

Transformer Protection Calculations & Settings

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Power Plant and Distribution
Protection Tracks
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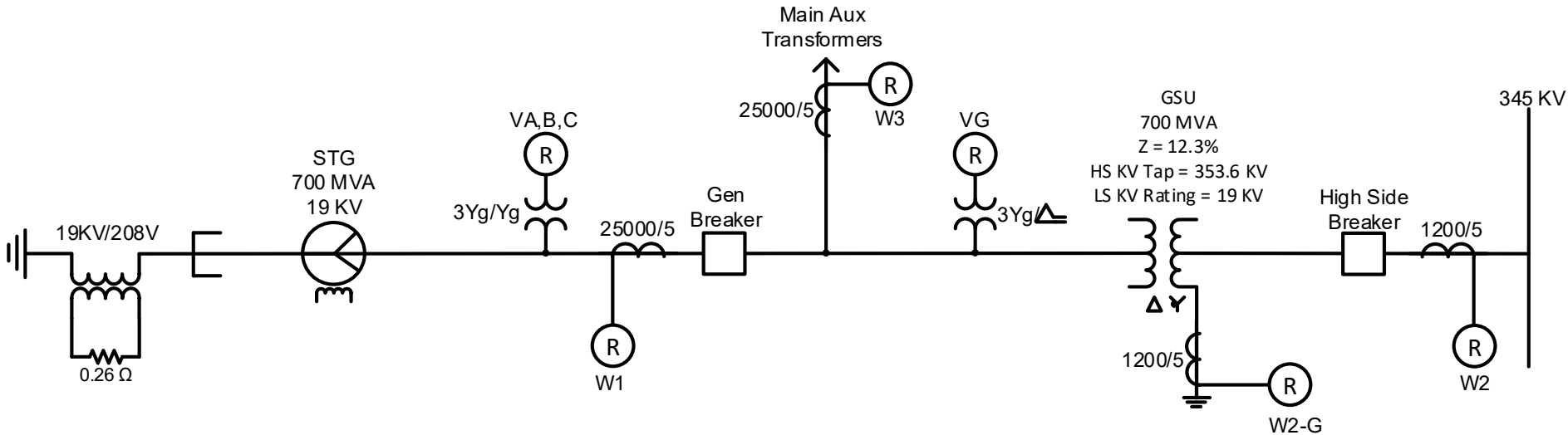
50BF/61BF – Breaker Failure/Breaker Flashover

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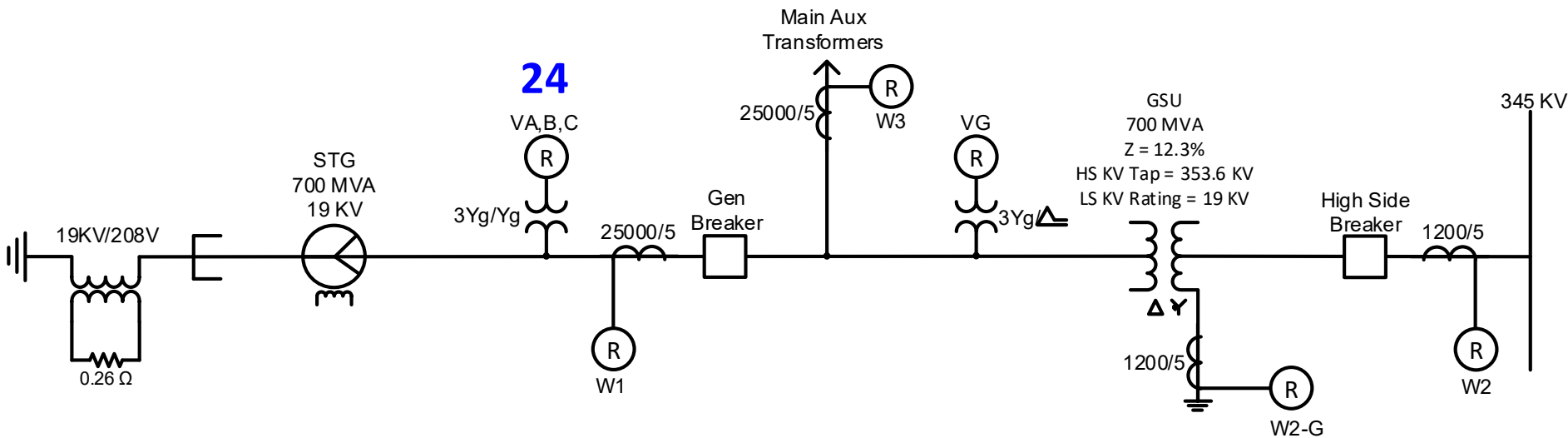
87GD – Ground Different Current

Example GSU Transformer



- $X_d'' = 0.224 \text{ pu}$
- $X_d' = 0.295 \text{ pu}$
- $X_d = 1.66 \text{ pu}$
- $Z_t = 0.123 \text{ pu}$
- $Z_{s1} = 0.1043 \text{ pu}$ (positive sequence system thev impedance)

24 – Volts/Hz (Overexcitation)



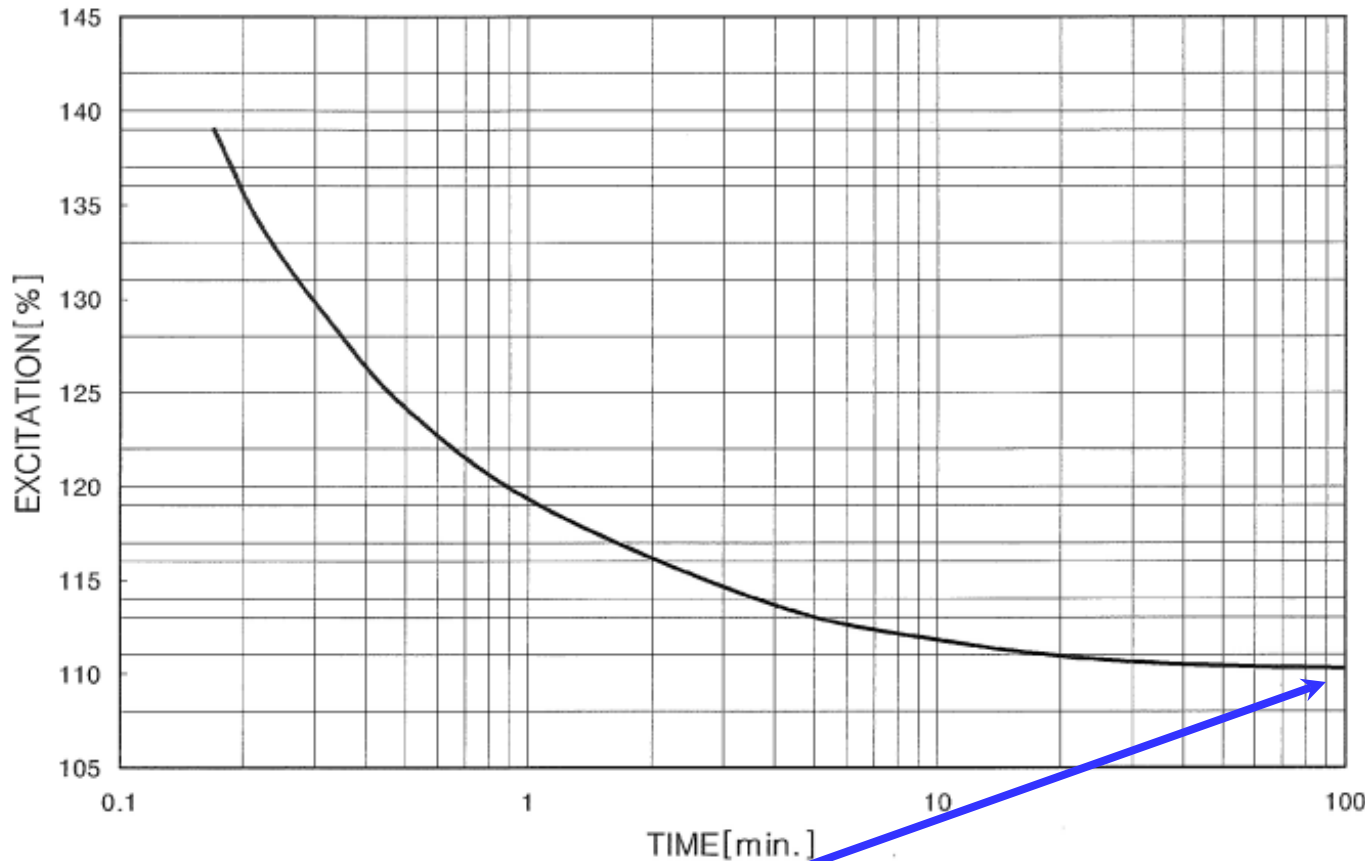
- *May need to comply with NERC PRC-019 and PRC-024 if BES unit*
- *Ideally, 24 should be driven from HS VTs but LS VTs are OK too*
- *frequency derived from the period of the voltage waveforms*
- *Recommend to set both 24 and 59 protection*

24 settings

- First, find the GSU mfg V/Hz withstand capability curve (or use typical):

per
C57.12:

Transformers: 1.05 p.u. at the transformer secondary (HV terminals) at rated load (power factor of 80% or higher and frequency at least 95% of rated value) or 1.10 p.u. at no load (at the HV terminals).



SHORT-TIME OVER EXCITATION

2004-12-07

TM-903

This curve is given on GSU HS so must take it to GSU LS to plot on common V/Hz curve set as the relays are on the GSU LS.

How to do so?

See next slide →

The asymptote of curve is 110%, so assume this curve is given at “No Load”

24 settings

Transfer the FL (105%, 0.8 PF) V/Hz design limit from HS to LS of GSU using a load of 1pu at 0.8 PF lagging with $V_{H-FL} = 1.05$ pu. This yields a current:

$$\text{where @ 1pu 0.8 PF load, } I = \frac{S^*}{V^*} = \frac{(1 \cos^{-1} 0.8)^*}{(1.05 \angle 0^\circ)^*} = 0.952 \text{ pu } \angle -36.9^\circ$$

Considering the voltage drop across the GSU during FL, the low side voltage is calculated:

$$V_{L-FL} = |V_{H-FL} + I * Zt| = |1.05 + (0.952 \text{ pu } \angle -36.9^\circ * (0.001621 + 0.123049j))| = 1.13 \text{ pu}$$

The NL voltage limit of 110% on the HS of the GSU is the same on the GSU LS because $I = 0$:

$$V_{L-NL} = V_{H-NL} = 1.10 \text{ pu}$$

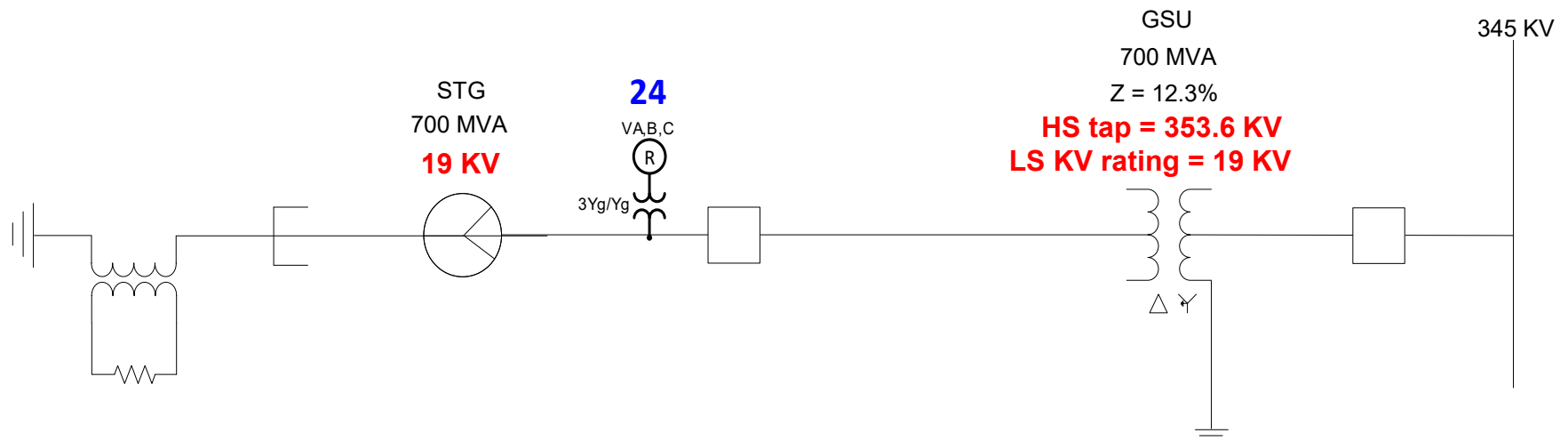
As overfluxing can occur at NL or FL, the more restrictive limit is plotted against the 24 Trip curve:

$$V_L = \min(V_{L-NL}, V_{L-FL}) = \min(1.10 \text{ pu}, 1.13 \text{ pu}) = 1.10 \text{ pu}$$

In most cases the 110% NL limit is more restrictive than the FL limit and would be plotted on the coordination curve set unless the GSU impedance is $\leq 7\%$ or so (Zt at max GSU MVA rating).

