Testing the SEL-700G 51V Element

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Introduction

This application guide describes how to test the voltage-restrained time-overcurrent element (51V) in an SEL-700G Generator Protection Relay. A similar test procedure can be followed for the SEL-300G Generator Relay (firmware Version R240/R320 and later). This guide assumes that the user is familiar with testing time-overcurrent elements and understands basic terminal commands. For more information about terminal commands, refer to the SEL-700G Instruction Manual.

The 51V element is typically used for generator backup protection during system phase faults. The generator current contribution to a fault is initially large because it is inversely proportional to the small subtransient reactance (X_d'') of the machine. As the fault persists, the larger machine steady-state synchronous reactance (X_d) begins to dominate and causes the fault current to be lower than the maximum load current in many cases. The 51V element uses the reduced voltage during fault conditions for dependable backup protection, but it remains secure during normal load conditions.

Review of 51V Settings

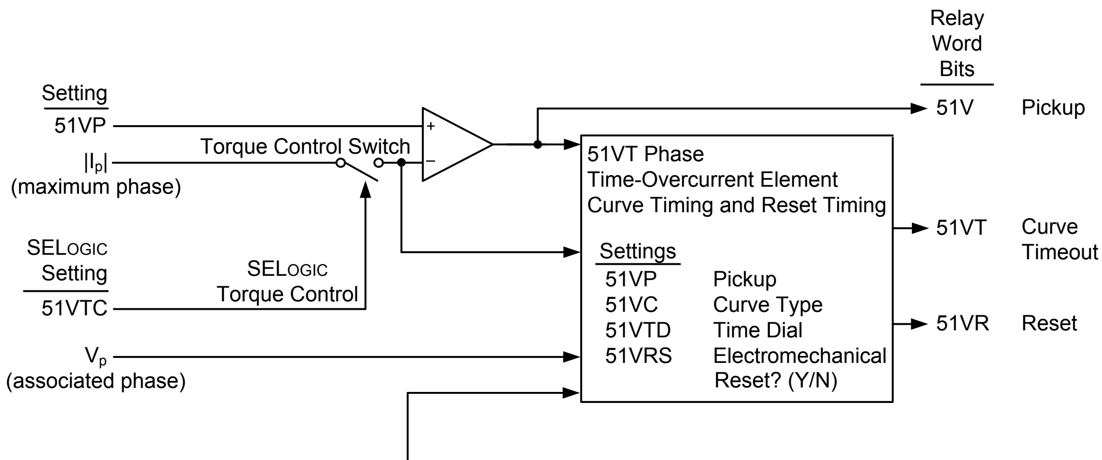
Settings associated with the 51V element are shown in Table 1. Note that the voltage-restrained settings are only settable if the backup element is set (EBUP := V or DC_V).

Table 1 51V Settings

Setting	Range	Description
EBUP	N, V, C; N, V, C, DC; or DC_V, DC_C	Backup protection enable (V for voltage restraint)
51VP	OFF, 2.00–16.00 A*	Voltage-restrained time-overcurrent pickup
51VCA	0°, –30°, 30°	Compensation angle
51VC	U1–U5, C1–C5	Curve type
51VTD	0.50–15.00 (U.S. curves), 0.05–1.00 (IEC curves)	Time-overcurrent time dial
51VRS	Y, N	Time-overcurrent electromechanical reset
51VTC	SELOGIC® control equations	Voltage-restrained time-overcurrent torque control
VNOM_X	0.20–1,000.00 kV	X-side nominal voltage (primary, line-to-line)

*Ranges are for 5 A current transformer (CT). Divide by 5 for 1 A-rated CTs.

Figure 1 shows the voltage-restrained logic. Torque control 51VTC is set to NOT LOPX by default, which disables the element if the X voltage channel detects a loss-of-potential (LOP) event such as a cleared potential transformer (PT) fuse. 51VTC can be set to logical 1 during testing, so it does not interfere, and then set back to its original value when tests are complete.



51VTC State	Torque Control Switch Position
Logical 1	Closed
Logical 0	Open

Setting 51VRS =	Reset Timing
Y	Electromechanical
N	1 Cycle

Figure 1 51V Logic Diagram

The time-overcurrent settings 51VC for curve type and 51VTD for time dial behave the same as they do for a regular phase time-overcurrent element. The pickup 51VP is scaled by a ratio of the applied voltage to the nominal voltage setting VNOM_X, as shown in Figure 2 and Equation (1).

