Negative-Sequence Impedance Directional Element

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INTRODUCTION

The SEL-321 Relay contains an innovative directional element which uses traditional negative-sequence quantities in a somewhat different fashion than traditional negative-sequence directional elements. This paper describes, and provides a method for testing, this new directional element.

WHAT IS NEGATIVE-SEQUENCE AND WHY DO WE USE NEGATIVE-SEQUENCE FOR DIRECTIONAL ELEMENTS?

Negative-sequence is one of three quantities used in the symmetrical component analysis of three-phase power systems. Symmetrical components are used to calculate unbalanced conditions on a three-phase system using only a single-phase calculation. This greatly simplifies the process of calculating fault quantities for phase-to-phase, phase-to-ground, and phase-to-phase-to-ground faults on power systems.

Symmetrical components consist of positive-, negative-, and zero-sequence quantities. Basically, positive-sequence quantities are those present during balanced, three-phase conditions. Positive-sequence quantities makeup the normal voltages and currents observed on power systems during typical, steady-state conditions. Negative-sequence quantities are a measure of the amount of unbalance existing on a power system. Zero-sequence quantities are most commonly associated with ground being involved in an unbalanced condition. Negative- and zero-sequence quantities are usually only present in substantial levels during unbalanced, faulted conditions on a power system.

Since negative- and zero-sequence quantities are only present in relatively large values for faulted conditions, they are often used to determine that a faulted condition exists on a power system. Negative-sequence can be used to detect phase-to-phase, phase-to-ground, and phase-to-phase-to-ground faults. Zero-sequence can be used to detect phase-to-ground and phase-to-phase-to-ground faults.

As an example, we will calculate the positive- and negative-sequence components of the following three phase-voltage conditions:

- A perfectly balanced system
- A perfectly unbalanced system or reverse phase rotation
- A typical A-phase-to-ground fault

The equations to calculate positive-and negative-sequence are given as:

$$V_1 = 1/3 \cdot (Va + aVb + a^2Vc)$$
$$V_2 = 1/3 \cdot (Va + a^2Vb + aVc)$$

V_1 is positive-sequence voltage, V_2 is negative-sequence voltage, and “a” is an operator equal to 1<120. Multiplying a phasor by “a” rotates that phasor 120 degrees counter-clockwise. When squared, the “a^2” operator becomes equal to 1<240 and rotates a phasor by 240 degrees counter-clockwise.

Consider a perfectly balanced system.

$Va = 67 < 0$ volts
$Vb = 67 < -120$ volts
$Vc = 67 < 120$ volts
$V_1 = 1/3 \cdot (67<0 + 1<120 \cdot 67<-120 + 1<240 \cdot 67<120)$
$= 1/3 \cdot (67<0 + 67<0 + 67<0) = 1/3 \cdot 3 \cdot 67<0 = 67<0$ volts
$V_2 = 1/3 \cdot (67<0 + 1<240 \cdot 67<-120 + 1<120 \cdot 67<120)$
$= 1/3 \cdot (67<0 + 67<120 + 67<240) = 1/3 \cdot 0 = 0$ volts

For a perfectly balanced system, positive-sequence voltage is equal to 67<0 volts and negative-sequence voltage is zero.

Next we examine a perfectly unbalanced system or a system that has reverse phase rotation.

$Va = 67 < 0$ volts
$Vb = 67 < 120$ volts
$Vc = 67 < -120$ volts
$V_1 = 1/3 \cdot (67<0 + 1<120 \cdot 67<120 + 1<240 \cdot 67<-120)$
$= 1/3 \cdot (67<0 + 67<240 + 67<120) = 1/3 \cdot 0 = 0$ volts
$V_2 = 1/3 \cdot (67<0 + 1<240 \cdot 67<120 + 1<120 \cdot 67<-120)$
$= 1/3 \cdot (67<0 + 67<0 + 67<0) = 1/3 \cdot 3 \cdot 67<0 = 67<0$ volts

For a perfectly unbalanced system, negative-sequence voltage is equal to 67<0 volts and positive-sequence voltage is zero.

Lastly, we examine a typical A-phase-to-ground fault.

