Single-Phase Testing of the SEL-487E Differential Element Without State Simulation

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INTRODUCTION

When testing a differential element, it is desirable to only use current on a single phase. Although this does not simulate actual conditions on a system, it does provide adequate proof that the relay has been set as desired. In addition, single-phase testing simplifies the test and makes it suitable for all test sets because not all test sets have six current channels to drive a three-phase test.

State simulation, or an automated test in which a fault state is applied after a prefault state is first applied, mimics actual conditions on a power system accurately. However, steady-state testing is often preferred because it can be done manually and is simpler. This application guide demonstrates steady-state, single-phase testing of the SEL-487E Transformer Protection Relay differential element and does not require state simulation. For a complete reference on testing this relay, refer to SEL Application Guide AG2010-07 [1].

The SEL-487E has a phase differential element that varies in its operation from the element found in other SEL transformer protection relays. The traditional percentage restraint differential characteristic is shown in Figure 1.

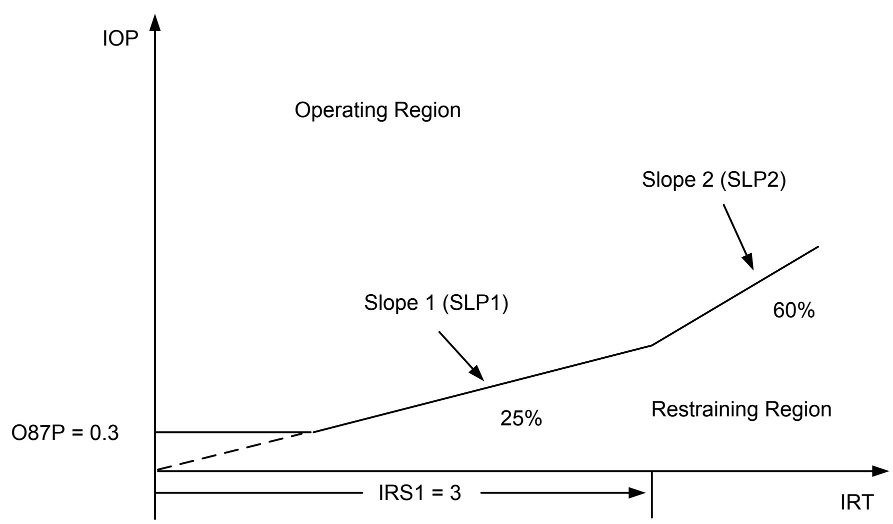

Figure 1 Traditional Percentage Restraint Differential Characteristic

The relay has four main settings that directly define the shape of the characteristic, as shown in Figure 1, but during operation, the characteristic is fixed. This makes single-phase testing of this element relatively straightforward.

The SEL-487E, on the other hand, has a differential characteristic that changes dynamically during operation. The relay operates on Slope 1 during normal operation but switches to a high-security mode (Slope 2) when an external fault is detected. The characteristic is shown in Figure 2.