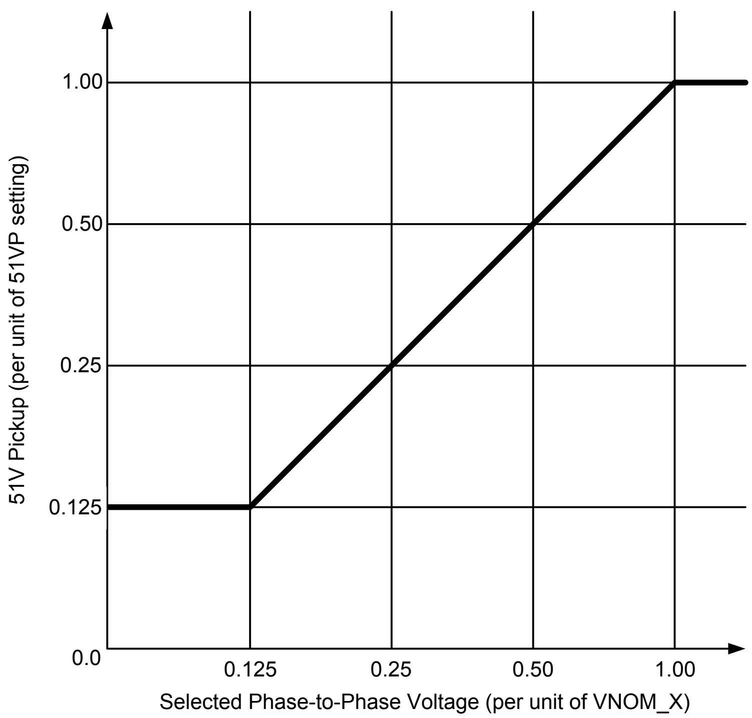


Figure 2 51V Pickup Scaled by Applied Voltage

$$
51VP_{scaled} = \begin{cases} 51VP \bullet \dfrac{\left|\overline{V_{restrain}}\right|}{\left(\dfrac{VNOM\_X \bullet 1000}{PTRX}\right)} \; if \; 0.125 \le \dfrac{\left|\overline{V_{restrain}}\right|}{\left(\dfrac{VNOM\_X \bullet 1000}{PTRX}\right)} \le 1 \\ 51VP \bullet 0.125 \; if \; \dfrac{\left|\overline{V_{restrain}}\right|}{\left(\dfrac{VNOM\_X \bullet 1000}{PTRX}\right)} < 0.125 \\ 51VP \; if \; \dfrac{\left|\overline{V_{restrain}}\right|}{\left(\dfrac{VNOM\_X \bullet 1000}{PTRX}\right)} > 1 \end{cases} \quad (1)
$$

Once the scaled pickup current is known, the time-overcurrent element expected pickup time can be found by using the equations in Appendix B. The time-overcurrent curve fully resets in one cycle when the applied current drops below the scaled pickup unless the electromechanical reset setting 51VRS is set to Y. In this case, the reset time follows the Appendix B reset equations.

When a transformer is used to tie a generator to a system, the winding connections affect which phase voltages become depressed at the generator during the fault. This can be seen by comparing Figure 8 and Figure 10 in Appendix A for each different type of fault. Setting 51VCA defines the type of phase shift that occurs in the transformer and selects the correct phase voltages to use when scaling 51VP. 51VCA := 0 is used for installations that do not have a step-up transformer or have no phase shift across the transformer. 51VCA := –30 is for transformers where the high-voltage (HV) side leads the low-voltage (LV) side by 30 degrees, as shown in Figure 9 in Appendix A. 51VCA := 30 is for transformers where the HV side lags the LV side by 30 degrees, as shown in Figure 7 in Appendix A.

The detailed voltage-restraint calculation is provided in Appendix C. The 51V element in the SEL-700G is intended for applications in which the generator is directly connected to a bus, to a wye-wye or a delta-delta transformer, or to the delta side of a delta-wye transformer.

TEST SETUP

In terminal mode, issue the **SHO** command and record the following relevant settings:

PTRX := ____________________

VNOM_X := ________________

PHROT := __________________

DELTAY_X := ______________

EBUP := ____________________

51VCA := ___________________

51VP := ____________________

51VC := ____________________

51VTD := ___________________

51VRS := ___________________

51VTC := ___________________

The test connections should be wired as shown in Figure 3 and Figure 4. If the setting DELTAY_X := WYE, use Figure 3. If the setting DELTAY_X := DELTA, use Figure 4. Notice that only two voltage sources are used with the delta connection.