$Va = 37 < 0$ volts
$Vb = 67 < -120$ volts
$Vc = 67 < 120$ volts
$V_1 = 1/3 \cdot (37<0 + 1<120 \cdot 67<-120 + 1<240 \cdot 67<120)$
$= 1/3 \cdot (37<0 + 67<0 + 67<0) = 1/3 \cdot 171<0 = 57<0$ volts
$V_2 = 1/3 \cdot (37<0 + 1<240 \cdot 67<-120 + 1<120 \cdot 67<120)$
$= 1/3 \cdot (37<0 + 67<120 + 67<240) = 1/3 \cdot 30<180 = 10<180$ volts

For an A-phase-to-ground fault, the positive-sequence voltage is reduced somewhat and the negative-sequence voltage is 180 degrees out-of-phase with the positive-sequence voltage.

Traditional Negative-Sequence Directional Element

When the term "Negative-Sequence Directional Element" is used, the most commonly thought of element is one that looks at the negative-sequence voltage on, and negative-sequence current through, a transmission line and compares the relative phase angles of the two quantities. A forward fault is declared when the negative-sequence current leads the negative-sequence voltage by 180 degrees minus the characteristic angle of the transmission line. This characteristic can be described by the following equation:

$$T32Q = |V_2| \cdot |I_2| \cdot \cos(\angle{-V_2} - (\angle I_2 + MTA))$$

T32Q is the "torque" produced by the negative-sequence directional element and MTA is the characteristic angle of the transmission line. A positive torque indicates a fault in the forward direction.

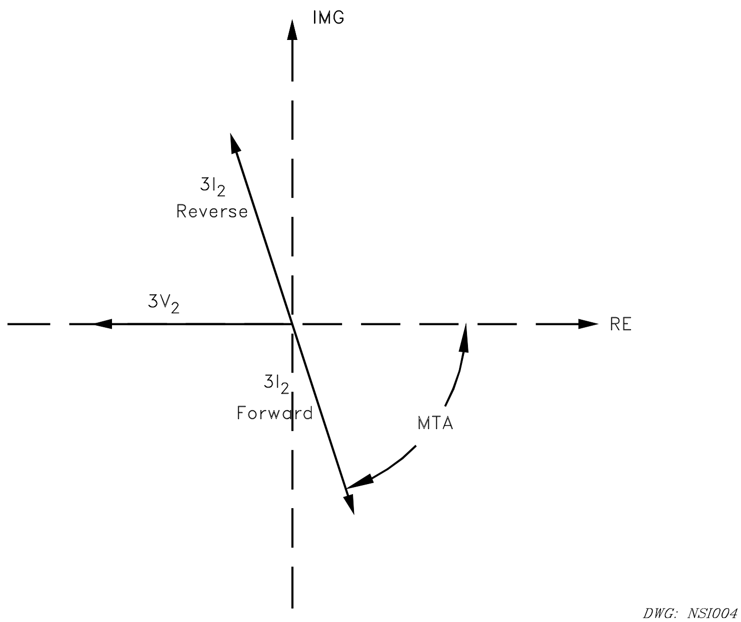

Figure 1: Traditional Negative-Sequence Directional Element Characteristics

For the typical A-phase-to-ground fault in the above section, the A-phase current would lag the A-phase voltage by the MTA of the line. For our simplified system, we will assume an MTA of 90 degrees. Therefore, the A-phase current would appear at an angle of -90 degrees. To calculate the negative-sequence current for this fault, we use the same equation as we used for the negative-sequence voltage substituting current for voltage. This gives:

$Ia = 9 \angle -90$ amps
$Ib = 0$ amps
$Ic = 0$ amps

$$I_2 = 1/3 \cdot (Ia + 1\angle 240 \cdot Ib + 1\angle 120 \cdot Ic) = 1/3 \cdot (9\angle -90 + 1\angle 240 \cdot 0 + 1\angle 120 \cdot 0)$$
$$= 1/3 \cdot 9\angle -90 = 3\angle -90 \text{ amps}$$

The negative-sequence current is 1/3 of the A-phase current and in the same direction (has the same phase angle as the A-phase current).

Now we can evaluate the torque equation for the traditional negative-sequence directional element.