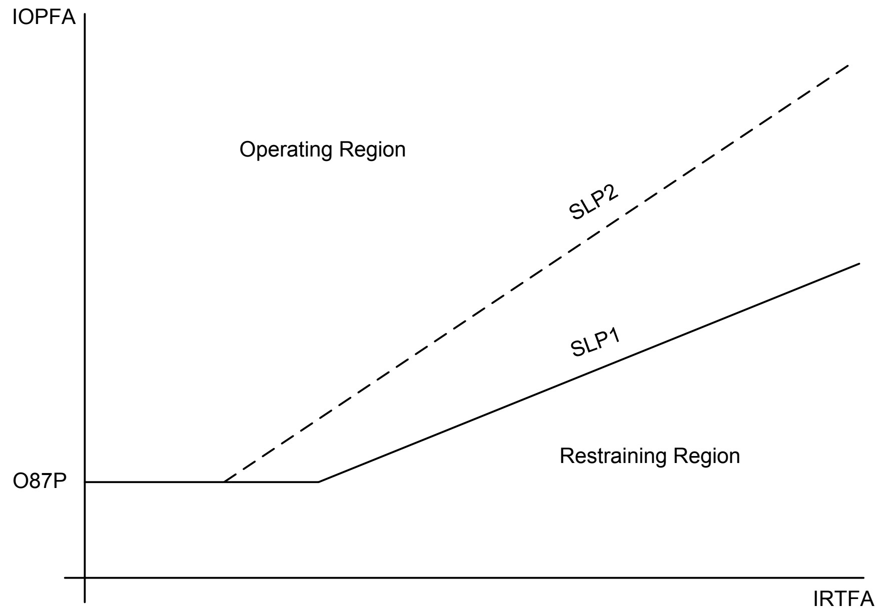

Figure 2 SEL-487E Filtered Differential Characteristic

Testing the Slope 1 (SLP1) setting is similar to the method used to test the slopes of the traditional characteristic. However, in order to test Slope 2 (SLP2), an external fault must be simulated to put the relay into high-security mode. This requirement obviously complicates the test procedure, but this application guide discusses a simple method to test the element. Five tests are run in total: U87P, O87P, SLP1, and two SLP2 tests.

Sample System

In order to explain the necessary tests, we use a sample transformer to calculate the test points. The three-line diagram of the system is shown in Figure 3, and the corresponding settings are listed in Table 1.

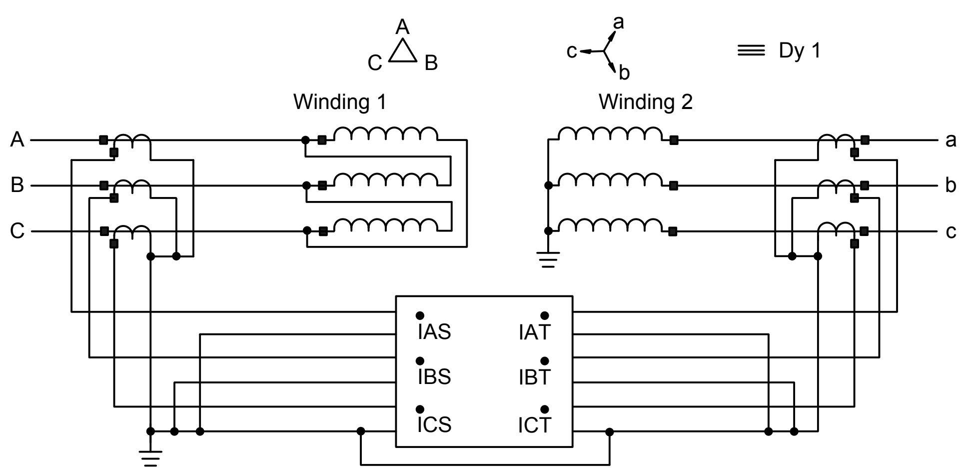

Figure 3 Sample System Three-Line Diagram

Table 1 Sample System Settings

Setting	Description	Units	Range	Assigned Value
ECTTERM	Enable the following current terminals	NA	S, T, U, W, X	S, T
E87	Include the following terminals in the differential element	NA	S, T, U, W, X	S, T
CTRS	Current transformer (CT) ratio for Terminal S	NA	1 to 50000	60
CTCONS	CT connection for Terminal S	NA	Y, D	Y
CTRT	CT ratio for Terminal T	NA	1 to 50000	500
CTCONT	CT connection for Terminal T	NA	Y, D	Y
E87TS	Include Terminal S in the differential element for the following conditions	SELOGIC® control equations	NA	1
E87TT	Include Terminal T in the differential element for the following conditions	SELOGIC control equations	NA	1
ICOM	Internal CT connection matrix compensation enabled	NA	Y, N	Y
TSCTC	Terminal S CT connection compensation	NA	0 to 12	12
TTCTC	Terminal T CT connection compensation	NA	0 to 12	1
MVA	Transformer maximum MVA rating	MVA	1 to 5000, OFF	50
VTERMS	Terminal S nominal line-to-line voltage	kV	1.00 to 1000.00	138
VTERMT	Terminal T nominal line-to-line voltage	kV	1.00 to 1000.00	12.47
TAPS	Terminal S current tap	A	0.50 to 175.00	3.48
TAPT	Terminal T current tap	A	0.50 to 175.00	4.63
U87P	Unrestrained element current pickup	Multiples of tap	1.00 to 20.00	8
O87P	Differential element operating current pickup	Multiples of tap	0.10 to 4.00	0.5
SLP1	Slope 1 setting	Percent	5.00 to 100.00	35
SLP2	Slope 2 setting	Percent	5.00 to 100.00	75
DIOPR	Incremental operate current pickup	Multiples of tap	0.10 to 10.00	1.2
DIRTR	Incremental restraint current pickup	Multiples of tap	0.10 to 10.00	1.2