24 settings

- *In some applications, the GSU LS voltage rating may be < the gen voltage rating to compensate for the voltage drop across the GSU (from GSU impedance) so when the generator is operating at nominal voltage the GSU HS can also be at its nominal voltage.*
- *However, this will have the effect of reducing the overfluxing capability of the GSU i.e. the GSU's V/Hz withstand capability curve will be plotted lower on the V/Hz vs time graph.*
- ***Alternately, and as was done for this sample application, the GSU HS Tap may be placed on a higher than nominal Tap to account for the voltage drop across the GSU and this may be preferable as it does not impinge on the V/Hz withstand capability of the GSU.***



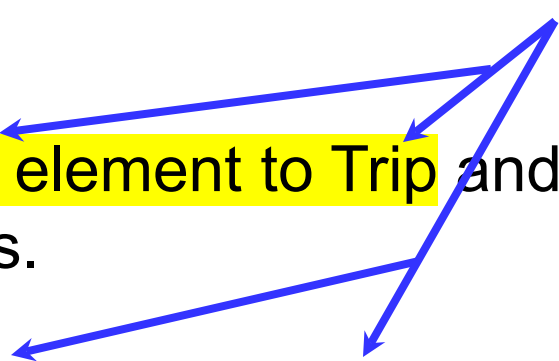
24 settings

- When plotting the mfg GSU and gen V/Hz withstand capability curves with the 24 curves, **if the GSU LS voltage rating is different than the generator voltage rating**, then to plot them on the same curve set the GSU curve must be converted to the gen voltage base.
- E.g. if this GSU low side voltage rating were 18 KV and with the gen rated at 19 KV, then to convert a point of 110 % on the mfg GSU curve to the gen voltage base:

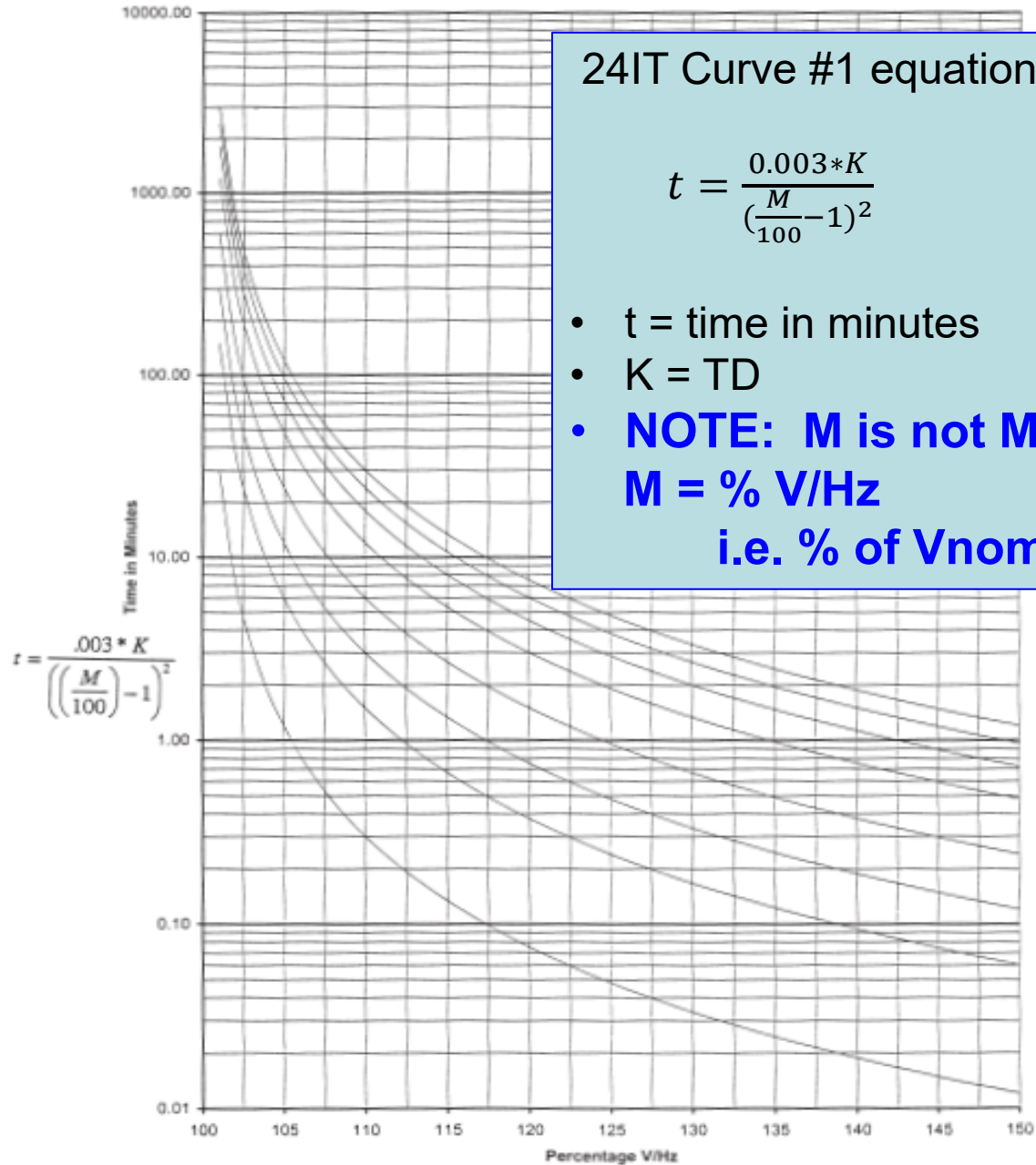
$$V/Hz_{GSU\ new} = \frac{V_{gsu\ LS\ rating}}{V_{gen\ rating}} * V/Hz_{GSU\ old} = \frac{18\ K}{19\ K} * 110 = 104.2\ \%$$

However, in this sample application, both the generator voltage rating and the GSU low side voltage rating are 19 KV, so no such conversion is necessary.

24 settings

- 24 settings typically informed by the GSU V/Hz withstand capability curve along with VPFL and possibly PRC-019 and PRC-024 if BES unit.
 - Use **Definite Time #1 element to Trip** and set it at 126% pickup and 5 seconds.
 - Use **Definite Time #2 element to Alarm** and set it at 108% pickup and 4 seconds.
 - Use the Inverse Time element to Trip as well and use Curve #1 at 109% pickup with a Time Dial of 8 and a **Reset Rate of 240 seconds (4 minutes)**.
- Requirement specific to this mfg relay type:
- 

24 settings



24IT Curve #1 equation:

$$t = \frac{0.003 * K}{\left(\frac{M}{100} - 1\right)^2}$$

- t = time in minutes
- K = TD
- **NOTE: M is not MPU**
M = % V/Hz
i.e. % of Vnom/fnom

Enter 24 settings into relay

24: Volts/Hz Overexcitation

Definite Time #1

Pickup: 100 200 (%)

Time Delay: 30 8160 (Cycles)

Outputs

1 2 3 4 5 6 7 8

9 10 11 12 13 14 15 16

Blocking Inputs

1 2 3 4 5 6 7 8 9

10 11 12 13 14 15 16 17 18

Definite Time #2

Pickup: 100 200 (%)

Time Delay: 30 8160 (Cycles)

Outputs

1 2 3 4 5 6 7 8

9 10 11 12 13 14 15 16

Blocking Inputs

1 2 3 4 5 6 7 8 9

10 11 12 13 14 15 16 17 18

Inverse Time

Pickup: 100 150 (%)

Time Dial: 1 100

Reset Rate: 1 999 (Sec)