$V_2 = 10<180$ volts
$I_2 = 3<-90$ amps

$$
\begin{aligned}
T32Q &= |V_2| \cdot |I_2| \cdot \cos(<-V_2 - (<I_2 + MTA)) \\
&= |10<180| \cdot |3<-90| \cdot \cos(<-10<180 - (<3<-90 + 90)) \\
&= |10| \cdot |3| \cdot \cos(0 - (-90 + 90)) = 30 \cdot \cos(0) = 30 \cdot 1 = 30 \text{ VA}
\end{aligned}
$$

For this simulated fault, we can see that a positive torque is produced indicating a forward direction.

A reverse fault could be evaluated the same way. All quantities would be the same except the A-phase current (and the resulting negative-sequence current) would be 180 degrees out-of-phase with the previous example. This would result in a negative torque and a reverse directional declaration.

This directional element has been used quite successfully for many years. However, it can be shown that the negative-sequence voltage developed during a fault is inversely proportional to the strength of the source either behind the relay for a forward fault or in front of the relay for a reverse fault. That is, the stronger the source (the lower the source impedance), the less the negative-sequence voltage produced. This fact, coupled with the effect of fault resistance, which tends to lower the amount of fault current (and negative-sequence current) available during a fault, produces a minimum sensitivity for the traditional negative-sequence directional element. You will notice above that the torque produced by this directional element is directly proportional to the negative-sequence voltage and the negative-sequence current available during a fault.

To overcome these limitations, a new negative-sequence directional element was developed.

NEGATIVE-SEQUENCE IMPEDANCE DIRECTIONAL ELEMENT

The SEL-321 Relay negative-sequence impedance directional element uses the same quantities as we covered in the previous sections but determines direction using a different equation. Instead of relying on the product of negative-sequence voltage and negative-sequence current, the SEL-321 Relay uses the ratio of these two quantities. This ratio of negative-sequence voltage to negative-sequence current gives a resulting negative-sequence impedance.

In general, the directional calculation which occurs is given as:

$$Z_2 = V_2 / I_2 \text{ or } 3V_2 / 3I_2$$

As we saw above, the negative-sequence voltage developed for a forward or reverse fault is always negative (for our example, $V_2 = 10<180$ or -10 volts). For a forward fault, the negative-sequence current lags the driving voltage (the faulted phase voltage) by the MTA of the line and is considered positive. For our example, the negative-sequence current for the forward fault was $3<-90$ (lagging the faulted A-phase voltage which was at 0 degrees). For a reverse fault, the negative-sequence current is 180 degrees out-of-phase, or in the reverse direction of the negative-sequence current for a forward fault. This direction is considered reverse or negative. For our example, the negative-sequence current for the reverse fault was $3<90$.

Since negative-sequence voltage is always negative, and negative-sequence current is positive for a forward fault and negative for a reverse fault, a simple relationship can be developed. For a forward fault, the negative-sequence impedance is always negative (Z_2 = negative value / positive value) and for a reverse fault, the negative-sequence impedance is always positive (Z_2 = negative value / negative value).

To summarize:

Forward fault

$Z_2 = V_2 / I_2 = 10<180 / 3<-90 = 3.33<270$ ohms or …

$Z_2 = -3.33$ ohms

Reverse fault

$Z_2 = V_2 / I_2 = 10<180 / 3<90 = 3.33<90$ ohms or …

$Z_2 = +3.33$ ohms

Since a ratio of voltage to current is used, faults with very little negative-sequence voltage can be detected. As negative-sequence voltage is reduced, negative-sequence impedance tends to zero. As will be covered in the next section, a negative-sequence impedance of essentially zero can be detected and acted upon based on the settings of the element. In general, a negative-sequence impedance of zero will be indicative of a forward fault.

Settings for the Negative-Sequence Impedance Directional Element

There are five settings required for the negative-sequence impedance directional element in the SEL-321 Relay. These settings consist of a forward and reverse negative-sequence impedance threshold (Z2F and Z2R), a forward and reverse negative-sequence current threshold (50QF and 50QR), and a positive-sequence current restraint factor (a2).