TEST PROCEDURE

U87P

The unrestrained differential element operates on the fundamental operate current calculated by the relay. As the name implies, it is unaffected by harmonic blocking or restraint elements enabled in the relay. The operate current is compared to the U87P setting, and the output (87U*n*, where *n* = A, B, or C) is asserted for values greater than the set point.

This element can be tested by applying a single-phase current to one winding in excess of the U87P setting and monitoring the 87U*n* Relay Word bit. However, note that the U87P setting is in per unit (pu) of the corresponding tap setting and, therefore, must be converted to amperes (A).

Figure 4 shows a block diagram of the differential element in the relay.

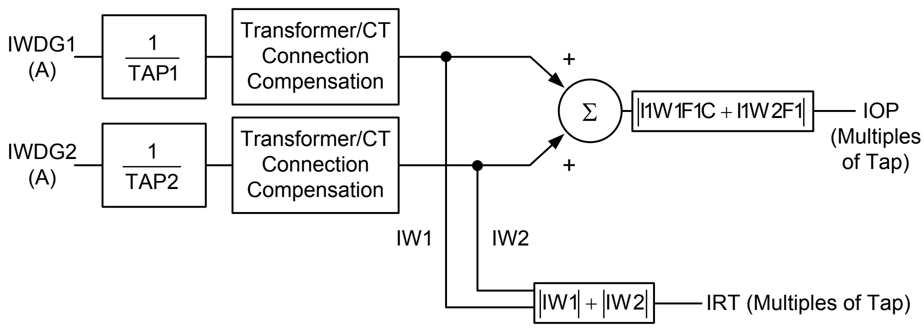

Figure 4 Differential Element Block Diagram

In addition to multiplying by the tap, the currents must also be scaled by the compensation constant found in Table 2 because a single-phase test is being performed instead of a three-phase test.

Table 2 Compensation Constants for Single-Phase Testing Using IA Inputs to Test Element 87-1

TnCTC Setting	A (Winding 1)	B (Winding 2)
0	1	1
1	$\sqrt{3}$	$\sqrt{3}$
2	3	3
3	$\sqrt{3}$ [1]	$\sqrt{3}$ [1]
4	–3	–3
5	$-\sqrt{3}$	$-\sqrt{3}$
6	–1.5	–1.5
7	$-\sqrt{3}$	$-\sqrt{3}$
8	–3	–3
9	$\sqrt{3}$ [2]	$\sqrt{3}$ [2]
10	3	3
11	$\sqrt{3}$	$\sqrt{3}$
12	1.5	1.5

[1] Inject current on ICn terminal instead of IAn terminal.

[2] Inject current on IBn terminal instead of IAn terminal.

Refer to the SEL-487E Instruction Manual, available at http://www.selinc.com, for a complete listing of the compensation matrices. In the T*n*CTC matrix notation, the columns represent IA*n*, IB*n*, and IC*n*, left to right, and the rows represent differential elements 87-1, 87-2, and 87-3, top to bottom. Using IA inputs to test element 87-1 results in the need to use the factors in the upper-left corner of the matrix. Note that the 87-2 and 87-3 elements may also assert during the tests discussed in this application guide, but they are to be disregarded. In Table 2, the compensation constants are derived as follows:

- The odd-numbered matrices are multiplied by $1/\sqrt{3}$, so it is necessary to multiply the test current by $\sqrt{3}$ to compensate. The factor in the upper-left corner of the matrix is 1, except for Matrices 3 and 9, so it has no effect. Matrices 3 and 9 have a zero in the upper-left corner and thus require current to be injected on either IBn or ICn, as noted in Table 2.
- Matrices 2, 4, 8, and 10 are multiplied by 1/3, so it is necessary to multiply the test current by 3 to compensate. The factor in the upper-left corner of the matrix is 1, so it has no effect.