Inverse Time Curves: #1 #2 #3 #4

Outputs

1 2 3 4 5 6 7 8

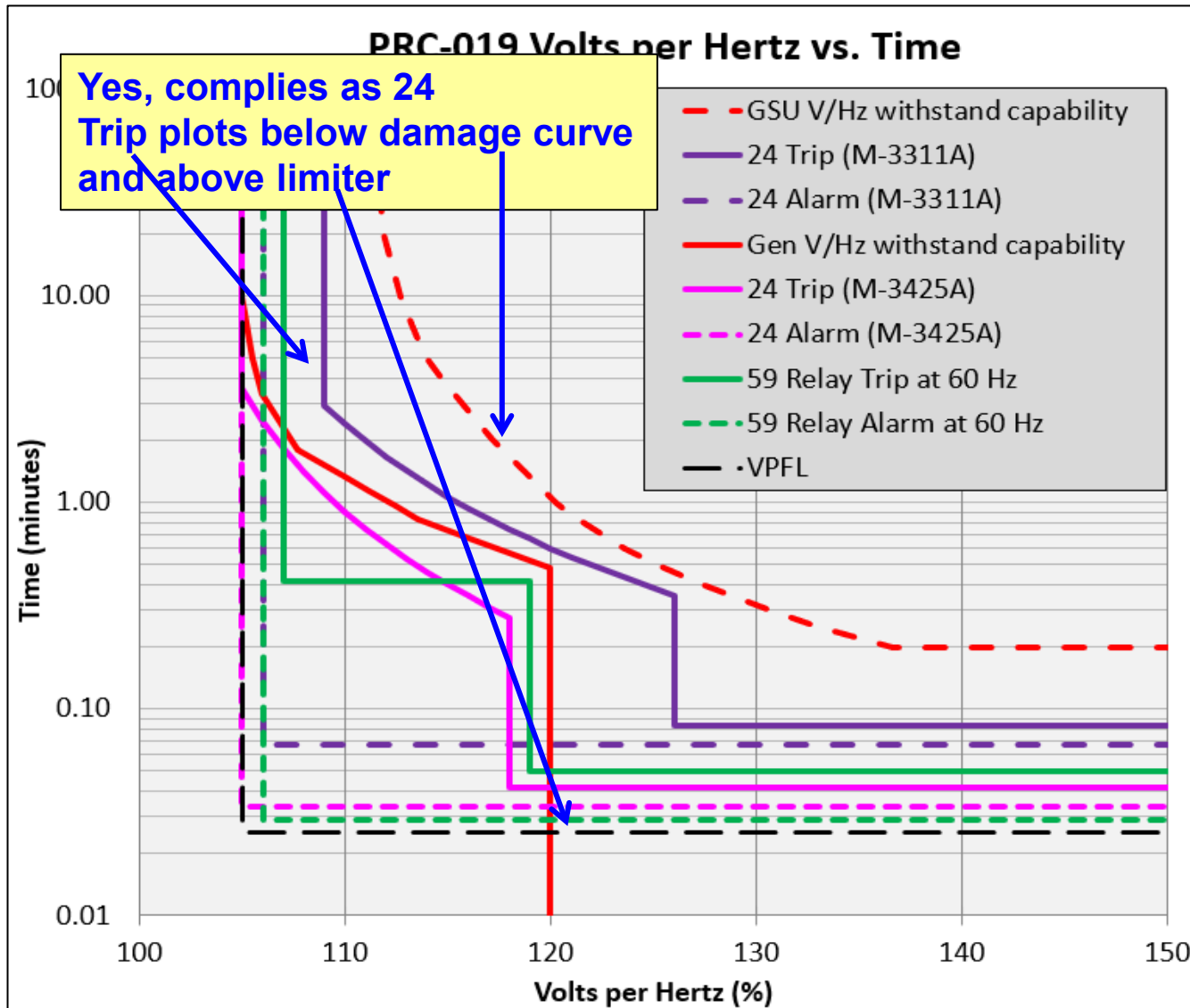
9 10 11 12 13 14 15 16

Blocking Inputs

1 2 3 4 5 6 7 8 9

10 11 12 13 14 15 16 17 18

PRC-019 compliance



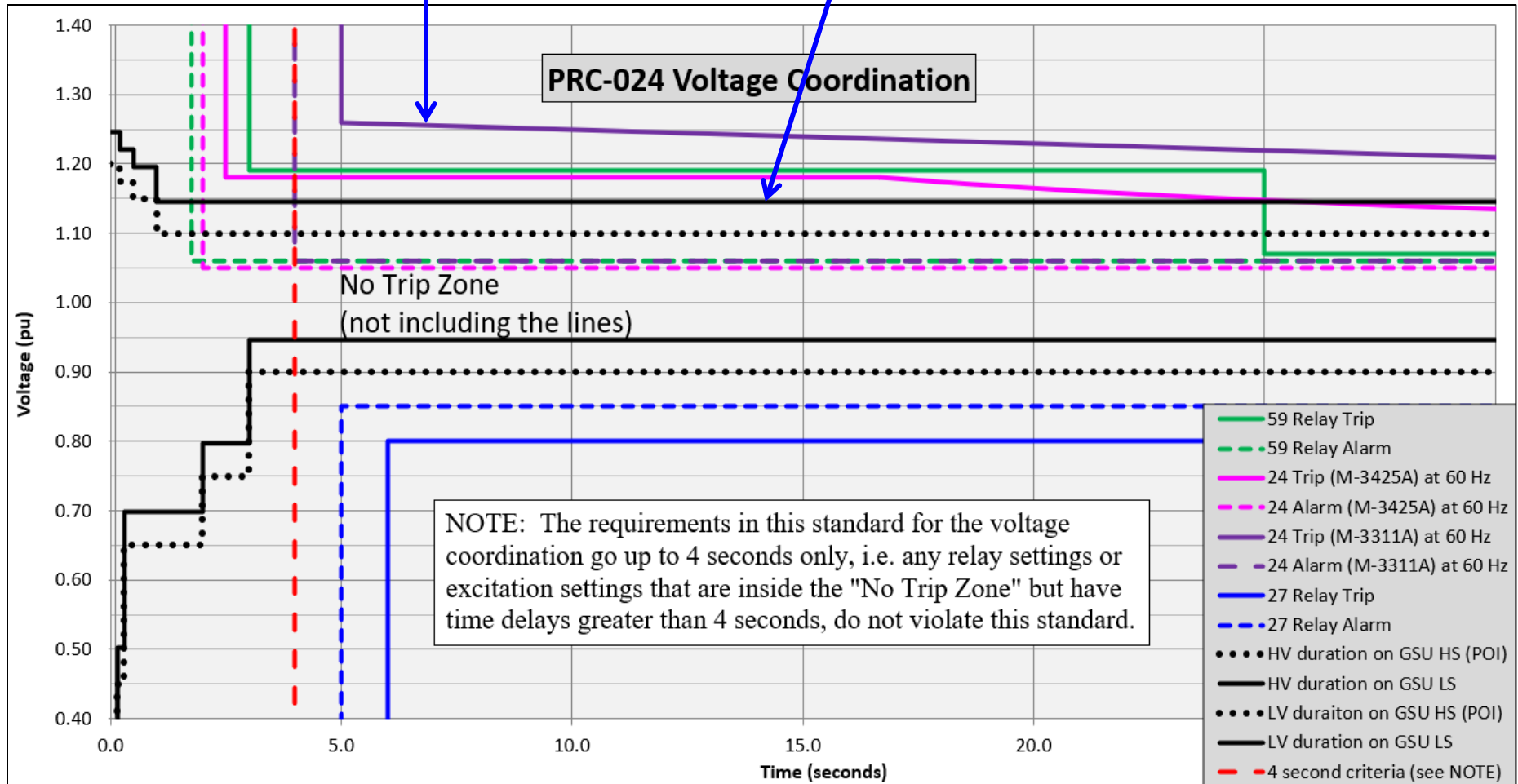
If possible, try to choose a 24 trip curve such that there is

clear space

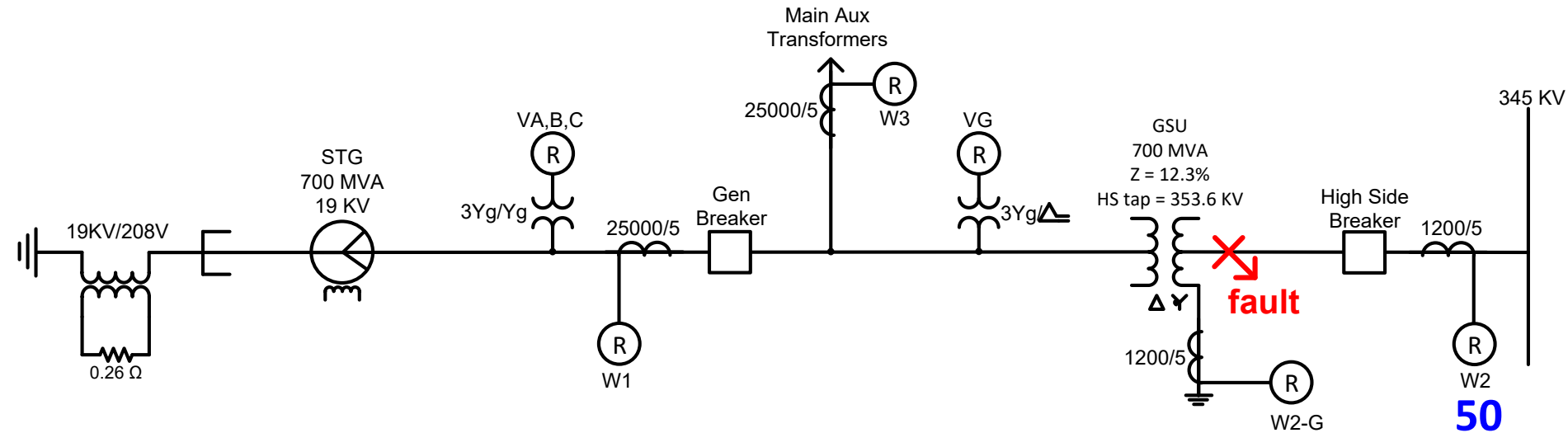
visual evidence that it plots below the GSU V/Hz damage curve and above the VPFL for easy verification by a NERC auditor.

PRC-024 compliance

Yes, complies as 24 Trip plots above HV duration curve on GSU LS at > 4 seconds



50 – Instantaneous Phase Overcurrent



- *Need to comply with PRC-025 and PRC-026 if BES unit*
- *Set 50 and 51 on GSU HS W2 as a backup to 87*
- *Set 50 to see high amperage faults on the GSU HS or not too deep into the HS Wye winding as fed from the system*

50 Settings Criteria

- Set 50 #1 < high magnitude faults on the high side of the transformer as fed from the system or not too deep into the transformer windings.

$$\text{internal HS } \Phi\Phi \text{ fault sys fed} = 0.866 * \frac{1}{0.1043} * \frac{700 M}{\sqrt{3} * 353.6 K * 240} = 39.5 \text{ Asec}$$

Set it > the following criteria:

- 1) PRC-025 = 8.75 A
- 2) PRC-026 = 10.7 A
- 3) max asymmetrical external fault on the system side of the W2 HS CTs as fed from the gen so it will not see any faults on the transmission system as this criterion makes it in-effect directional via its pickup setting (even though the 50 element is non-directional)
- 4) max LS fault as fed from the system (depend on 51 to see LS faults)
- 5) transformer inrush

$$\max \text{ asym HS gen fed fault} = 1.6 * \frac{1}{0.224 + 0.123} * \frac{700 M}{\sqrt{3} * 353.6 K * 240} = 22.0 \text{ Asec}$$

$$\max \text{ LS fault as fed from system} = \frac{1}{0.1043 + 0.123} * \frac{700 M}{\sqrt{3} * 353.6 K * 240} = 21.0 \text{ Asec}$$

Set above max Transformer Inrush current:

- 8 * IFL (Transformers < 2.5 MVA)
- 10 * IFL (Transformers > 2.5 MVA)
- 6 * IFL (digital relays using Discrete Fourier Transformation (DFT) processing)

✓ IFL is at the base self-cooled rating, not max 65°C, all fans on rating

$$\text{XFMR inrush} = 6 * \frac{420 M}{\sqrt{3} * 353.6 K * 240} = 17.1 \text{ Asec}$$

PRC, HS (gen), LS (sys), inrush < Pickup < internal HS $\Phi\Phi$ fault as fed from sys

8.75, 10.7, 22.0, 21.0, 17.1 < Pickup < 39.5

Pickup = 30 sec amps (6.3 * xfmr max rating)

- Time Delay = 8 cycles
- Give it an 8 cycle delay to get above inrush and so that the 87T and 87H differential elements in this relay take precedence and also to ensure the 87B HS bus differential relay (if present) has dibs for a fault inside the high side interrupting device.
- This time delay does not need to be set ≥ 15 cycles to get above PRC-026 criteria as it complies with PRC-026 via the current magnitude criteria.
- Current Selection = W2 (HS current inputs)

Enter 50 settings into relay

50: Instantaneous Phase Overcurrent X

#1	#2	#3	#4	#5	#6	#7	#8
----	----	----	----	----	----	----	----

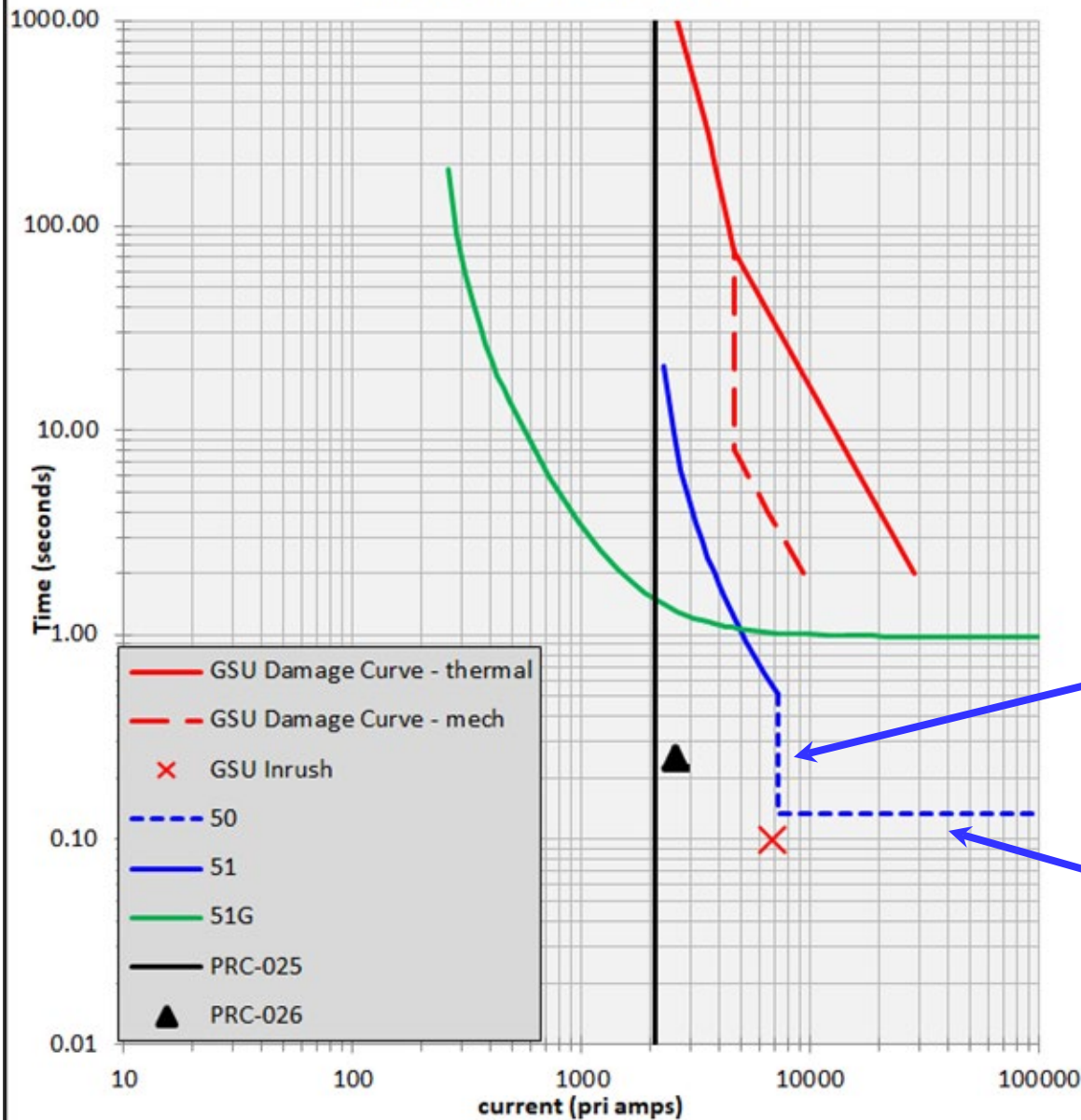
Pickup: 1.0

Time Delay: 1

Current Selection: Sum1 Sum2 W1 W2 W3

Outputs								Blocking Inputs									
<input checked="" type="checkbox"/> 1	<input checked="" type="checkbox"/> 2	<input checked="" type="checkbox"/> 3	<input checked="" type="checkbox"/> 4	<input checked="" type="checkbox"/> 5	<input type="checkbox"/> 6	<input checked="" type="checkbox"/> 7	<input checked="" type="checkbox"/> 8	<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4	<input type="checkbox"/> 5	<input type="checkbox"/> 6	<input type="checkbox"/> 7	<input type="checkbox"/> 8	<input type="checkbox"/> 9	
<input checked="" type="checkbox"/> 9	<input checked="" type="checkbox"/> 10	<input type="checkbox"/> 11	<input type="checkbox"/> 12	<input type="checkbox"/> 13	<input type="checkbox"/> 14	<input type="checkbox"/> 15	<input type="checkbox"/> 16	<input type="checkbox"/> 10	<input type="checkbox"/> 11	<input type="checkbox"/> 12	<input type="checkbox"/> 13	<input type="checkbox"/> 14	<input type="checkbox"/> 15	<input type="checkbox"/> 16	<input type="checkbox"/> 17	<input type="checkbox"/> 18	