The settings Z2F and Z2R are the main settings for this directional element. Since a reverse fault gives a negative-sequence impedance which is positive and a forward fault gives a negative-sequence impedance which is negative, Z2R is always set more positive than Z2F. For practically every application, Z2F can be set for ½ the positive-sequence impedance of the line and Z2R can be set equal to Z2F + 0.1 ohms. Any measured negative-sequence impedance which is less than the Z2F setting is declared as a forward fault and any measured negative-sequence impedance which is more than Z2R is considered a reverse fault.

The 50QF and 50QR settings act as fault detectors for forward and reverse faults respectively. These elements act on $3I_2$, not I_2. For a forward fault declaration, the magnitude of $3I_2$ must exceed the 50QF setting. For a reverse fault declaration, the magnitude of $3I_2$ must exceed the 50QR setting. Typical settings for these elements are 50QF = 0.5 amps and 50QR = 0.25 amps.

The positive-sequence current restraint factor acts as a supervisory condition for the directional element. The negative-sequence impedance directional element detects all unbalanced fault types and is not intended for balanced faults (three-phase faults). Line asymmetries result in a small amount of negative-sequence current and thereby negative-sequence voltage being present during balanced three-phase faults. The a2 element prevents the negative-sequence impedance directional element from operating by requiring the negative-sequence current (I_2) to exceed the positive-sequence current times the a2 setting. Typical settings for the a2 element are 0.07 to 0.1 (this setting is a ratio and therefore unitless).

TESTING THE NEGATIVE-SEQUENCE IMPEDANCE DIRECTIONAL ELEMENT

To test the negative-sequence impedance directional element, we will need to know the values for the above five settings; Z2F, Z2R, 50QF, 50QR, and a2. In addition, we will need to know the characteristic angle of the line which is given with the Z1ANG setting.

For this example, we will use the following settings:

Z2F = 3.9 ohms
Z2R = 4.0 ohms
50QF = 0.5 amps
50QR = 0.25 amps
a2 = 0.1
Z1ANG = 83.97 degrees

Next we will prepare the SEL-321 Relay. We are interested in testing only the directional element so we will isolate the forward and reverse outputs of the directional element. A forward directional decision is indicated by the 32QF Relay Word bit and a reverse directional decision is indicated by the 32QR Relay Word bit. To assign these Relay Word bits to individual output contacts, issue the following commands from Access Level 2 in the SEL-321 Relay.

```
=>>SET L OUT7 TERSE
SELogic group 1

OUT7  =NA

 ? 32QR
OUT8  =NA

 ? 32QF
OUT9  =NA

 ? END
Save changes (Y/N) ? Y
Settings saved
```

Any outputs may be used. This example is using Output 7 to indicate a reverse decision and Output 8 to indicate a forward decision.

We will also disable loss-of-potential (LOP) logic by making the following settings. Disabling the LOP logic will prevent this logic from asserting during the testing. When LOP logic asserts, the negative-sequence impedance directional element defaults to a forward decision. A typical pickup for the LOP logic is 14 volts of negative-sequence voltage which is easy to achieve during testing.

```
=>>SET ELOP TERSE
GROUP 1

Enable Loss-of-Potential: (Y/N)                ELOP  = Y       ? N
Loss-Of-Potential Delay: (TDPU)(1-60 cyc)      LOPD  = 3.00    ? END
Save changes (Y/N) ? Y
Settings saved
```

To test the negative-sequence directional element, the outputs assigned to 32QR and 32QF will need to be monitored. In this example, these are Outputs 7 and 8.

To calculate pickup and dropout values, we will use the equation $Z_2 = V_2 / I_2$ or $3V_2 / 3I_2$. We will apply a simulated single-phase-to-ground fault and monitor the directional element.

To calculate negative-sequence voltage and negative-sequence current for our phase-to-ground fault, we will use simplified equations.