- The 6 and 12 matrices are multiplied by 1/3, so it is necessary to multiply the test current by 3 to compensate. These matrices include a factor of 2 in the upper-left position, so it is necessary to divide the test current by 2 to compensate. The resulting compensation factor is 1.5.
- If the sign of the compensation constant is negative, the phase angle for that current does not need to be rotated by 180 degrees in the restraint tests.

Using the sample system settings, the calculated test point for A-phase on Terminal S is:

$$\text{IAS} = \text{U87P} \bullet \text{TAPS} \bullet \text{A} = 8 \bullet 3.48 \bullet 1.5 = 41.76 \text{ A} \tag{1}$$

Note that this value is well above the continuous rating (15 A) of the current input channels on the relay. However, the relay inputs are rated for 500 A for 1 second. This is equivalent to 250000 A secondary (I^2t). Therefore, we can solve for the maximum time the test current may be applied without damage to the input as follows:

$$\frac{250000}{I_{\text{test}}^{2}} = \frac{250000}{41.76^{2}} = 143 \text{ s} \tag{2}$$

Therefore, apply 35 A to the IAS relay terminal, and increase the current while monitoring the 87UA Relay Word bit using the **TAR 87UA 10000** command in the terminal window. 87UA should assert at 41.76 A, ± 5 percent.

O87P

The O87P setting defines the minimum operate current required to have a differential element operation. It is tested using the same method as the U87P test described in the previous section.

The test point for the sample system is:

$$\text{IAS} = \text{O87P} \bullet \text{TAPS} \bullet \text{A} = 0.5 \bullet 3.48 \bullet 1.5 = 2.61 \text{ A} \tag{3}$$

Therefore, apply 2 A to the IAS relay terminal, and increase the current while monitoring the 87RA Relay Word bit using the **TAR 87RA 10000** command in the terminal window. 87RA should assert at 2.61 A, ± 5 percent.

SLP1

The first step in the SLP1 test is to determine an acceptable restraint value. This is done by determining the point where SLP1 intersects the minimum operate restriction, O87P. Below this restraint value, the relay does not operate on SLP1. Therefore, a valid test point must be beyond this point. The smallest restraint value that can be selected is shown in (4), along with the corresponding value for the sample system.

$$\text{IRT} = \text{O87P} \bullet \frac{100}{\text{SLP1}} = 0.5 \bullet \frac{100}{35} = 1.43 \text{ pu} \tag{4}$$

Therefore, to make it simple, we will select IRT = 2.0 pu as our test point. The corresponding operate current for the point on the SLP1 line is then:

$$\text{IOP} = \text{IRT} \bullet \frac{\text{SLP1}}{100} = 2.0 \bullet \frac{35}{100} = 0.70 \text{ pu} \tag{5}$$

Similar to the first two tests, this pu point must be converted to input current. Unlike the first two tests, the SLP1 test requires the use of two currents, IAS and IAT. Referencing Figure 4, the compensated currents, IW1 and IW2, can be found by beginning with $\frac{\text{IRT}}{2}$ for each, with IW1 at 0 degrees and IW2 at 180 degrees. This gives the correct amount of restraint current but no operate current. Adding half of the desired operate current to IW1 and subtracting half of the desired operate current from IW2 give both the correct operate and restraint values. The equations are as follows:

$$\text{IW1} = \frac{(\text{IRT} + \text{IOP})}{2} = \frac{(2.0 + 0.7)}{2} = 1.35 \text{ pu} \tag{6}$$

$$\text{IW2} = \frac{(\text{IRT} - \text{IOP})}{2} = \frac{(2.0 - 0.7)}{2} = 0.65 \text{ pu} \tag{7}$$

IW1 and IW2 can now be converted to IAS and IAT, respectively, by multiplying by the corresponding tap and compensation constant.