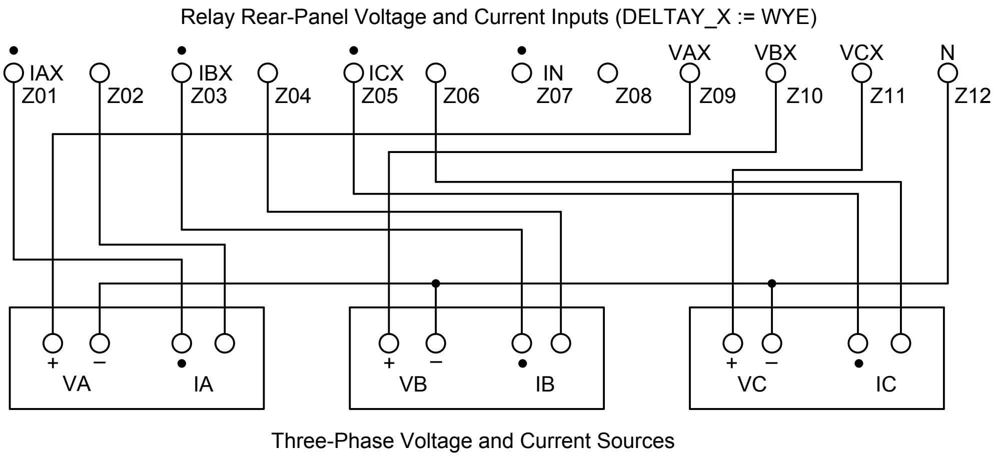


Figure 3 Test Connections for Wye-Connected PTs

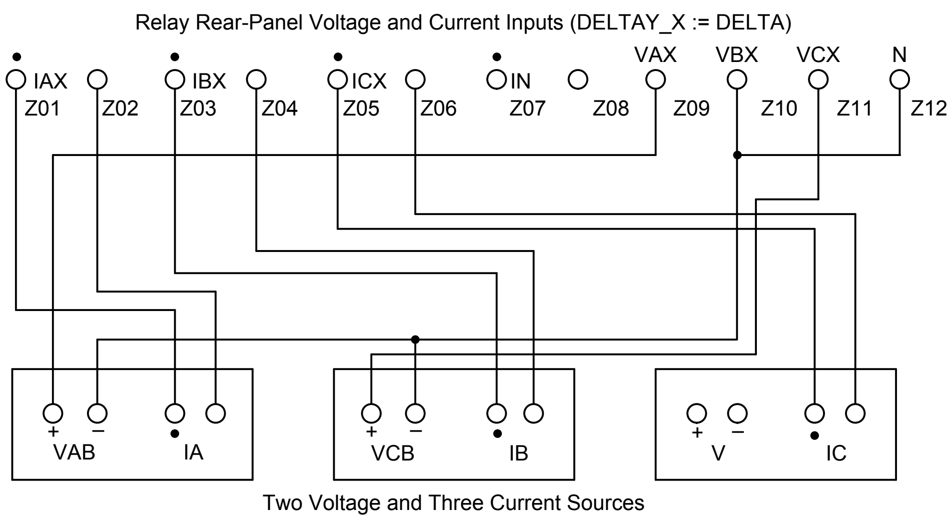


Figure 4 Test Connections for Delta-Connected PTs

The test voltage angles for wye potentials are shown in Figure 5.

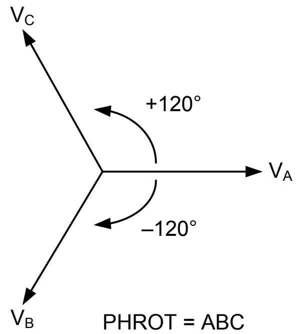


Figure 5 Wye AC Potential Connection Test Voltage Signals

When setting PHROT = ABC and DELTAY_X := WYE, set the test source phase angles as follows:

$\angle V_A = \angle I_A = 0°$

$\angle V_B = \angle I_B = -120°$

$\angle V_C = \angle I_C = 120°$

When setting PHROT = ACB and DELTAY_X := WYE, set the test source phase angles as follows:

$\angle V_A = \angle I_A = 0°$

$\angle V_B = \angle I_B = 120°$

$\angle V_C = \angle I_C = -120°$

The test voltage angles for open-delta potentials shown in Figure 6.

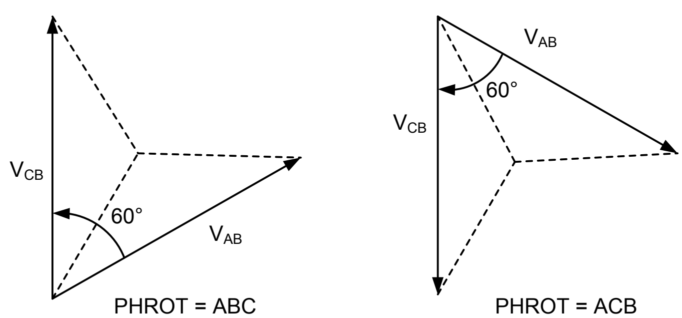


Figure 6 Open-Delta AC Potential Connection Test Voltage Signals

When setting PHROT = ABC and DELTAY_X := DELTA, set the test source phase angles as follows:

$\angle I_A = 0°$

$\angle I_B = -120°$

$\angle I_C = 120°$

$\angle V_{AB} = 30°$

$\angle V_{CB} = 90°$

When setting PHROT = ACB and DELTAY_X := DELTA, set the test source phase angles as follows:

$\angle I_A = 0°$

$\angle I_B = 120°$

$\angle I_C = -120°$

$\angle V_{AB} = -30°$

$\angle V_{CB} = -90°$

TEST PROCEDURE

Step 1

Ensure that the connections and voltage and current angles are set as described in the Test Setup section. Apply voltage on all three phases as specified by (2) if wye-connected PTs (DELTAY_X := WYE) are being used.

$$\frac{VNOM\_X \cdot 1000}{PTRX \cdot \sqrt{3}} \quad (2)$$

Apply voltage on all three phases as specified by (3) for V_{AB} and V_{CB} if delta-connected PTs (DELTAY_X := DELTA) are being used.

$$\frac{VNOM\_X \cdot 1000}{PTRX} \quad (3)$$

Do not exceed the maximum continuous voltage input of the relay (300 Vac). Verify that the metered voltages on the relay are at the nominal voltage based on the VNOM_X setting and that the correct phase angles are displayed.

