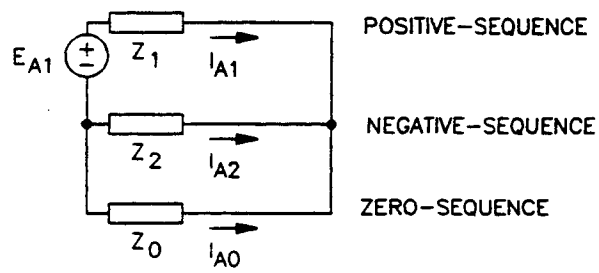


$$I_A = I_{A1} + I_{A2} = 0$$
$$I_B = I_{B1} + I_{B2}$$
$$I_C = I_{C1} + I_{C2}$$



$$|\sqrt{3}\, I_{B2}| = |I_B|$$
$$|\sqrt{3}\, I_{C2}| = |I_C|$$
$$|\sqrt{3}\, I_2| = |I_P|$$
$$|3\, I_2| = |\sqrt{3}\, I_P|$$
$$\left|\frac{3\, I_2}{I_P}\right| = \sqrt{3} \qquad (I-2)$$

Phase-to-Phase-to-Ground (BCG) Fault



$$I_{A2} = -I_{A1} \frac{Z_0}{Z_0 + Z_2}$$

$$I_{A0} = -I_{A1} \frac{Z_2}{Z_0 + Z_2}$$

$$I_B = a^2 I_{A1} + a\, I_{A2} + I_{A0}$$

$$a = 1 \angle 120^\circ$$

FROM THE ABOVE EQUATIONS,
THE FOLLOWING EQUATION CAN BE DERIVED:

$$\left|\frac{3\, I_2}{I_P}\right| = \left|\sqrt{\frac{3}{1 + \frac{Z_2}{Z_0} + \left(\frac{Z_2}{Z_0}\right)^2}}\right| \qquad (I-3)$$

Z_0 INCLUDES GROUND FAULT RESISTANCE, IF PRESENT

$\left\lvert \frac{Z_0}{Z_2} \right\rvert$	$\left\lvert \frac{3\,I_2}{I_P} \right\rvert$	$\left\lvert \frac{3\,I_2}{3\,I_0} \right\rvert$
0.00	0.00	0.00
$\downarrow$	$\downarrow$	$\downarrow$
∞	$\boxed{\sqrt{3}}$	∞ (I–4)

$\left\lvert \frac{Z_0}{Z_2} \right\rvert \Rightarrow \infty$ (AS GROUND FAULT RESISTANCE INCREASES)

APPENDIX II

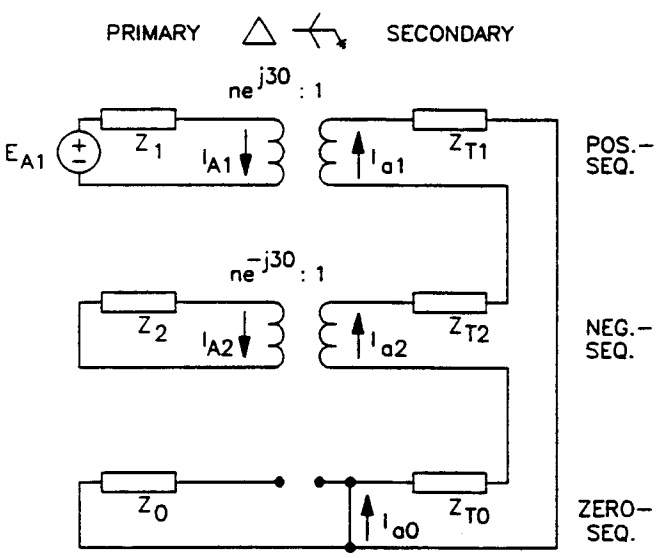
FAULTS ON THE SECONDARY OF A DELTA-WYE TRANSFORMER

Refer to Figure 2.