$$\text{IAS} = \text{IW1} \bullet \text{TAPS} \bullet \text{A} = 1.35 \bullet 3.48 \bullet 1.5 = 7.05\angle 0° \text{ A} \tag{8}$$

$$\text{IAT} = \text{IW2} \bullet \text{TAPT} \bullet \text{T} = 0.65 \bullet 4.63 \bullet 1.73 = 5.21\angle 180° \text{ A} \tag{9}$$

This test is performed by applying the calculated value to the IAS terminal and a current greater than the calculated value (6.0∠180° A) to the IAT terminal. This results in a smaller operate value, and the relay will be in the restraint region below the SLP1 line. **Slowly** decrease the current applied to the IAT terminal while monitoring the 87RA Relay Word bit. The element should assert when IAT = 5.21 A, ± 5 percent.

The path of this test is shown in Figure 5, where point [2.1, 0.6] corresponds to the initial current of IAS = 7.05∠0° A and IAT = 6.0∠180° A.

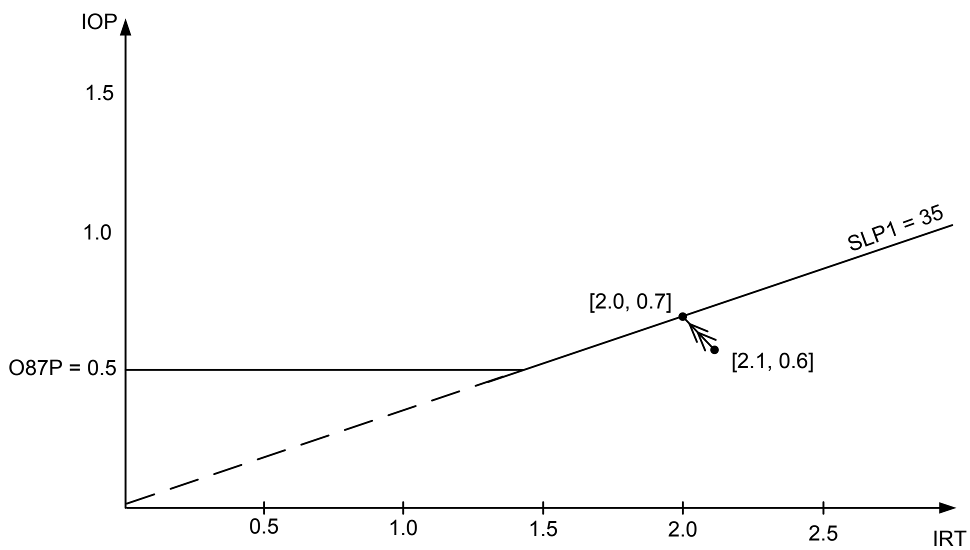

Figure 5 SLP1 Test

SLP2

As previously discussed, the testing method will not suffice for testing SLP2 because this slope is only active while the relay is in high-security mode. This is controlled by the CON*n* Relay Word bit that may be asserted for a minimum of 3 cycles and a maximum of 60 cycles, or 1 second. The fault detection logic is shown in Figure 6.