Step 2

The 51VP pickup setting is in secondary A, but the actual pickup is scaled according to (1). To verify the voltage-restraint characteristic, calculate the current pickup (Iop) at the five different applied voltage levels (Vop) using Table 2.

Table 2 Test Values

Test	Applied Voltage[1]	Pickup Current
105%	$Vop1 = \frac{1.05 \bullet VNOM\_X \bullet 1000}{PTRX \bullet \sqrt{3}}$ =_____ if DELTAY_X := WYE $Vop1 = \frac{1.05 \bullet VNOM\_X \bullet 1000}{PTRX}$ = _____ if DELTAY_X := DELTA	Iop1 = 51VP =_____
95%	$Vop2 = \frac{0.95 \bullet VNOM\_X \bullet 1000}{PTRX \bullet \sqrt{3}}$ = _____ if DELTAY_X := WYE $Vop2 = \frac{0.95 \bullet VNOM\_X \bullet 1000}{PTRX}$ =_____ if DELTAY_X := DELTA	Iop2 = 0.95 • 51VP =______
50%	$Vop3 = \frac{0.5 \bullet VNOM\_X \bullet 1000}{PTRX \bullet \sqrt{3}}$ =_____ if DELTAY_X := WYE $Vop3 = \frac{0.5 \bullet VNOM\_X \bullet 1000}{PTRX}$ =_____ if DELTAY_X := DELTA	Iop3 = 0.5 • 51VP =______
15%	$Vop4 = \frac{0.15 \bullet VNOM\_X \bullet 1000}{PTRX \bullet \sqrt{3}}$ =_____ if DELTAY_X := WYE $Vop4 = \frac{0.15 \bullet VNOM\_X \bullet 1000}{PTRX}$ =_____ if DELTAY_X := DELTA	Iop4 = 0.15 • 51VP =______
7.5%	$Vop5 = \frac{0.075 \bullet VNOM\_X \bullet 1000}{PTRX \bullet \sqrt{3}}$ =_____ if DELTAY_X := WYE $Vop5 = \frac{0.075 \bullet VNOM\_X \bullet 1000}{PTRX}$ =_____ if DELTAY_X := DELTA	Iop5 = 0.125 • 51VP =______

[1]If DELTAY_X := WYE, then $|Vop| = |V_A| = |V_B| = |V_C|$ (see Figure 3). If DELTAY_X := DELTA, then $|Vop| = |V_{AB}| = |V_{CB}|$ (see Figure 4).

Step 3

If 51VCA := 0, simulate an AB fault by slowly increasing the current magnitude from 0 A on Phases A and B simultaneously for each test in Table 2. If 51VCA := 30 or 51VCA := –30, slowly increase the current magnitude from 0 A on Phase A only for each test in Table 2. Monitor the status of Relay Word bit 51V by issuing a target command (**TAR 51V 1000**) in a terminal window (to cancel the command, press **<Ctrl+X>**). Observe 51V asserting for each test when the applied current exceeds the calculated pickup. Record the pickup test currents in Table 3 and calculate the error.

Table 3 Test Values

Test	Measured Pickup Current	Error[1]
105%	Itest1 = ____________	$\text{Error1} = \frac{\text{Itest1} - \text{Iop1}}{\text{Iop1}} \cdot 100\% =$ ____________
95%	Itest2 = ____________	$\text{Error2} = \frac{\text{Itest2} - \text{Iop2}}{\text{Iop2}} \cdot 100\% =$ ____________
50%	Itest3 = ____________	$\text{Error3} = \frac{\text{Itest3} - \text{Iop3}}{\text{Iop3}} \cdot 100\% =$ ____________
15%	Itest4 = ____________	$\text{Error4} = \frac{\text{Itest4} - \text{Iop4}}{\text{Iop4}} \cdot 100\% =$ ____________
7.5%	Itest5 = ____________	$\text{Error5} = \frac{\text{Itest5} - \text{Iop5}}{\text{Iop5}} \cdot 100\% =$ ____________

[1]Steady pickup accuracy is ±5% ±0.1 A for a 5 A relay and ±5% ±0.02 A for a 1 A relay.

Step 4

Perform an overcurrent timing test by using Relay Word bits 51V (pickup) and 51VT (timeout) in the relay Sequential Events Recorder (SER) or with a test set. The curve equations are provided in Appendix B. It is recommended to test at or above 2.5 multiples of pickup.

Select a pair of Vop and Iop from Table 2. Calculate the test current magnitudes and expected operate times for different multiples of pickup in Table 4. Apply the voltage and current as described in Table 5, Table 6, Table 7, and Table 8 for respective DELTAY_X and 51VCA settings, and record the measured operate time and error.