- Negative-Sequence Current, Single-Phase

  We will assume a radial system so that only a single-phase current is involved. That way, $3I_2$ will equal the faulted phase current in magnitude and angle.

$$I_2 = 1/3 \cdot (Ia + a^2Ib + aIc)$$
$$\text{if } Ib = Ic = 0, \text{ then}$$
$$3I_2 = Ia$$

- Negative-Sequence Voltage, Single-Phase

  If a single-phase voltage source is used, the same principle holds true. $3V_2$ will equal the single-phase voltage applied in magnitude and angle.

$$V_2 = 1/3 \cdot (Va + a^2Vb + aVc)$$
$$\text{if } Vb = Vc = 0, \text{ then}$$
$$3V_2 = Va$$

- Negative-Sequence Voltage, Three-Phase

  In our negative-sequence voltage calculation above, we saw that for balanced phase angles (0, -120, 120), $3V_2$ = 'healthy phase voltage' - 'faulted phase voltage' at a phase angle 180 degrees opposite of the faulted phase voltage. That is, our example used:

$$Va = 37<0$$
$$Vb = 67<-120$$
$$Vc = 67<120$$
$$3V_2 = 67 - 37 = 30<180 \text{ volts}$$

Use these equations to determine negative-sequence voltage and current for testing purposes.

Next, calculate the pickups for each of the negative-sequence impedance thresholds.

$Z2F = 3.9 \text{ ohms} = 3V_2 / 3I_2$
therefore, $3I_2 = 3V_2 / Z2F = 3V_2 / 3.9$

Choose a suitable value of $3V_2$ which gives a reasonable (and obtainable) $3I_2$. For this example, a negative-sequence voltage of $3V_2 = 30$ volts will work fine.

$3I_2 = 3V_2 / Z2F = 30 / 3.9 = 7.69$ amps

Do the same calculation for the reverse pickup.

$Z2R = 4.0 \text{ ohms} = 3V_2 / 3I_2$
therefore, $3I_2 = 3V_2 / Z2R = 30 / 4.0 = 7.5$ amps

Apply $3V_2 = 30<180$ volts to the relay by one of the two methods described above.

Single-Phase	Three-Phase
Va = 30<180 volts	Va = 37<0 volts
	Vb = 67<-120 volts
	Vc = 67<120 volts

Next, apply the current and slowly raise the magnitude keeping the phase angle constant. Since both thresholds in this example are positive (Z2F=3.9 ohms, Z2R=4.0 ohms) indicating a reverse fault, the current applied will have a phase angle of 180 degrees out-of-phase for a forward fault. We are using A-phase for this example so a forward fault would have an angle of <Va - MTA or 0 - 83.97 = -83.97 degrees. Add 180 to this to get 96.03 degrees for the test angle.

Adjust the current phase angle to +96.03 degrees and slowly raise the current applied to the Ia input on the relay. At the 50QR setting of 0.25 amps, the 32QR element should pick up indicating a reverse fault. At the Z2R threshold of 7.5 amps, the 32QR element should drop out. At the Z2F threshold of 7.69 amps, the 32QF element should pickup.