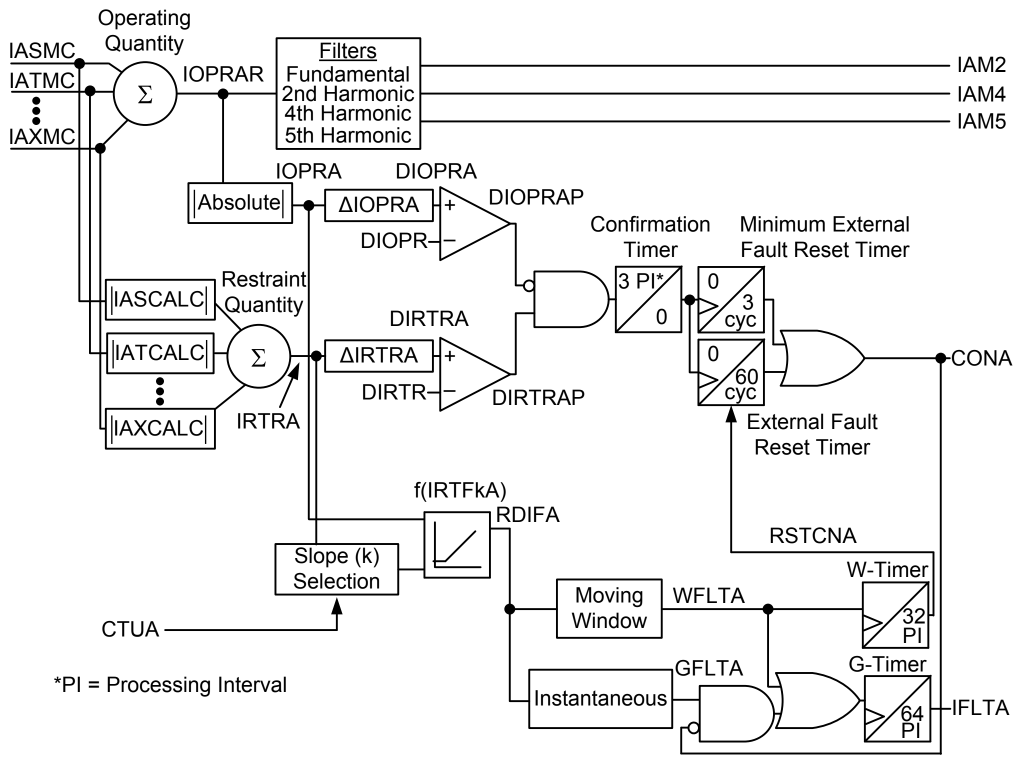

Figure 6 Fault Detection Logic Diagram

First of all, note that the fault detection logic operates on raw differential quantities rather than the filtered quantities used to determine relay operation (87U*n* and 87R*n*). Therefore, because these are instantaneous raw values, the 60 Hz component is $\sqrt{2}$ larger than the filtered quantities. This fact is very important in calculating correct test points for the SLP2 tests.

An external fault is detected when a change in restraint current greater than DIRTR (relay setting) occurs without a corresponding change in operate current greater than DIOPR (relay setting). When this occurs for $\frac{3}{32}$ cycle, the relay asserts the CON Relay Word bit for the corresponding phase, driving both the raw and filtered differential elements to a high-security mode for up to 1 second. (Note that DIRTR and DIOPR should **not** be changed from their default values of 1.2 without sufficient simulation and testing.)

Because this does not allow enough time to ramp currents, two separate tests must be performed to verify the SLP2 setting. The points for the sample system are illustrated in Figure 7 and discussed in the following sections.