Table 4 Timing Test: Multiples of Pickup

Multiples of Pickup[1]	Test Current Pickup	Expected Operate Time[2]	Measured Operate Time[3]	Error (%)[4]
M1 =_______	Itp1 = M1 • Iop =______	texp1 = ______	top1 =______	$\frac{\text{top1} - \text{texp1}}{\text{texp1}} \cdot 100 =$ ______
M2 =_______	Itp2 = M2 • Iop =______	texp2 = ______	top2 =______	$\frac{\text{top2} - \text{texp2}}{\text{texp2}} \cdot 100 =$ ______
M3 =_______	Itp3 = M3 • Iop =______	texp3 = ______	top3 =______	$\frac{\text{top3} - \text{texp3}}{\text{texp3}} \cdot 100 =$ _______

[1]Choose multiples of pickup greater than or equal to 2.5, but do not exceed the thermal rating of the relay (15 A continuous for a 5 A relay and 3 A continuous for a 1 A relay).

[2]See Appendix B.

[3]Apply current and voltage as described in Table 5, Table 6, Table 7, and Table 8 for the phase pair being tested.

[4]Accuracy is ±4% ±1.5 cycles for current between 2 and 20 multiples of pickup.

Table 5 Test Currents When DELTAY_X := WYE and 51VCA = 0[1, 2]
(VAX = Vopn∠0°, VBX = Vopn∠–120°, and VCX = Vopn∠120°)

AB Fault	IAX = Itpm∠0°	IBX = Itpm∠–120°	ICX = 0
BC Fault	IAX = 0	IBX = Itpm∠–120°	ICX = Itpm∠120°
CA Fault	IAX = Itpm∠0°	IBX = 0	ICX = Itpm∠120°

[1]ABC rotation is assumed. Modify angles according to Figure 5 for ACB rotation. Wye test connections are shown in Figure 3.

[2]Vopn = applied voltage for chosen Iopn (n = 1, 2, … 5) from Table 2, and Itpm = test pickup current (m = 1, 2, or 3) from Table 4 in multiples of Iopn.

Table 6 Test Currents When DELTAY_X := DELTA and 51VCA = 0[1, 2]
(VABX = Vopn∠30° and VCBX = Vopn∠90°)

AB Fault	IAX = Itpm∠0°	IBX = Itpm∠–120°	ICX = 0
BC Fault	IAX = 0	IBX = Itpm∠–120°	ICX = Itpm∠120°
CA Fault	IAX = Itpm∠0°	IBX = 0	ICX = Itpm∠120°

[1]ABC rotation is assumed. Modify angles according to Figure 6 for ACB rotation. Delta test connections are shown in Figure 4.

[2]Vopn = applied voltage for chosen Iopn (n = 1, 2, … 5) from Table 2, and Itpm = test pickup current (m = 1, 2, or 3) from Table 4 in multiples of Iopn.

Table 7 Test Currents When DELTAY_X := WYE and 51VCA = ±30[1, 2, 3]
(VAX = Vopn∠0°, VBX = Vopn∠–120°, and VCX = Vopn∠120°)

AB Fault (51VCA := 30) and CA Fault (51VCA := –30)	IAX = Itpm∠0°	IBX = 0	ICX = 0
BC Fault (51VCA := 30) and AB Fault (51VCA := –30)	IAX = 0	IBX = Itpm∠–120°	ICX = 0
CA Fault (51VCA := 30) BC Fault (51VCA := –30)	IAX = 0	IBX = 0	ICX = Itpm∠120°

[1]ABC rotation is assumed. Modify angles according to Figure 5 for ACB rotation. Wye test connections are shown in Figure 3.

[2]Vopn = applied voltage for chosen Iopn (n = 1, 2, … 5) from Table 2, and Itpm = test pickup current (m = 1, 2, or 3) from Table 4 in multiples of Iopn.

[3]Fault types shown are on the system side of the transformer.

Table 8 Test Currents When DELTAY_X := DELTA and 51VCA = ±30[1, 2, 3]
(VABX = Vopn∠30° and VCBX = Vopn∠90°)

AB Fault (51VCA := 30) and CA Fault (51VCA := –30)	IAX = Itpn∠0°	IBX = 0	ICX = 0
BC Fault (51VCA := 30) and AB Fault (51VCA := –30)	IAX = 0	IBX = Itpn∠–120°	ICX = 0
CA Fault (51VCA := 30) and BC Fault (51VCA := –30)	IAX = 0	IBX = 0	ICX = Itpn∠120°

[1]ABC rotation is assumed. Modify angles according to Figure 6 for ACB rotation. Delta test connections are shown in Figure 4.

[2]Vopn = applied voltage for chosen Iopn (n = 1, 2, … 5) from Table 2, and Itpm = test pickup current (m = 1, 2, or 3) from Table 4 in multiples of Iopn.

[3]Fault types shown are on the system side of the transformer.