Pri Amps at HS Tap



$30 * 240 = 7200$ Apri

$8/60 = 0.133$ sec

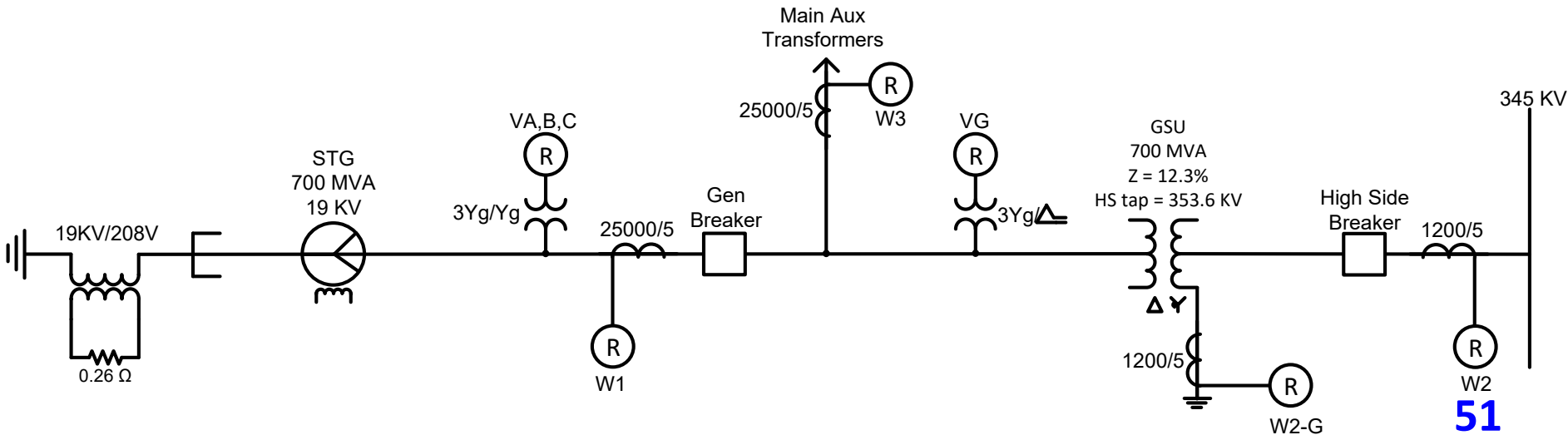
PRC-025 compliance

PRC-025: Table 1 Option 15a - M-3311A GSU HS 50			
50 pickup	30.0	A	
50 timer	8	cycles	
Q =	714	MVAR	
Vbus =	293.25	KV	
S =	591.77+714j	MVA	
S =	927.36	MVA	
arg(S) =	50.35	degrees	
Ipri =	1165.0761084	pri amps	
Ipri =	1826	pri amps	
arg(Ipri) =	-50.35	degrees	
Isec =	4.8544837851	sec amps	
Isec =	7.607	sec amps	
arg(Isec) =	-50.35	degrees	
1.15*Isec =	5.5826563529	sec amps	
1.15*Isec =	8.749	sec amps	
arg(1.15*Isec) =	-50.35	degrees	
50 > 1.15*Isec	TRUE	therefore, yes this complies with standard	

PRC-026 compliance

<u>PRC-026: M-3311A GSU HS 50</u>			
50 pickup	30.0	A	
50 timer	8	cycles	
Es at 120 deg =	-0.5+0.866 pu		
1.05*Es at 120 deg =	-0.525+0.9 pu		
ER at 0 deg =	1		
1.05*ER at 0 deg =	1.05		
Es - ER =	-1.575+0.9 pu		
Isys =	1.1016372 pu		
Ibase =	1142.945 pri amps		
Isys =	2570.856 pri amps		
Isys =	10.7119 sec amps		
50 > Isys	TRUE	therefore, yes this complies with standard	

51 – Inverse Time Phase Overcurrent



- *Need to comply with PRC-025 and PRC-026 if BES unit*
- *Set 51 on W2 on GSU HS in conjunction with 50 as a backup to 87*
- *Set to protect GSU damage curve*

51 settings criteria

- Set 51 #1 from the GSU HS W2 current inputs to protect the transformer in concert with the 50 function as a backup to the differential elements

Set the 51 Pickup < the minimum phase fault current as seen by these GSU HS CTs for a LS $\Phi\Phi$ fault as fed from the system:

min LS phase fault as fed from system

$$= I_{pu} * I_{base}$$

$$= 0.866 * \frac{V_s}{Z_{s1} + Z_t} * \frac{S_t}{\sqrt{3} * V_{LL_{HSTap}} * CTR}$$

$$= 0.866 * \frac{1}{0.1043 + 0.123} * \frac{700 M}{\sqrt{3} * 353.6 K * 240}$$

$$= 18.1 Asec$$

51 settings criteria

Set the 51 Pickup \geq the following criteria:

- 1) 150% of max transformer rating = $1.50 * 4.76 = 7.14$ A
- 2) PRC-025 = 8.75 A (does not need to comply with PRC-025 if the chosen Pickup complies with criteria 4 below).
- 3) PRC-026 = 10.7 A (does not need to comply with PRC-026 if the 51 Curve plots > 0.25 seconds at the max fault current, which it does here).
- 4) max external fault on the HS (system side of the sensing CTs) as fed from the generator at 1 second = 5.68 A (from the generator decrement curve).
 - Therefore, it will not see any faults out on the transmission system – there is no inherent directionality to the 51 function, but using this criteria makes it de-facto directional just via the Pickup setting itself.

51 settings criteria

$150\% \text{ xfmr rating, PRC, HS ext. } 3\Phi \text{ fault at 1 sec} \leq \text{Pickup} < \text{LS } \Phi\Phi \text{ fault}$
 $7.14, 8.75, 10.7, 5.68 \leq \text{Pickup} < 18.1$

- Set Pickup = 8.76 sec amps

which is $8.76 * 240 = 2102$ pri amps

- Choose a curve and a time dial to get below the GSU damage curve and above the GSU inrush.
- To ensure compliance with PRC-026, ensure that the curve plots above 0.25 seconds at the PRC-026 calculated current criteria of $10.7 * 240 = 2568$ pri amps.
- After plotting several curve types, selected IEEE Very Inverse Curve. Using the IEEE Very Inverse curve equation from the M-33311A IB and solving for TD for a LS 3 Φ fault as fed from system = $18.1*240/0.866 = 5016$ pri amps:

$$TD = \frac{5 * t}{\frac{19.61}{M^2 - 1} + 0.491} = \frac{5 * 1}{\frac{19.61}{\left(\frac{5016}{2102}\right)^2 - 1} + 0.491} = 1.1$$

- Current Selection = W2
- Inverse Time Curve = IEEE Very Inverse

Enter 51 settings into relay

51: Inverse Time Phase Overcurrent

#1 | #2 | #3 | #4

Pickup: 0.50 12.00 (A)

Time Dial: 0.5 15.0

Current Selection: Sum1 Sum2 W1 W2 W3

Inverse Time Curves

BECO Definite Time BECO Inverse BECO Very Inverse BECO Extremely Inverse

IEC Inverse IEC Very Inverse IEC Extremely Inverse IEC Long Time Inverse

IEEE Moderately Inverse IEEE Very Inverse IEEE Extremely Inverse

Outputs

1 2 3 4 5 6 7 8

9 10 11 12 13 14 15 16

Blocking Inputs

1 2 3 4 5 6 7 8 9

10 11 12 13 14 15 16 17 18



trip gen, HS, MAT LS breakers, 86G LORs, auto-transfer, DCS, RTU

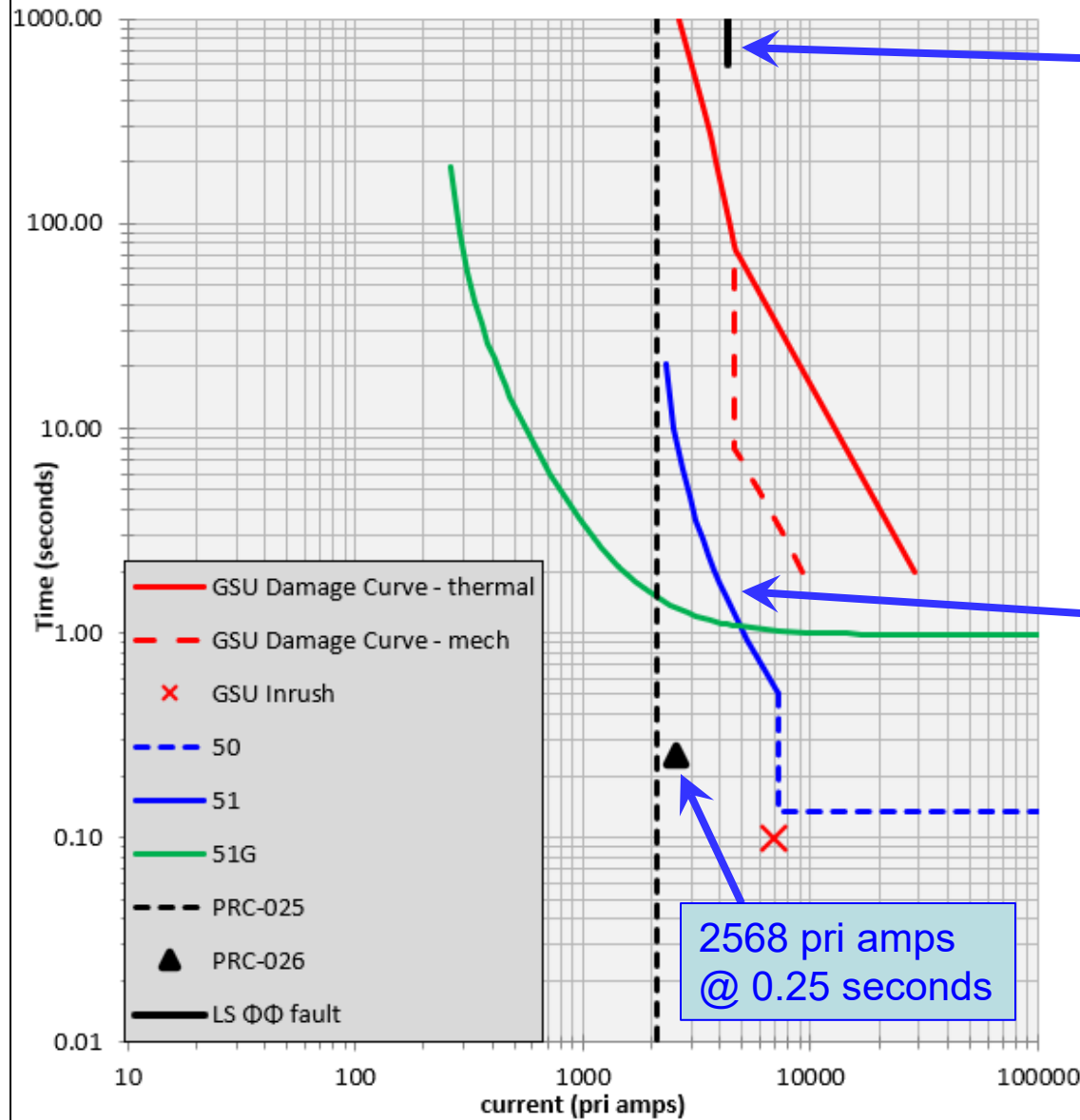
PRC-025 compliance

PRC-025: Table 1 Option 15a - M-3311A GSU HS 51			
51 pickup	8.76	A	
51 curve	U3		51P TD 1.1
Q =	714	MVAR	
Vbus =	293.25	KV	
S =	591.77+714j	MVA	
S =	927.36	MVA	
arg(S) =	50.35	degrees	
Ipri =	1165.0761084	pri amps	
Ipri =	1826	pri amps	
arg(Ipri) =	-50.35	degrees	
Isec =	4.8544837851	sec amps	
Isec =	7.607	sec amps	
arg(Isec) =	-50.35	degrees	
1.15*Isec =	5.5826563529	sec amps	
1.15*Isec =	8.749	sec amps	
arg(1.15*Isec) =	-50.35	degrees	
51 > 1.15*Isec	TRUE		because PRC-025 is for gen output and because this 51 element is made directional in-effect as its pickup is set such that it cannot see faults out on the system, therefore 51 would not necessarily have to comply with PRC-025

PRC-026 compliance

<u>PRC-026: M-3311A GSU HS 51</u>			
51 pickup	8.76	A	
51 curve	U3		51P TD 1.1
ES at 120 deg = $-0.5+0.866j$ pu			
1.05*ES at 120 deg = $-0.525+0.9j$ pu			
ER at 0 deg = 1			
1.05*ER at 0 deg = 1.05			
ES - ER = $-1.575+0.9j$ pu			
I _{sys} = 1.1016372 pu			
I _{base} = 1142.945 pri amps			
I _{sys} = 2570.856 pri amps			
I _{sys} = 10.7119 sec amps			
51 > I _{sys}	FALSE	however, it complies via time delay criterion	