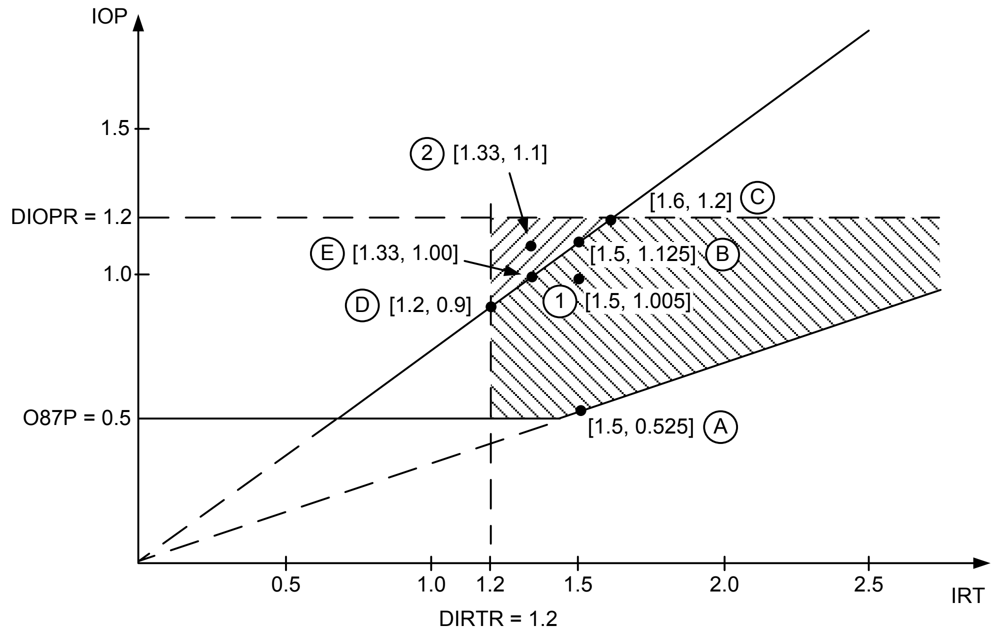

Figure 7 SLP2 Raw Test Points

The Microsoft® Excel® spreadsheet, SEL-487E Slope Characteristic, available for download with this application guide at http://www.selinc.com, is provided to assist users in calculating test points and visualizing these tests.

Test 1

The purpose of Test 1 is to force the relay into high-security mode and verify that the relay is secure for 1 second (CON*n* maximum seal-in time) for a test point greater than SLP1 and slightly below SLP2.

The first step is to select a restraint value greater than 1.2. However, note that the corresponding operate value must be less than 1.2. This causes the relay to detect an external fault and switch to high-security mode, enabling SLP2. For the sample system, we select a restraint value of 1.5. Note that the **SEL-487E Slope Characteristic** spreadsheet automatically selects a restraint value in this range to match that of Point 2 in Figure 7. See (18) for calculation details.

The corresponding operate value may be selected anywhere between SLP1 and SLP2, but it is recommended that a point closer to SLP2 be used to more accurately prove the SLP2 setting. On the sample system, we calculate operate values at Points A and B, which correspond to SLP1 and SLP2, respectively.

$$A_{OP} = 1.5 \bullet \frac{\text{SLP1}}{100} = 1.5 \bullet \frac{35}{100} = 0.525 \text{ pu} \tag{10}$$

$$B_{OP} = 1.5 \bullet \frac{\text{SLP2}}{100} = 1.5 \bullet \frac{75}{100} = 1.125 \text{ pu} \tag{11}$$

The selected test point is 80 percent of the distance from SLP1 to SLP2.

$$1_{OP} = A_{OP} + 0.8\,(B_{OP} - A_{OP}) = 0.525 + 0.8(1.125 - 0.525) = 1.005 \text{ pu} \tag{12}$$

Now that Test Point 1 has been selected, [1.5, 1.005], the point must be converted to amperes, similar to the O87P test. One extra factor must be added in this test: the compensated quantities must be divided by $\sqrt{2}$ to convert from instantaneous raw values to steady-state test quantities. The calculations for the sample system are shown below.

$$\text{IW1} = \frac{(\text{IRT} + \text{IOP})}{2} = \frac{(1.5 + 1.005)}{2} = 1.25 \text{ pu} \tag{13}$$

$$\text{IW2} = \frac{(\text{IRT} - \text{IOP})}{2} = \frac{(1.5 - 1.005)}{2} = 0.25 \text{ pu} \tag{14}$$

Converting to amperes using tap, compensation constant, and $\sqrt{2}$ yields:

$$\text{IAS} = \text{IW1} \bullet \text{TAPS} \bullet \frac{\text{A}}{\sqrt{2}} = 1.25 \bullet 3.48 \bullet \frac{1.5}{\sqrt{2}} = 4.61\angle 0° \text{ A} \tag{15}$$

$$\text{IAT} = \text{IW2} \bullet \text{TAPT} \bullet \frac{\text{B}}{\sqrt{2}} = 0.25 \bullet 4.63 \bullet \frac{1.73}{\sqrt{2}} = 1.42\angle 180° \text{ A} \tag{16}$$

Before applying the test, it is important to add both 87RA and CONA to the Sequential Events Recorder (SER) using a **SET R** command in the terminal window or the report settings in the Settings Editor of the ACSELERATOR QuickSet® SEL-5030 Software.