Step 5

If 51VCA := 0, repeat Steps 3 and 4 for the BC and CA current pair. If 51VCA := –30 or 51VCA := 30, repeat Steps 3 and 4 first for the Phase B current and then for the Phase C current.

CONCLUSION

This application guide demonstrates how to test the voltage-restrained time-overcurrent element (51V) in an SEL-700G. The principle can also be applied to the SEL-300G. The test procedure shown in this application guide uses balanced line-to-line voltage and, therefore, the restraint voltage and scaled current pickup are easy to calculate. Although it is not covered in this guide, unbalanced voltage testing can be performed using (1) and Appendix C. Consider setting the torque control equation 51VTC to 1 during testing to ensure that it does not interfere with the procedure, but remember to return it to its original programmed value. The torque control equation can be tested independently.

APPENDIX A – TRANSFORMER CONNECTION IMPACT ON 51V

Figure 7 shows the connection diagram for a delta-wye transformer where the HV wye side lags the LV side by 30 degrees (51VCA := 30). Figure 8 shows the current distribution through this transformer for several HV-side faults.

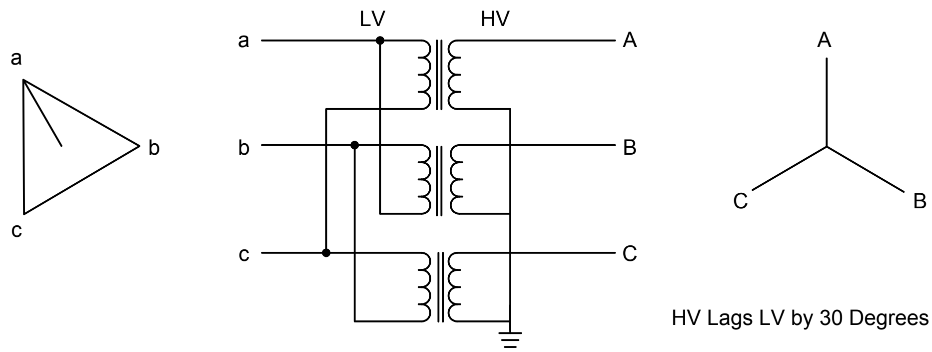


Figure 7 Transformer Connection for 51VCA := 30

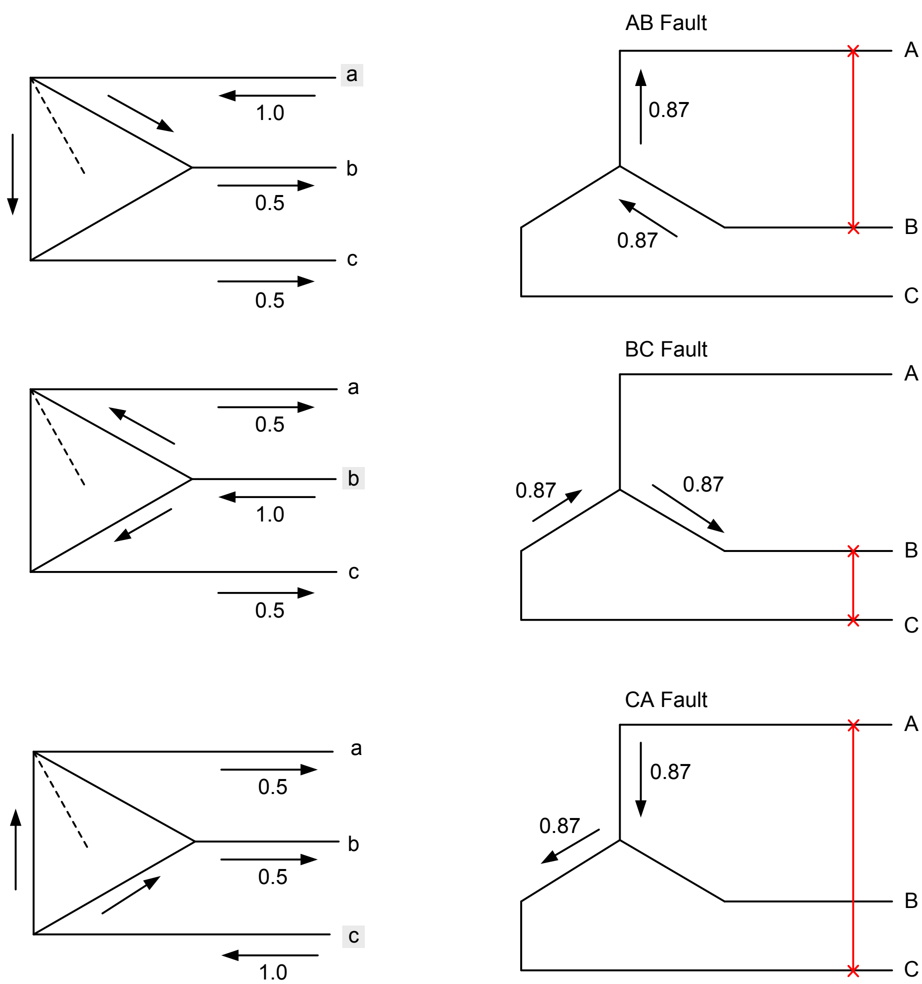


Figure 8 System Phase-to-Phase Fault Impact for 51VCA := 30

Figure 9 shows the connection diagram for a delta-wye transformer where the HV wye side leads the LV side by 30 degrees (51VCA := –30). Figure 10 shows the current distribution through this transformer for several HV-side faults.