Pri Amps at HS Tap

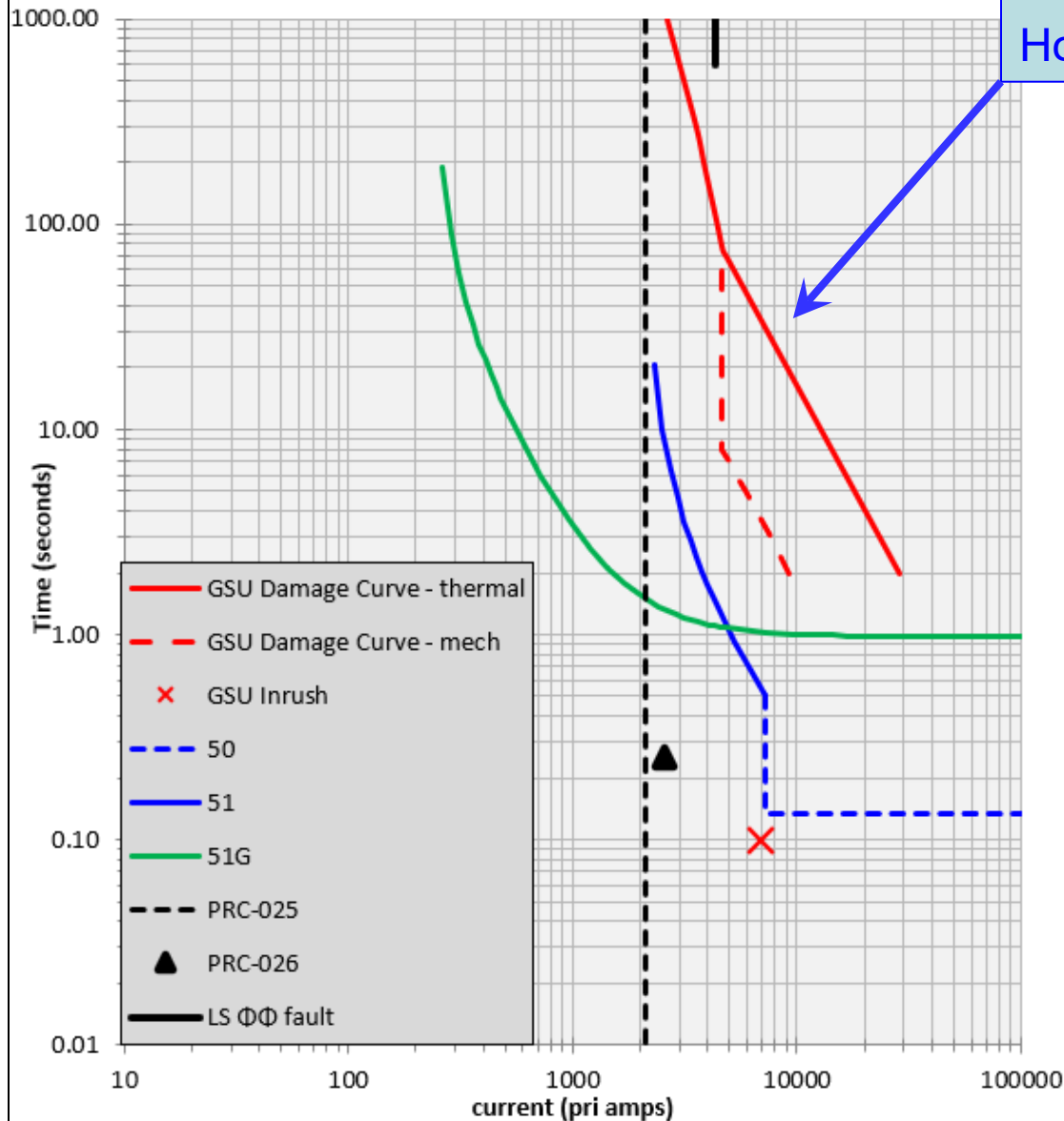


18.1 * 240 =
4344 pri amps

51 plots below
GSU damage
curve and above
inrush

2568 pri amps
@ 0.25 seconds

Pri Amps at HS Tap



SIDEBAR:
How to plot the GSU damage curve:

IEEE Standard references for thru fault withstand capability:

- **C57.12.00: General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers.**
- **C57.109: Guide for Liquid-immersed Transformer Through-fault-current Duration.**
- **C37.91: Guide for Protective Relay Applications to Power Transformers**

Table 11 from C57.12.00-2015:

7.1.2 Transformer categories

Four categories for the rating of transformers are recognized, as shown in Table 11.

Table 11 —Category of transformer ratings

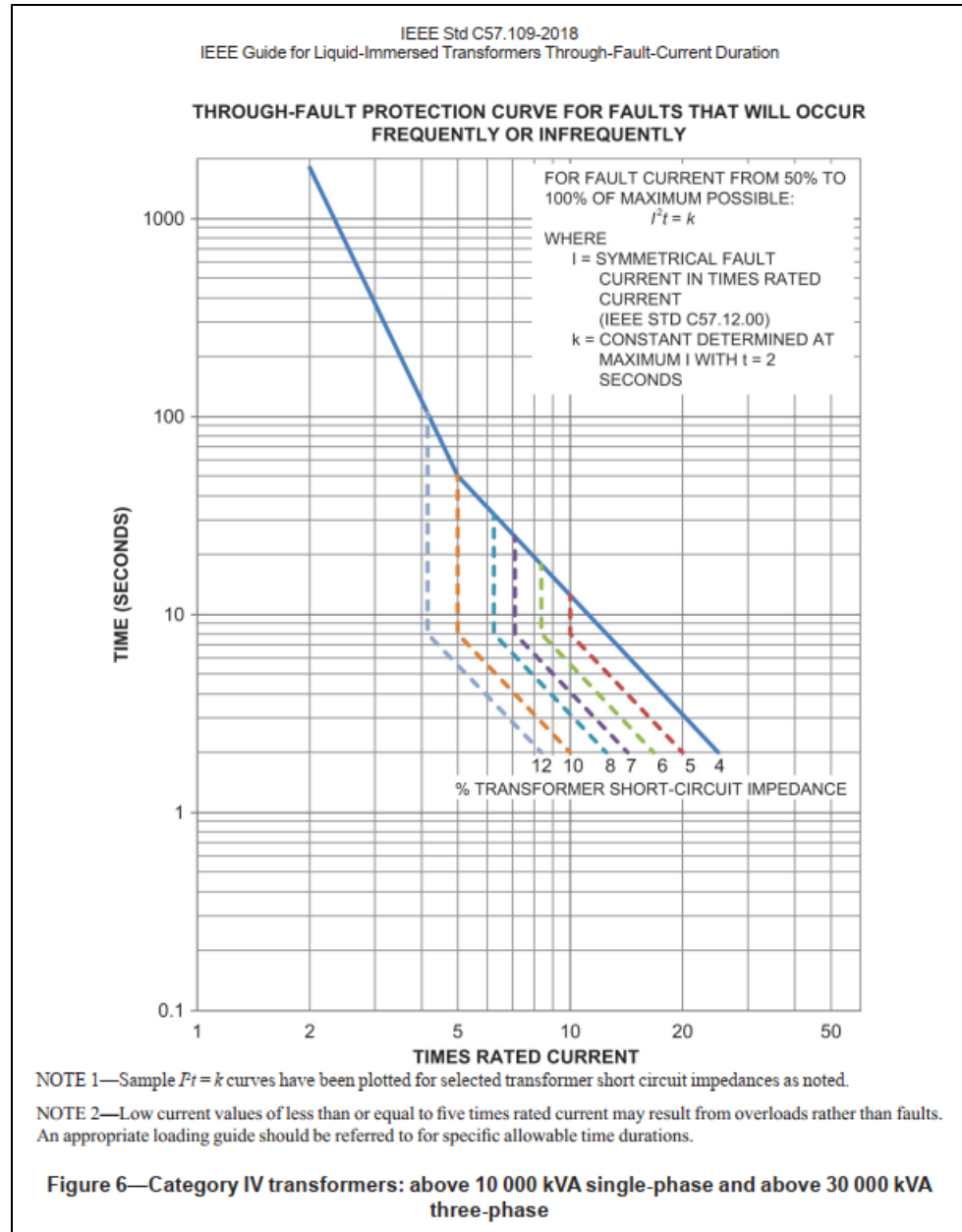
Category	Single phase (kVA)	Three phase (kVA)
I ^a	5 to 500	15 to 500
II	501 to 1667	501 to 5000
III	1668 to 10 000	5001 to 30 000
IV	Above 10 000	Above 30 000

Our sample
GSU is 700
MVA
therefore it is
Category IV

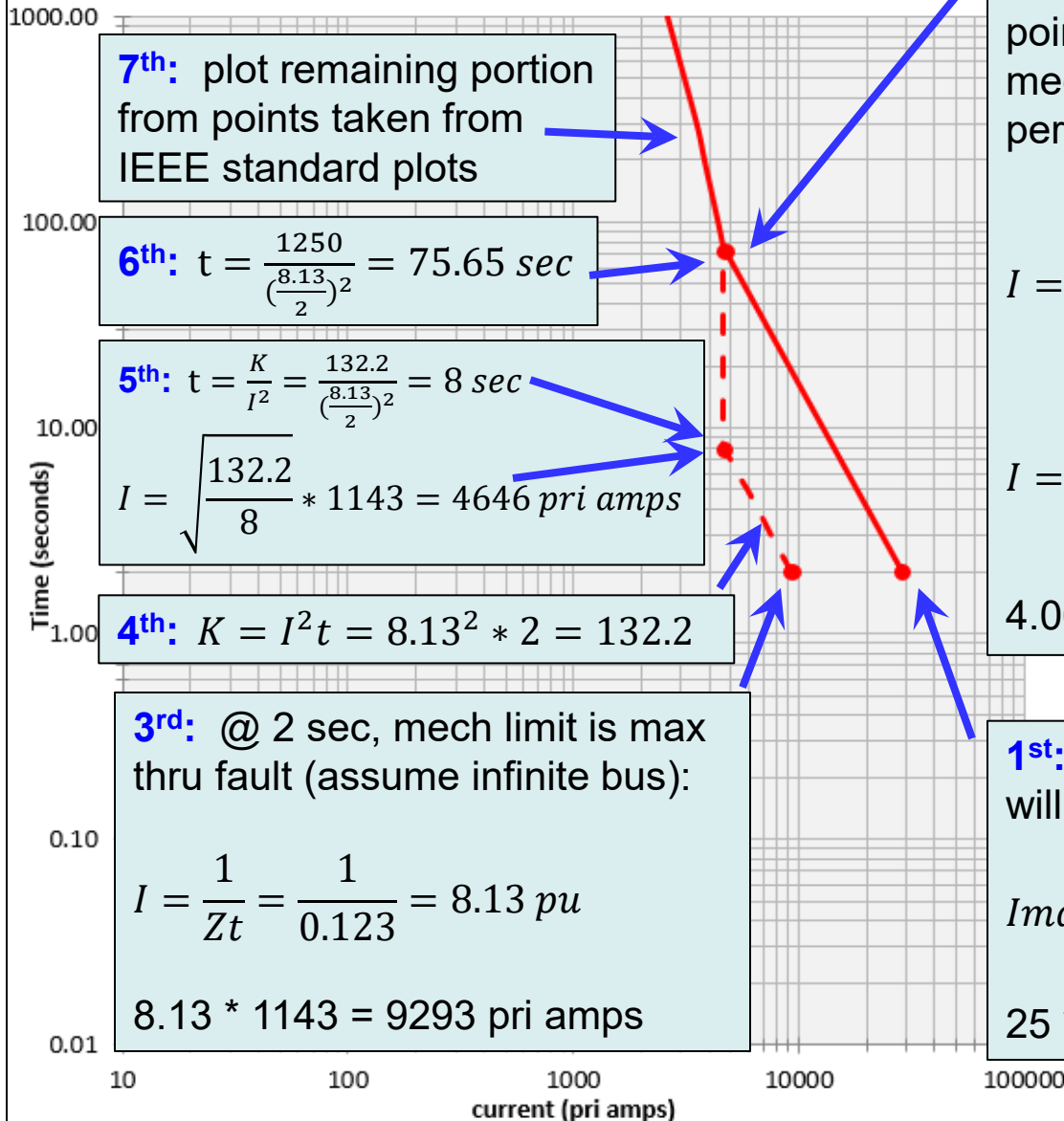
NOTE—All kVA ratings listed are minimum nameplate kVA for the principal windings.