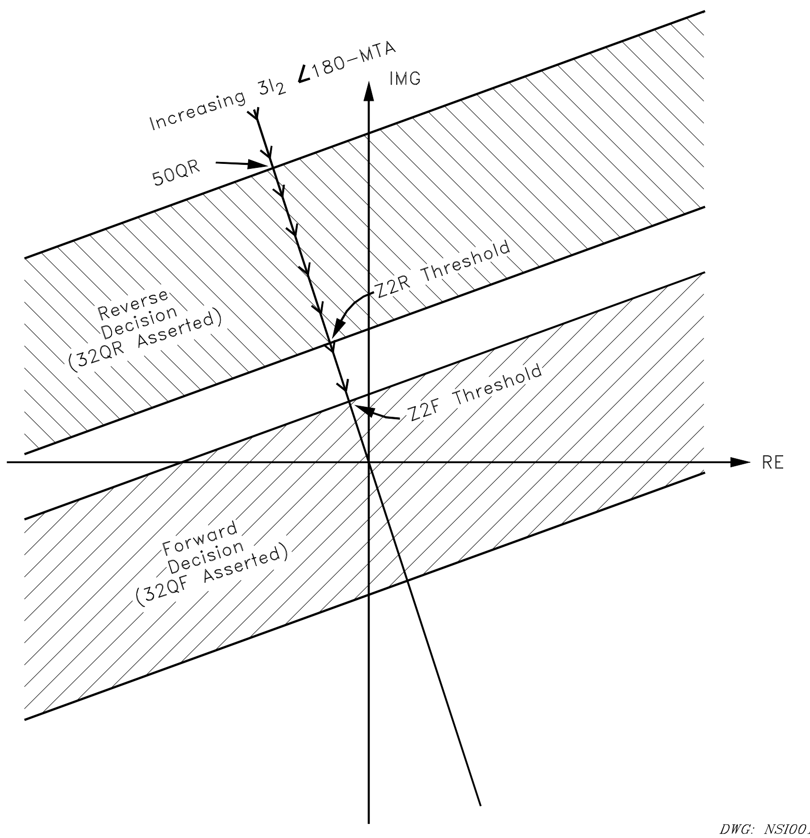

Figure 2: Both Z2R and Z2F are Positive

For most applications, Z2F and Z2R will be set to positive values. It is possible to encounter situations where Z2R and Z2F are negative. Specifically, two other conditions can occur: Z2R is positive and Z2F is negative or Z2R and Z2F are both negative. Testing these two conditions require a slight modification to the above procedures.

If Z2R is positive and Z2F is negative, two separate tests must be ran to test the entire directional element. First, start with the current phase angle adjusted for a reverse fault and slowly raise the current. At the 50QR setting, 32QR will assert. As the current is raised further, the 32QR element will drop out at the calculated Z2R threshold. Next, start with the current phase angle adjusted for a forward fault and slowly raise the current. At the 50QF setting the 32QF element will assert. As the current is raised further, the 32QF element will drop out at the calculated Z2F threshold.

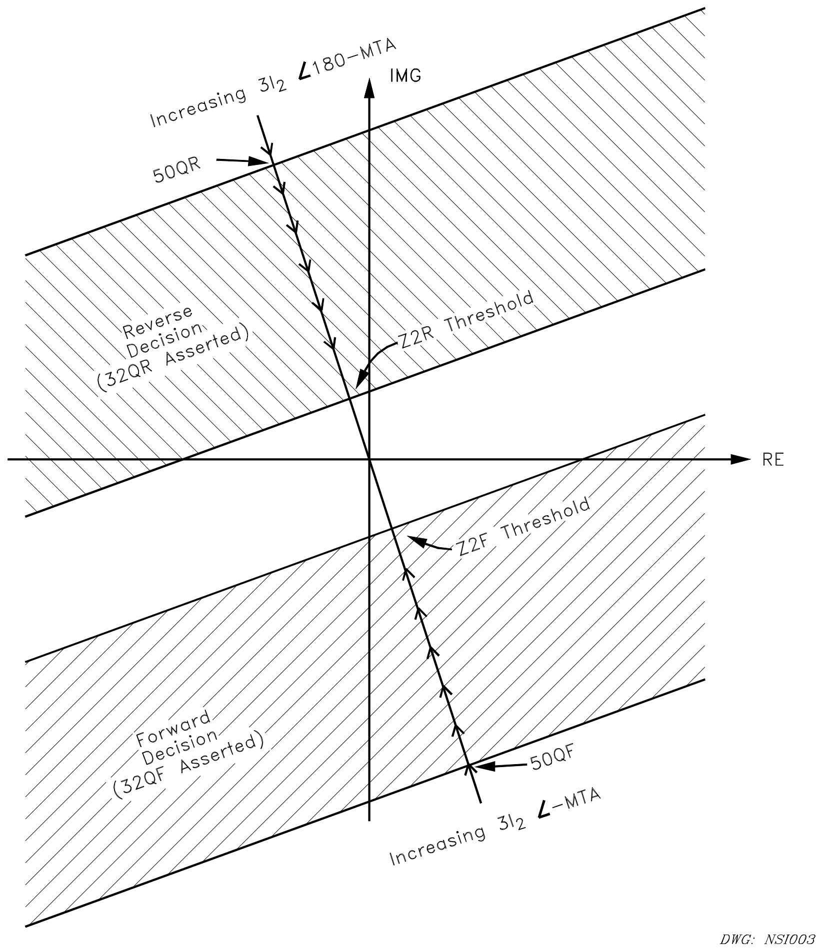

Figure 3: Z2R is Positive and Z2F is Negative

If Z2R and Z2F are both negative, only one test is needed to test the entire directional element. Adjust the current phase angle for a forward fault and slowly raise the current magnitude. At the 50QF setting, 32QF will assert. As the current is raised further, the 32QF element will drop out at the calculated Z2F threshold. As the current is raised further, the 32QR element will assert as the current magnitude reaches the calculated Z2R threshold.