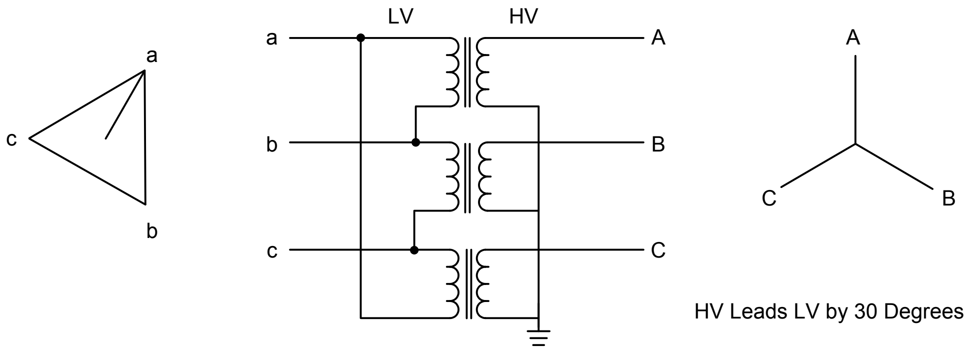


Figure 9 Transformer Connection for 51VCA := –30

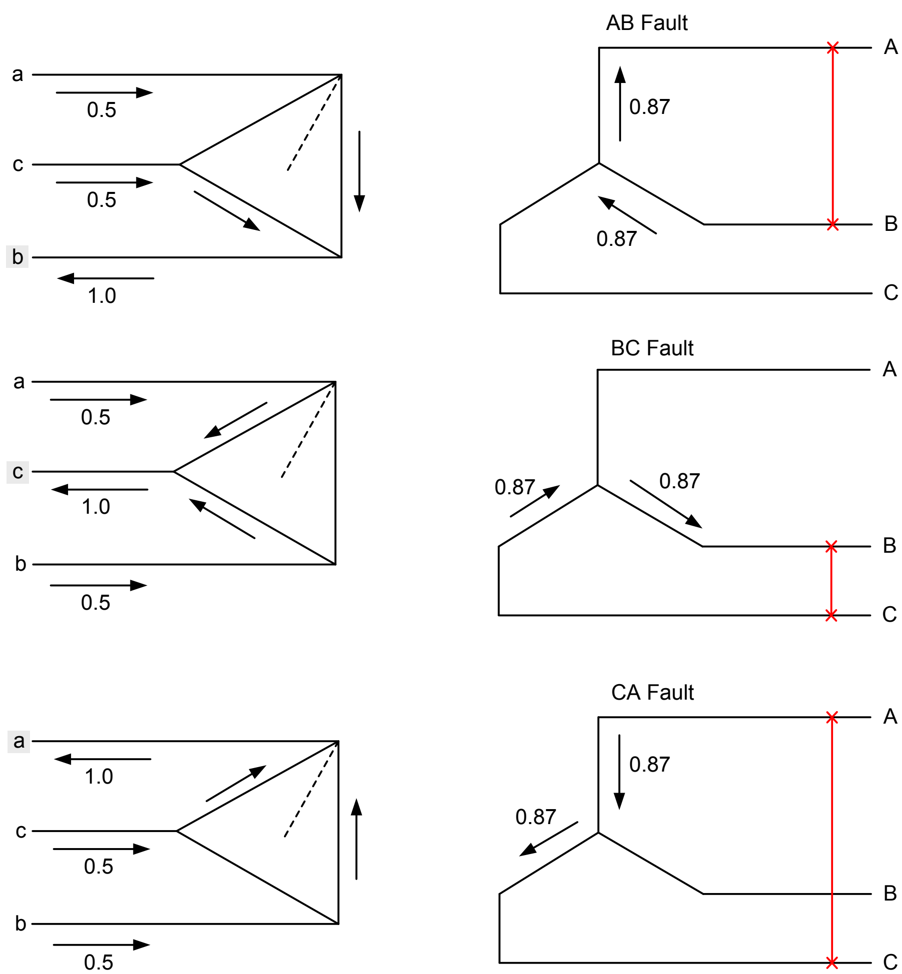


Figure 10 System Phase-to-Phase Fault Impact for 51VCA := –30

APPENDIX B – 51V OVERCURRENT PICKUP AND RESET EQUATIONS

Table 9 and Table 10 show the operate and reset time equations for standard U.S. and IEC time-overcurrent curves.