^aAutotransformers with equivalent two-winding kVA of 500 or less, which are manufactured as distribution transformers in accordance with IEEE Std C57.12.20™ [B32], IEEE Std C57.12.23™ [B33], IEEE Std C57.12.24™ [B34], IEEE Std C57.12.34™ [B35], IEEE Std C57.12.36™ [B36], IEEE Std C57.12.38™ [B37], or IEEE Std C57.12.40™ [B38] shall be included in Category I, even though their nameplate kVA may exceed 500.

Figure 6 from C57.109-2018:

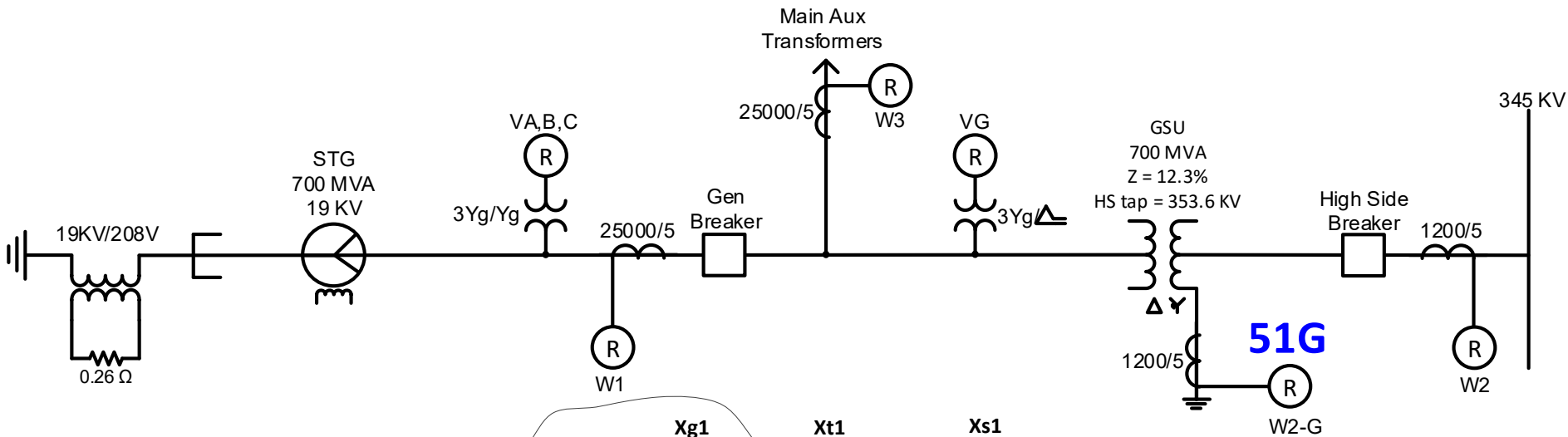


Pri Amps at HS Tap

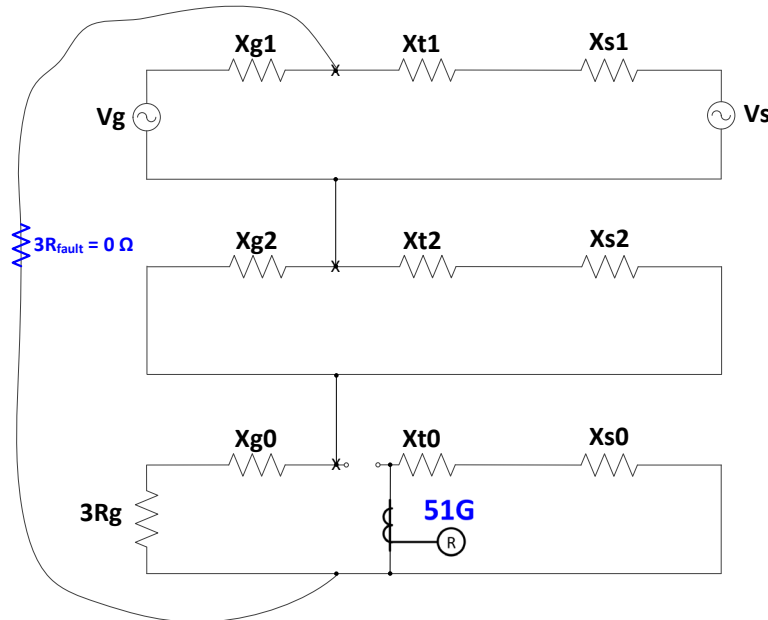


51G – Inverse Time Ground Overcurrent

- *Set 51G as a backup for uncleared system ground faults*



- *Will 51G see a Φ G fault on the LS of the GSU?*



51G settings criteria

Use W2 51G from the IG2 ground current input for system backup ground fault protection.

Set the Pickup per the following criteria:

- Set > highest unbalance expected, assume it is 10% of max output of generator. On HS of GSU, the ground CT would see $0.10 \times 4.88 = 0.488$ sec amps.
- Set < 25% of the max HS ground fault current. The W2 ground CT will see $(0.25 \times 2343/240) = 2.44$ sec amps.

$$0.488 \leq W2\ 51G\ Pickup \leq 2.44$$

W2 51G Pickup = 1.00 A

Time Dial = 10.0 (choose TD to flatten out at about 1 second to coordinate with transmission line ground protection)

Inverse Time Curve = IEEE Very Inverse

Enter 51G settings into relay

51G: Inverse Time Ground Overcurrent

Winding 2 | Winding 3 | Winding 4

Pickup: 0.50 12.00 (A)

Time Dial: 0.5 15.0

Inverse Time Curves

BECO Definite Time BECO Inverse BECO Very Inverse BECO Extremely Inverse

IEC Inverse IEC Very Inverse IEC Extremely Inverse IEC Long Time Inverse

IEEE Moderately Inverse IEEE Very Inverse IEEE Extremely Inverse

Outputs

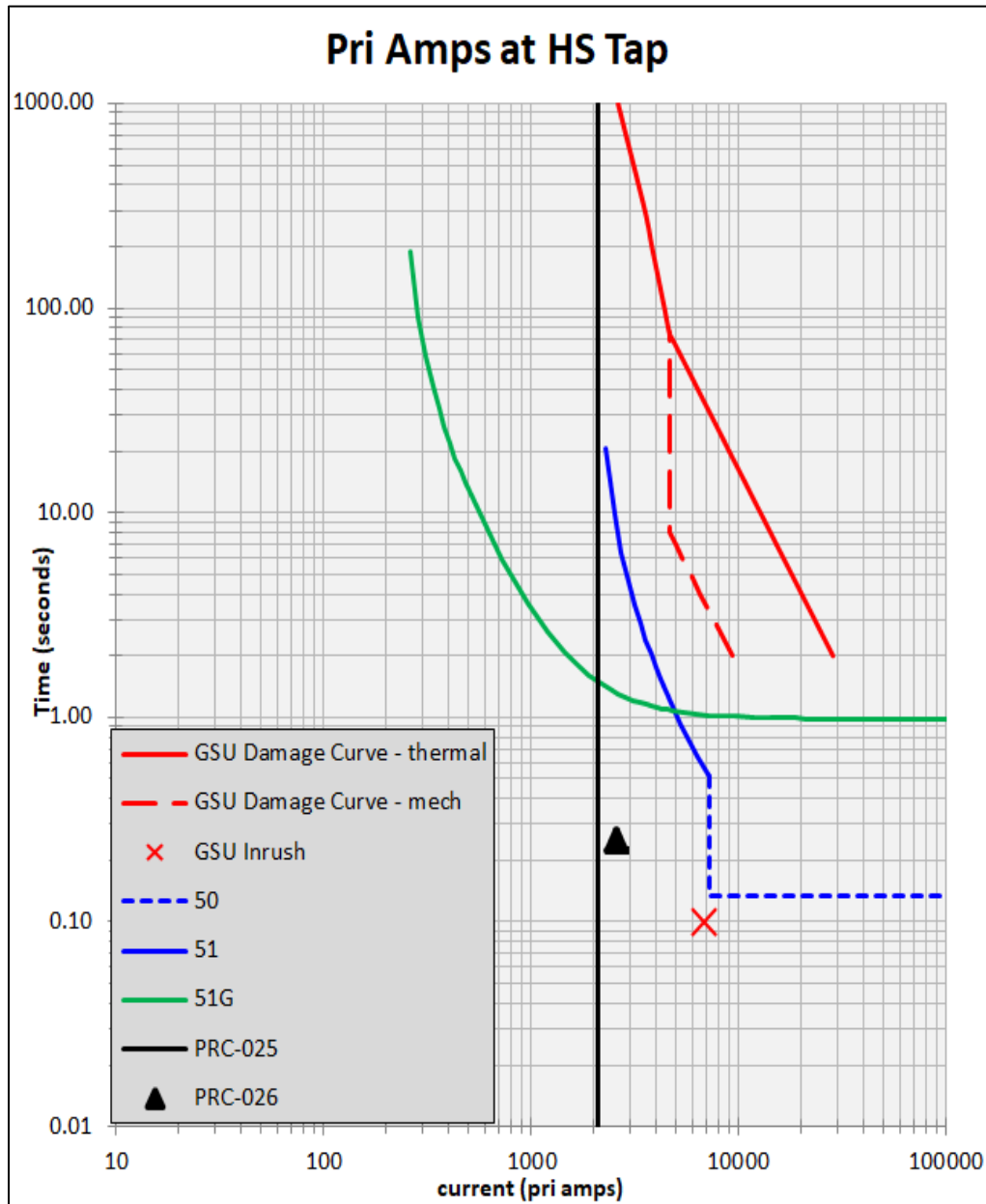
1 2 3 4 5 6 7 8

9 10 11 12 13 14 15 16

Blocking Inputs

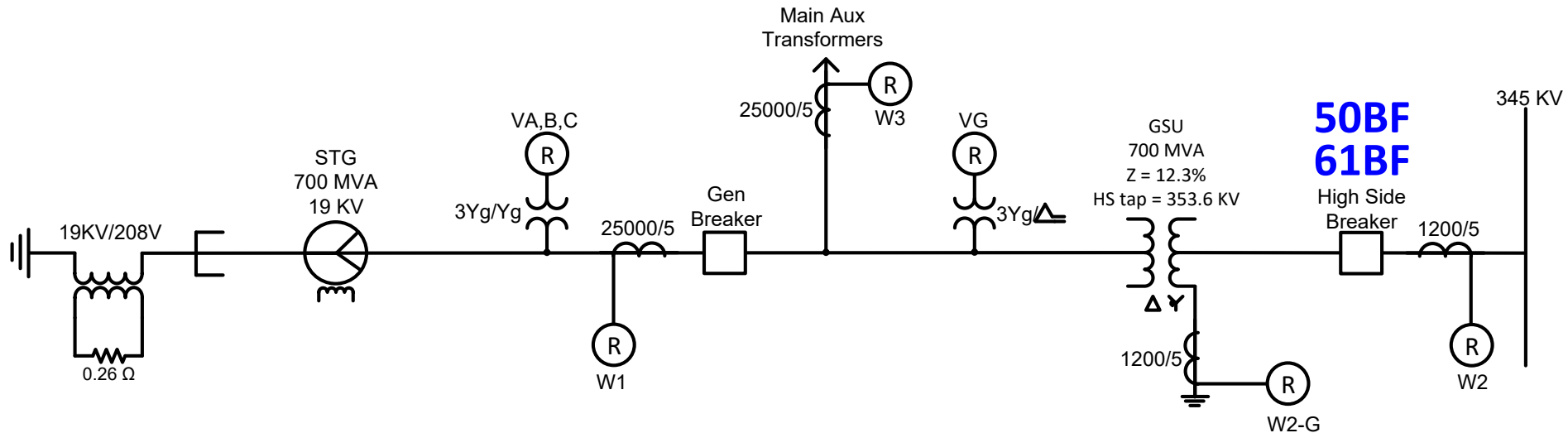
1 2 3 4 5 6 7 8 9

10 11 12 13 14 15 16 17 18



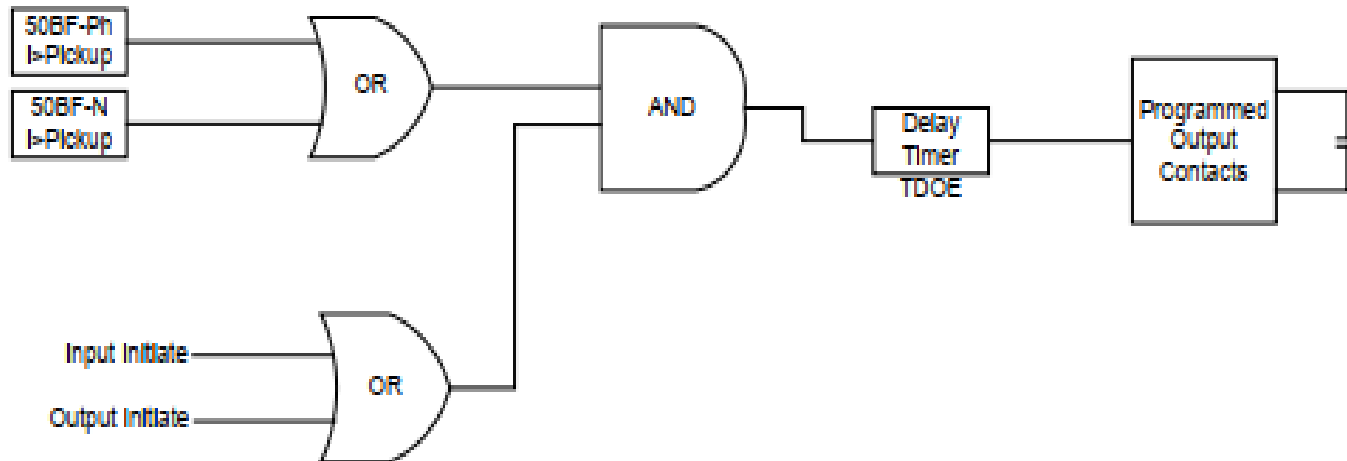
flattens out at about 1 second to coordinate with transmission line ground protection