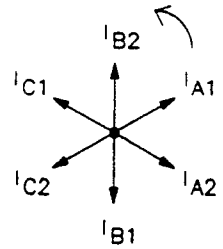
$n = (V_{L\text{-}N}\ \text{pri.})/V_{L\text{-}N}\ \text{sec.})$

Z_T = transformer impedance

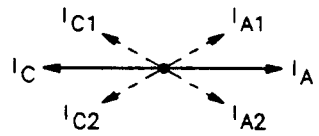
Phase-to-Ground (ag) Fault



$|I_{A1}| = |I_{A2}|$ $\qquad$ $I_{a1} = I_{a2} = I_{a0}$



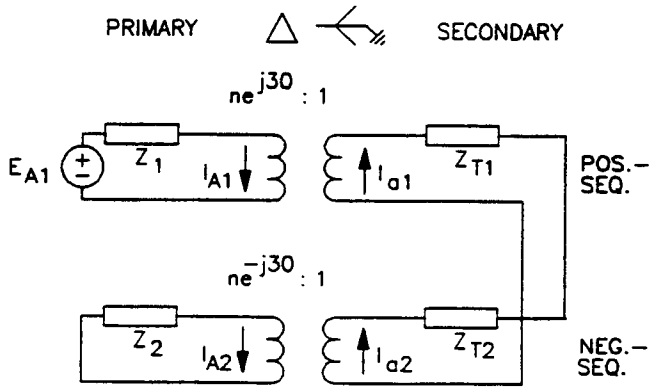
$$I_A = I_{A1} + I_{A2}$$
$$I_B = I_{B1} + I_{B2} = 0$$
$$I_C = I_{C1} + I_{C2}$$

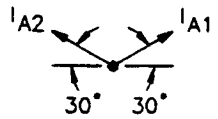


$$|\sqrt{3}\ I_{A2}| = |I_A|$$
$$|\sqrt{3}\ I_{C2}| = |I_C|$$

$$|\sqrt{3}\ I_2| = |I_P|$$
$$|3\ I_2| = |\sqrt{3}\ I_P|$$
$$\left\lvert \frac{3\ I_2}{I_P} \right\rvert = \sqrt{3} \quad \text{(II–1)}$$

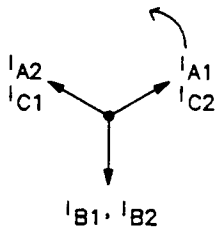
Phase-to-Phase (bc) Fault



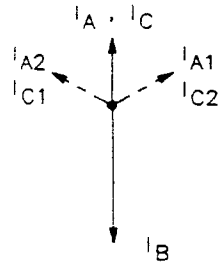


$|I_{A1}| = |I_{A2}|$

$I_{a2} = -I_{a1}$



$$I_A = I_{A1} + I_{A2}$$
$$I_B = I_{B1} + I_{B2}$$
$$I_C = I_{C1} + I_{C2}$$

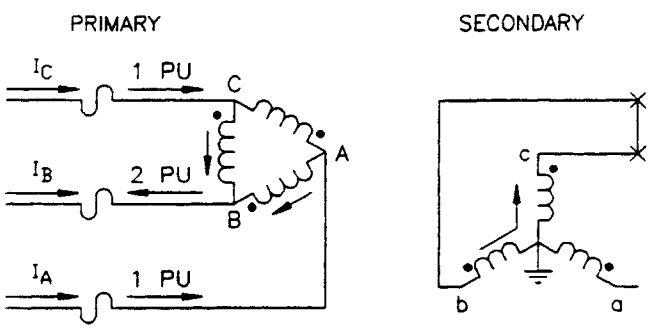


$$|I_{A2}| = |I_A|$$
$$|I_{C2}| = |I_C|$$
$$2\,I_{B2} = I_B$$

$$|3\,I_2| = |3\,I_A| = |3\,I_C|$$
$$= |1.5\,I_B|$$
$$|3\,I_2| = |1.5\,I_{P(MAX)}|$$
$$\frac{|3\,I_2|}{I_{P(MAX)}} = 1.5 \qquad \text{(II-2)}$$

Further study shows that primary phase B has twice the magnitude of fault current as compared to primary phase A or C for a phase-to-phase (bc) fault on the secondary of a delta-wye transformer:

$$|2I_A| = |I_B| = |2I_C| \qquad \text{(II-3)}$$



After phase B fuse blows, no fault current flows in primary phases A and C. Thus coordination with $I_{P(MAX)}$ is appropriate (equation II-2).

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Edmund O. Schweitzer, III (M '74, SM '89, F '91) is President of Schweitzer Engineering Laboratories, Inc., Pullman, Washington, U.S.A., a company that designs and manufacturers microprocessor-based protective relays for electric power systems. He is also an Adjunct Professor at Washington State University. He received his BSEE at Purdue University in 1968 and MSEE at Purdue University in 1971. He earned his PhD at Washington State University in 1977. He has authored or co-authored over 30 technical papers. He is a member of Eta Kappa Nu and Tau Beta Pi and serves on three IEEE PES Power System Relaying Committee Working Groups: Effectiveness of Distribution Protection, Line Protection with Digital Computers, and Single Phase Tripping of Transmission Lines.

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