The test should be applied for just over 1 second. The result is that CONA should assert for exactly 1 second. Once it deasserts, the relay returns to SLP1, and 87RA trips. This sequence is shown below.

```
#      DATE         TIME              ELEMENT     STATE
40     09/29/2009   12:24:12.9454     CONA        Asserted
39     09/29/2009   12:24:13.9455     CONA        Deasserted
38     09/29/2009   12:24:13.9605     87RA        Asserted
```

Test 2

The second test is to verify that if the relay is in high-security mode, it will operate for a point above SLP2. Therefore, the test point must be selected in the upper triangle in Figure 7, where operate current is less than 1.2, restraint current is above 1.2, and operate current over restraint current is greater than $\frac{\text{SLP2}}{100}$. To find the best test point, find the restraint value for Point C and select a restraint value that is $\frac{1}{3}$ of the distance from Point D to Point C.

The calculations for the sample system are as follows:

$$\text{C}_{\text{RT}} = \text{DIOPR} \bullet \frac{100}{\text{SLP2}} = 1.2 \bullet \frac{100}{75} = 1.60 \text{ pu} \tag{17}$$

$$2_{\text{RT}} = 1.2 + \frac{(1.6 - 1.2)}{3} = 1.33 \text{ pu} \tag{18}$$

Now that we have selected a restraint quantity, the corresponding operate current should be chosen halfway between SLP2 and DIOPR. Again, the sample system calculations are shown below.

$$E_{OP} = 2_{RT} \bullet \frac{SLP2}{100} = 1.33 \bullet \frac{75}{100} = 1.00 \text{ pu} \tag{19}$$

$$2_{OP} = E_{OP} + \frac{(DIOPR - E_{OP})}{2} = 1.10 \text{ pu} \tag{20}$$

Similar to Test 1, Test Point 2, [1.33, 1.10], must be converted to amperes. The sample system calculations are as follows:

$$IW1 = \frac{(IRT + IOP)}{2} = \frac{(1.33 + 1.10)}{2} = 1.215 \text{ pu} \tag{21}$$

$$IW2 = \frac{(IRT - IOP)}{2} = \frac{(1.33 - 1.10)}{2} = 0.115 \text{ pu} \tag{22}$$

Converting to amperes using tap, compensation constant, and $\sqrt{2}$ yields:

$$IAS = IW1 \bullet TAPS \bullet \frac{A}{\sqrt{2}} = 1.215 \bullet 3.48 \bullet \frac{1.5}{\sqrt{2}} = 4.48\angle 0° \text{ A} \tag{23}$$

$$IAT = IW2 \bullet TAPT \bullet \frac{B}{\sqrt{2}} = 0.115 \bullet 4.63 \bullet \frac{1.73}{\sqrt{2}} = 0.65\angle 180° \text{ A} \tag{24}$$

The test should be applied for less than 1 second. The result is that CONA should assert first, followed by 87RA a couple of cycles later. The assertion of 87RA resets the CONA bit that deasserts 3 cycles, or 50 milliseconds, later. This sequence is shown below.

#	DATE	TIME	ELEMENT	STATE
34	09/29/2009	12:29:07.1996	CONA	Asserted
33	09/29/2009	12:29:07.2286	87RA	Asserted
32	09/29/2009	12:29:07.2326	87RA	Deasserted
31	09/29/2009	12:29:07.2496	CONA	Deasserted

This test procedure for SLP2 Test 2 works for SLP2 ≤ 85. For SLP2 > 85, state simulation is required. Use the SLP2 Test Point 1 for 30 cycles, and then remove IAT, making IOP = IRT. This forces the relay into high-security mode for 30 cycles before simulating an internal fault, at which time 87RA will assert.

CONCLUSION

This application guide demonstrates a simple method of testing both the restrained and unrestrained differential elements of the SEL-487E with single-phase, steady-state current injection. Five tests are required to prove the pickup and slope settings stored in the relay. In addition, the method provided in this application guide for testing the Slope 2 setting is simple and does not require state simulation. A detailed example with the required test point calculations and explanations has been included for ease of understanding.

REFERENCE

[1] G. Alexander, D. Costello, B. Heilman, and J. Young, "Testing the SEL-487E Relay Differential Elements," SEL Application Guide (AG2010-07), 2010. Available: http://www.selinc.com.

FACTORY ASSISTANCE

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