50BF/61BF – Breaker Failure/Breaker Flashover



- *May provide breaker failure and breaker flashover protection for up to (4) breakers for a 4W relay*
- *Here just do it for the HS breaker*

Here is a logic diagram of the 50BF function:



50BF: Breaker Failure

Winding 1 | Winding 2 | Winding 3 | Winding 4

Phase Pickup: 0.10 ◀ ▶ 10.00 (A) Disable

Residual Pickup: 0.10 ◀ ▶ 10.00 (A)

Time Delay: 1 ◀ ▶ 8160 (Cycles)

Output Initiate

<input type="checkbox"/> 1	<input checked="" type="checkbox"/> 2	<input checked="" type="checkbox"/> 3	<input type="checkbox"/> 4	<input type="checkbox"/> 5	<input type="checkbox"/> 6	<input type="checkbox"/> 7	<input type="checkbox"/> 8
<input type="checkbox"/> 9	<input type="checkbox"/> 10	<input type="checkbox"/> 11	<input type="checkbox"/> 12	<input type="checkbox"/> 13	<input type="checkbox"/> 14	<input type="checkbox"/> 15	<input type="checkbox"/> 16

Input Initiate

<input checked="" type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4	<input type="checkbox"/> 5	<input type="checkbox"/> 6	<input type="checkbox"/> 7	<input type="checkbox"/> 8	<input checked="" type="checkbox"/> 9
<input type="checkbox"/> 10	<input type="checkbox"/> 11	<input type="checkbox"/> 12	<input type="checkbox"/> 13	<input type="checkbox"/> 14	<input type="checkbox"/> 15	<input type="checkbox"/> 16	<input type="checkbox"/> 17	<input type="checkbox"/> 18

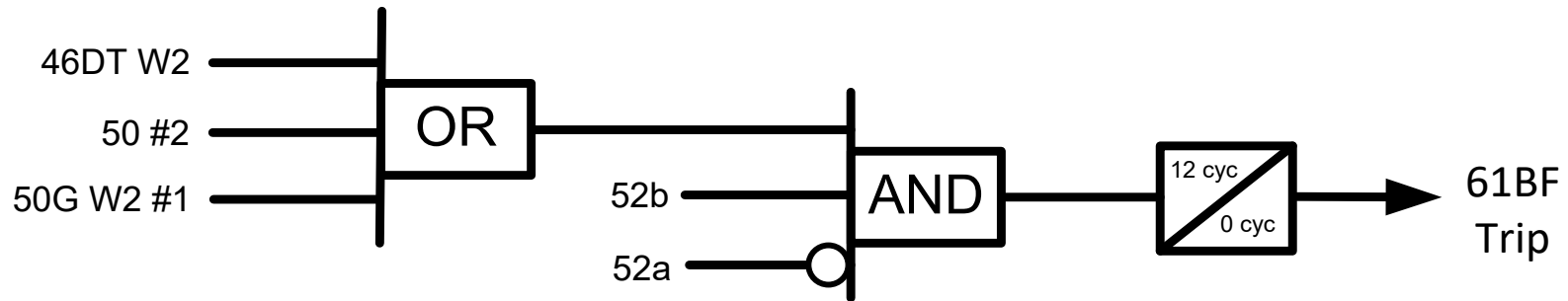
Outputs

<input checked="" type="checkbox"/> 1	<input checked="" type="checkbox"/> 2	<input checked="" type="checkbox"/> 3	<input checked="" type="checkbox"/> 4	<input checked="" type="checkbox"/> 5	<input checked="" type="checkbox"/> 6	<input checked="" type="checkbox"/> 7	<input checked="" type="checkbox"/> 8
<input checked="" type="checkbox"/> 9	<input checked="" type="checkbox"/> 10	<input type="checkbox"/> 11	<input type="checkbox"/> 12	<input type="checkbox"/> 13	<input type="checkbox"/> 14	<input type="checkbox"/> 15	<input type="checkbox"/> 16

Blocking Inputs

<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input type="checkbox"/> 4	<input type="checkbox"/> 5	<input type="checkbox"/> 6	<input type="checkbox"/> 7	<input type="checkbox"/> 8	<input type="checkbox"/> 9
<input type="checkbox"/> 10	<input type="checkbox"/> 11	<input type="checkbox"/> 12	<input type="checkbox"/> 13	<input type="checkbox"/> 14	<input type="checkbox"/> 15	<input type="checkbox"/> 16	<input type="checkbox"/> 17	<input type="checkbox"/> 18

Here is a logic diagram of the 61BF function created with IPSlogic:



IPSlogic

#1 | #2 | #3 | #4 | #5 | #6

Initiating Outputs: 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16

Initiating 97H/T Phase: A B C

Initiating Inputs: 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18

Blocking Inputs: 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18

Delay: 12 1 65500 (Cycles)

Reset/Dropout Delay: 0 0 65500 (Cycles) Reset Dropout

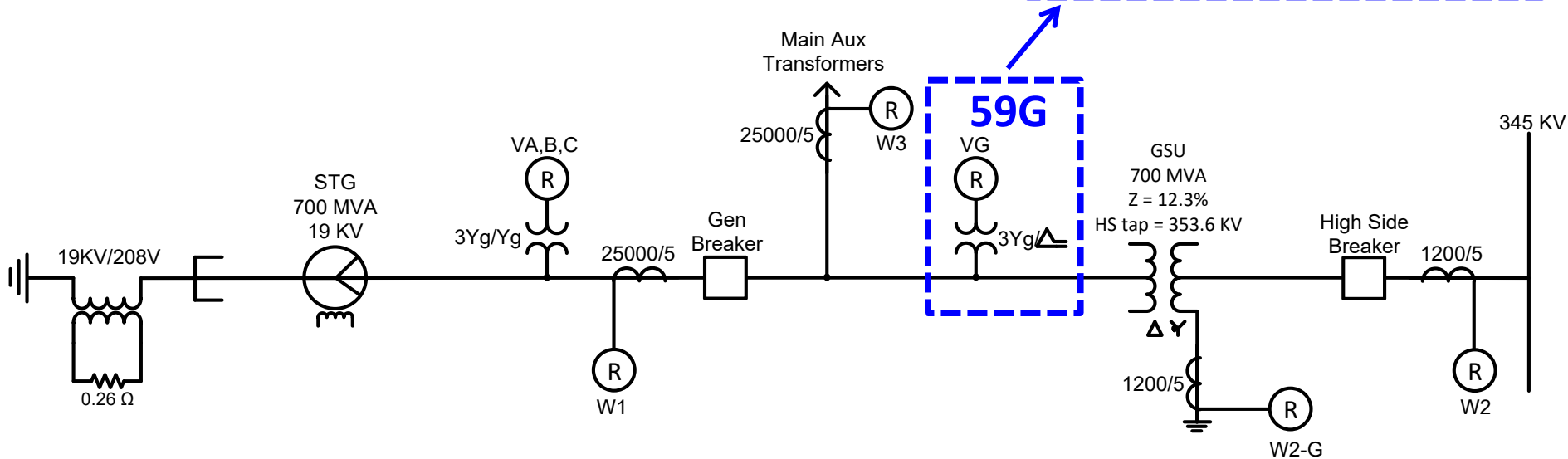
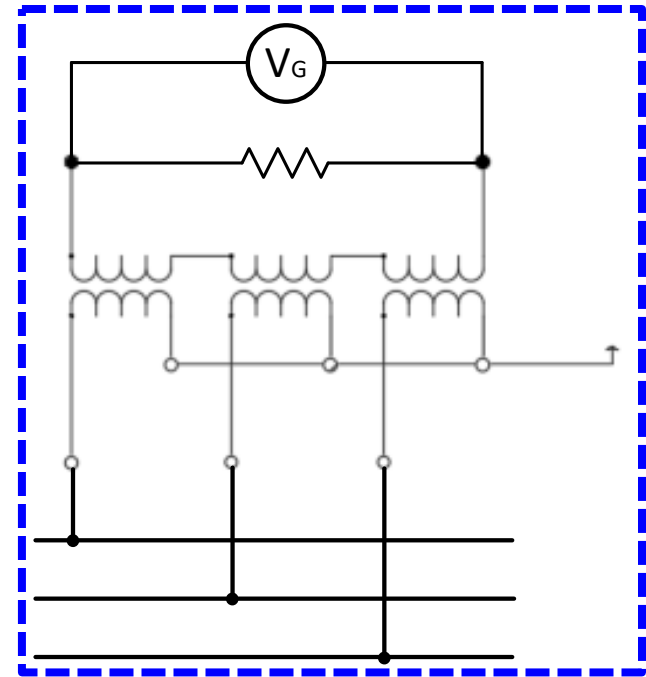
Outputs: 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16

Profile Switch: #1 #2 #3 #4 Not Activated

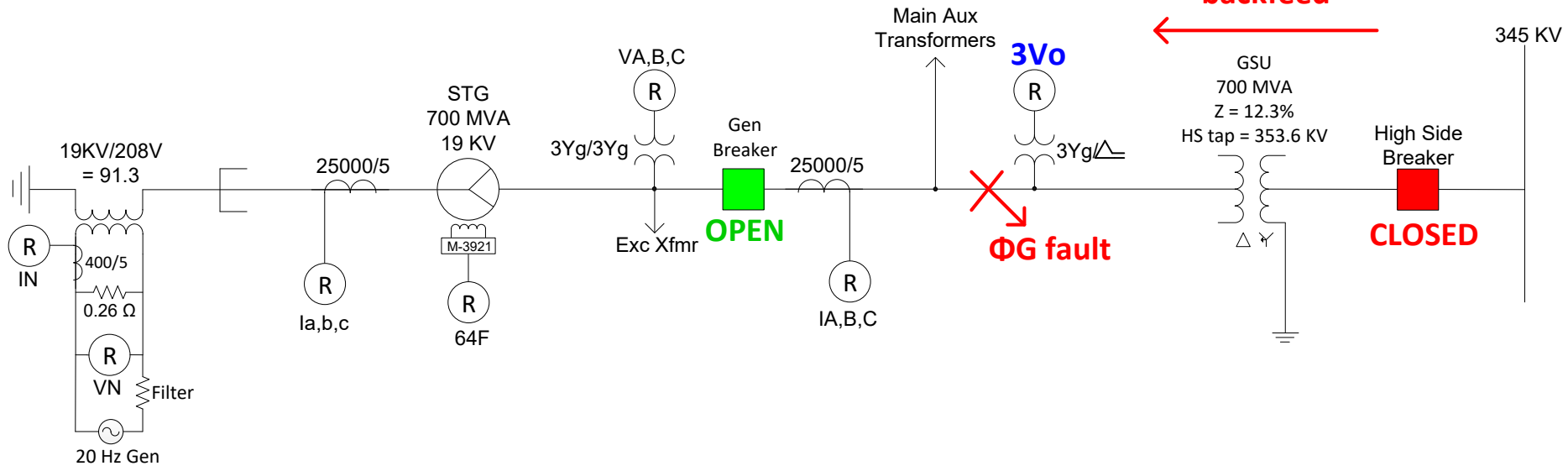
59G – Ground Overvoltage

VG voltage input is wired across the ballast/loading resistor of the broken delta VTs

Backup to 59X/3Vo function in M-3425A



3Vo Bus Ground fault protection



- Provides Gen Bus Ground fault protection prior to the unit being synched on-line and during back-feed scenarios where the generator breaker is open, or the generator links are removed with the GSU back energized from the system.
- Must trip HS breaker to clear system fault contribution into a bus ground fault.