Table 9 Equations Associated With U.S. Curves

Curve Type	Operating Time	Reset Time
U1 (Moderately Inverse)	$t_p = TD \bullet \left(0.0226 + \frac{0.0104}{M^{0.02} - 1}\right)$	$t_r = TD \bullet \left(\frac{1.08}{1 - M^2}\right)$
U2 (Inverse)	$t_p = TD \bullet \left(0.180 + \frac{5.95}{M^2 - 1}\right)$	$t_r = TD \bullet \left(\frac{5.95}{1 - M^2}\right)$
U3 (Very Inverse)	$t_p = TD \bullet \left(0.0963 + \frac{3.88}{M^2 - 1}\right)$	$t_r = TD \bullet \left(\frac{3.88}{1 - M^2}\right)$
U4 (Extremely Inverse)	$t_p = TD \bullet \left(0.0352 + \frac{5.67}{M^2 - 1}\right)$	$t_r = TD \bullet \left(\frac{5.67}{1 - M^2}\right)$
U5 (Short-Time Inverse)	$t_p = TD \bullet \left(0.00262 + \frac{0.00342}{M^{0.02} - 1}\right)$	$t_r = TD \bullet \left(\frac{0.323}{1 - M^2}\right)$

Table 10 Equations Associated With IEC Curves

Curve Type	Operating Time	Reset Time
C1 (Standard Inverse)	$t_p = TD \bullet \left(\frac{0.14}{M^{0.02} - 1}\right)$	$t_r = TD \bullet \left(\frac{13.5}{1 - M^2}\right)$
C2 (Very Inverse)	$t_p = TD \bullet \left(\frac{13.5}{M - 1}\right)$	$t_r = TD \bullet \left(\frac{47.3}{1 - M^2}\right)$
C3 (Extremely Inverse)	$t_p = TD \bullet \left(\frac{80}{M^2 - 1}\right)$	$t_r = TD \bullet \left(\frac{80}{1 - M^2}\right)$
C4 (Long-Time Inverse)	$t_p = TD \bullet \left(\frac{120}{M - 1}\right)$	$t_r = TD \bullet \left(\frac{120}{1 - M}\right)$
C5 (Short-Time Inverse)	$t_p = TD \bullet \left(\frac{0.05}{M^{0.04} - 1}\right)$	$t_r = TD \bullet \left(\frac{4.85}{1 - M^2}\right)$

where:

t_p = operating time in seconds.

t_r = electromechanical induction-disk emulation reset time in seconds (if electromechanical reset setting selected).

TD = time-dial setting.

M = applied multiples of pickup current (for operating time [t_p], $M > 1$; for reset time [t_r], $M \leq 1$).

APPENDIX C – RESTRAINT VOLTAGE CALCULATION

The value of $\overline{V_{restrain}}$ in (1) depends on setting 51VCA, as shown in Table 11 and Table 12. The voltage restraint calculation ensures that the voltage drop on the high side and low side of a transformer are proportional during system phase-to-phase faults. This is especially apparent when there is a phase-to-phase fault on the high side of a wye-delta transformer (51VCA = ±30) because the voltages must be chosen carefully on the delta side to accurately represent the voltage drop on the high side.

Note: The line-to-line voltages measured by the relay in this application guide are all balanced with proper phase rotation and equal magnitudes, so the restraint voltage is the same for all fault types. This simplifies testing because the restraint voltage is equal to the line-to-line voltage and is very easy to calculate.

Table 11 Restraint Voltage When 51VCA = 0

Fault Type	$\overline{V_{restrain}}$
AB	$\overline{VABX} = \overline{VAX} - \overline{VBX}$
BC	$\overline{VBCX} = \overline{VBX} - \overline{VCX}$
CA	$\overline{VCAX} = \overline{VCX} - \overline{VAX}$
ABC[1]	$\overline{VABX}$

[1]Metered line-to-line voltages should be equal on all phases for a three-phase fault.

Table 12 Restraint Voltage When 51VCA = ±30

Phase With Maximum Current	$\overline{V_{restrain}}$ When 51VCA = 30	$\overline{V_{restrain}}$ When 51VCA = –30	Operate Current
A	$\left\lvert\overline{VABX_{+30}}\right\rvert = \frac{\overline{VABX} - \overline{VCAX}}{\sqrt{3}}$	$\left\lvert\overline{VCAX_{-30}}\right\rvert = \frac{\overline{VCAX} - \overline{VABX}}{\sqrt{3}}$	|IAX|
B	$\left\lvert\overline{VBCX_{+30}}\right\rvert = \frac{\overline{VBCX} - \overline{VABX}}{\sqrt{3}}$	$\left\lvert\overline{VABX_{-30}}\right\rvert = \frac{\overline{VABX} - \overline{VBCX}}{\sqrt{3}}$	|IBX|
C	$\left\lvert\overline{VCAX_{+30}}\right\rvert = \frac{\overline{VCAX} - \overline{VBCX}}{\sqrt{3}}$	$\left\lvert\overline{VBCX_{-30}}\right\rvert = \frac{\overline{VBCX} - \overline{VCAX}}{\sqrt{3}}$	|ICX|

FACTORY ASSISTANCE

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