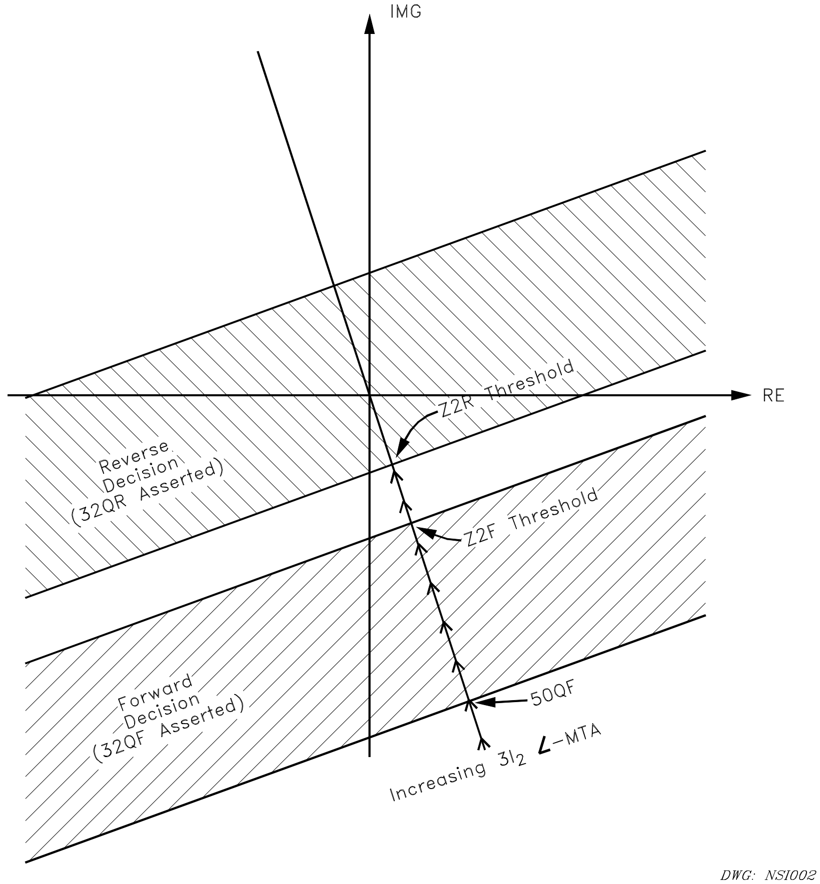

Figure 4: Both Z2R and Z2F are Negative

SUMMARY

To test the negative-sequence impedance directional element:

1. Determine the settings for Z2R and Z2F by examining the SEL-321 Relay settings.

2. Calculate the pickup current ($3I_2$) for these values using the equations $3I_2 = 3V_2$ / Z2R for the reverse threshold and $3I_2 = 3V_2$ / Z2F for the forward threshold.

3. Select a suitable $3V_2$ test voltage to apply which gives reasonable (and obtainable) $3I_2$ values for the reverse and forward threshold tests.

4. Apply the selected $3V_2$ using a single-phase voltage (at an angle of 180) or three-phase voltage (with the voltage at 0 degrees depressed) as discussed above.

5. When both (Z2R and Z2F) thresholds are positive, apply A-phase current at an angle of 180 - MTA. Slowly raise the current watching as the reverse element (32QR) picks up at the 50QR setting and drops out at the calculated reverse threshold. Continue to raise the current watching as the forward element picks up at the calculated forward threshold.

6. When Z2R is positive and Z2F is negative, first apply A-phase current at an angle of 180-MTA. Slowly raise the current watching as the reverse element (32QR) picks up at the 50QR setting and drops out at the calculated reverse threshold. Next, apply A-phase current at an angle of -MTA. Slowly raise the current watching as the forward element (32QF) picks up at the 50QF setting and drops out at the calculated forward threshold.

7. When both (Z2R and Z2F) thresholds are negative, apply A-phase current at an angle of -MTA. Slowly raise the current watching as the forward element (32QF) picks up at the 50QF setting and drops out at the calculated forward threshold. Continue to raise the current watching as the reverse element picks up at the calculated reverse threshold.