59G settings criteria

For a ground fault on a high impedance grounded generator, I_0 approaches zero and V_0 approaches the phase-ground value of the nominal voltage:

$$V_0 = \frac{\text{pri LL Nominal Voltage}}{\sqrt{3} VTRG} = \frac{19 \text{ K}}{274.2} = 40 \text{ Vsec}$$

The broken delta VT on the gen bus VTs is measuring $3V_0$, not V_0 , therefore:

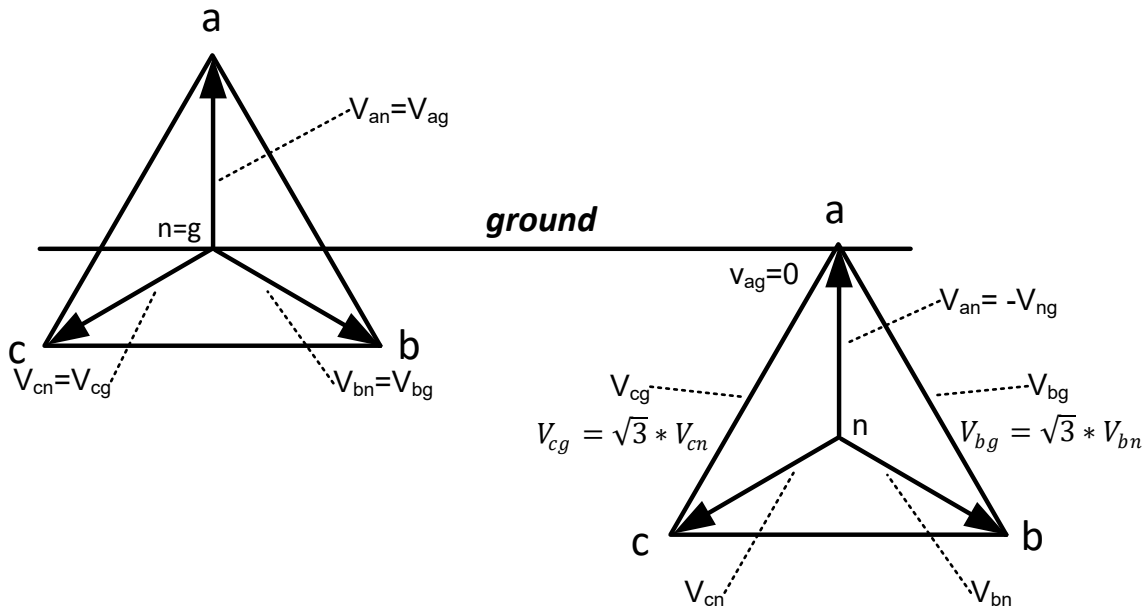
$$3V_0 = 3 * 40 = 120 \text{ Vsec}$$

For normal operation:

$$3V_0 = V_A + V_B + V_C = 40 \underline{/0^\circ} + 40 \underline{/-120^\circ} + 40 \underline{/120^\circ} = 0 \text{ V}$$

- Now for a ΦG fault on the 19 KV bus, the voltage across each of the two unfaulted VT secondaries will approach a phase-phase value ($40 \times 1.732 = 69.3 \text{ V}$) due to the neutral shift on high-impedance or ungrounded systems.
- Then the total measured voltage across the broken delta will be the vector addition of those 2 secondary voltages ($69.3 \times 1.732 = 120 \text{ V}$):

$$3V_0 = V_A + V_B + V_C = 0 + 69.3 \underline{-150^\circ} + 69.3 \underline{150^\circ} = 120 \underline{180^\circ} \text{ V}$$



- Here is the pickup setting criterion (% is listed as a % of the 120 V max $3V_0$ for a ΦG fault):

$SF * \text{max unbalance}; \text{min pickup} \leq 59G \text{ Pickup} \leq SM * 3V_0 \Phi G \text{ fault}; VT \text{ pri FL}$

$2 * 2.3\% \text{ or } 4.6\%; 4.2\% \leq 59G \text{ Pickup} \leq 0.25 * 100\% \text{ or } 25\%; 33\%$

$5.5 V; 5 V \leq 59G \text{ Pickup} \leq 30 V; 40 V$

- SF = Security Factor ≥ 2
- SM = Sensitivity Margin ≤ 0.25
- Max unbalance during backfeed, pre-synchronizing period, and on-line was measured to be 2.3%.
- Min pickup range for this setting is 5 V.
- VT primary fuse loss is calculated as follows:
 - ✓ $3V_0 = V_A + V_B + V_C = 40 \underline{/0^\circ} + 40 \underline{/-120^\circ} + 40 \underline{/120^\circ} = 0 \text{ V}$ under normal conditions with all fuses intact
 - ✓ $3V_0 = V_A + V_B + V_C = 0 + 40 \underline{/-120^\circ} + 40 \underline{/120^\circ} = 40 \underline{/180^\circ} \text{ V}$ for 1 blown fuse
 - ✓ $3V_0 = V_A + V_B + V_C = 40 \underline{/0^\circ} + 0 + 0 = 40 \underline{/0^\circ} \text{ V}$ for 2 blown fuses
 - ✓ $3V_0 = V_A + V_B + V_C = 0 + 0 + 0 = 0 \text{ V}$ for 3 blown fuses

Set 2 trips at 5% and 4 seconds and 15% and 2 seconds of the max 3Vo for a ground fault:

$$59G \#1 = 0.05 * 120 = 6 \text{ Vsec}$$

$$59G \#1 \text{ Time Delay} = 240 \text{ cycles (4 seconds)}$$

$$59G \#2 = 0.15 * 120 = 18 \text{ Vsec}$$

$$59G \#2 \text{ Time Delay} = 120 \text{ cycles (2 seconds)}$$

Zero Sequence Voltage Selection = VG (measured from broken delta of gen bus VTs)

- NOTE: 59G must trip the high side breaker as it is providing bus ground fault protection under backfeed scenarios and during the pre-synchronizing period.
- However, because 59G will also provide on-line ground fault protection, ensure it is a backup and coordinated with 59N from the M-3425A relays i.e. give 59N precedence and let it go first as it does not trip the high side breaker.
- To coordinate 59N/M-3425A and 59G/M-3311A (along with 59X/M-3425A if using), the setpoints must be compared on a primary basis, rather than secondary, because of the different ratios:

59N trip = 59N pickup * VTNR = 6.0 * 91.3 = 548 pri volts, 5 seconds or 10 cycles (accelerated scheme)

59G #1 trip = 59G #1 pickup * VTRG = 6 * 274.2 = 1645 pri volts, 4 seconds

59G #2 trip = 59G #2 pickup * VTRG = 18 * 274.2 = 4936 pri volts, 2 seconds

Enter 59G settings into relay

59G: Ground Overvoltage X

#1

Pickup: 5
Time Delay: 1

Outputs: 1 2 3 4 5 6 7 8
 9 10 11 12 13 14 15 16

Blocking Inputs: 1 2 3 4 5 6 7 8 9
 10 11 12 13 14 15 16 17 18

#2

Pickup: 5
Time Delay: 1

Outputs: 1 2 3 4 5 6 7 8
 9 10 11 12 13 14 15 16

Blocking Inputs: 1 2 3 4 5 6 7 8 9
 10 11 12 13 14 15 16 17 18

#3

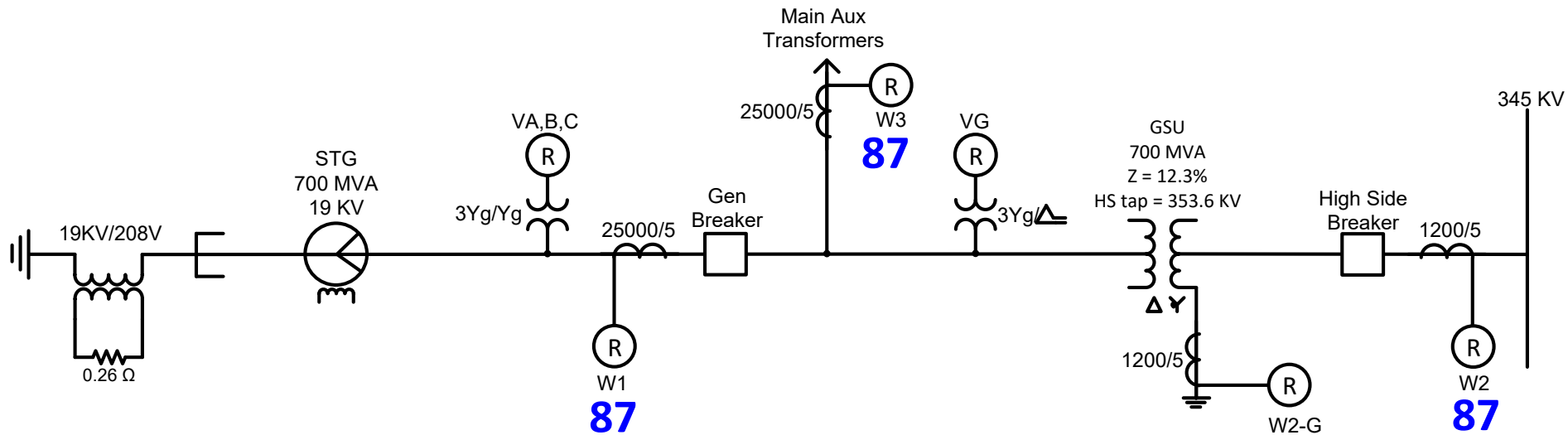
Pickup: 5
Time Delay: 1

Outputs: 1 2 3 4 5 6 7 8
 9 10 11 12 13 14 15 16

Blocking Inputs: 1 2 3 4 5 6 7 8 9
 10 11 12 13 14 15 16 17 18

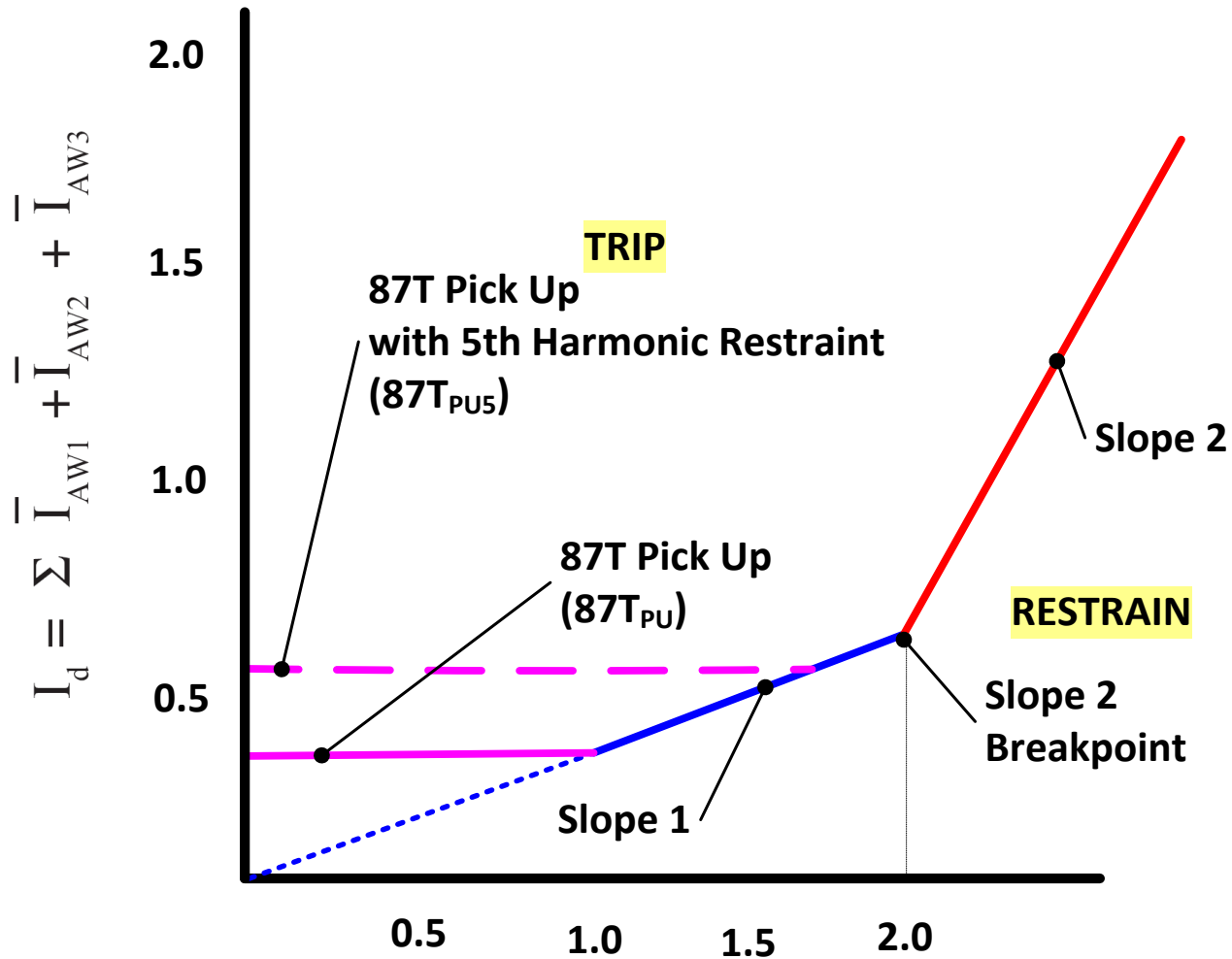
Zero Sequence Voltage Selection: VG 3Vo

87 – Phase Differential Current



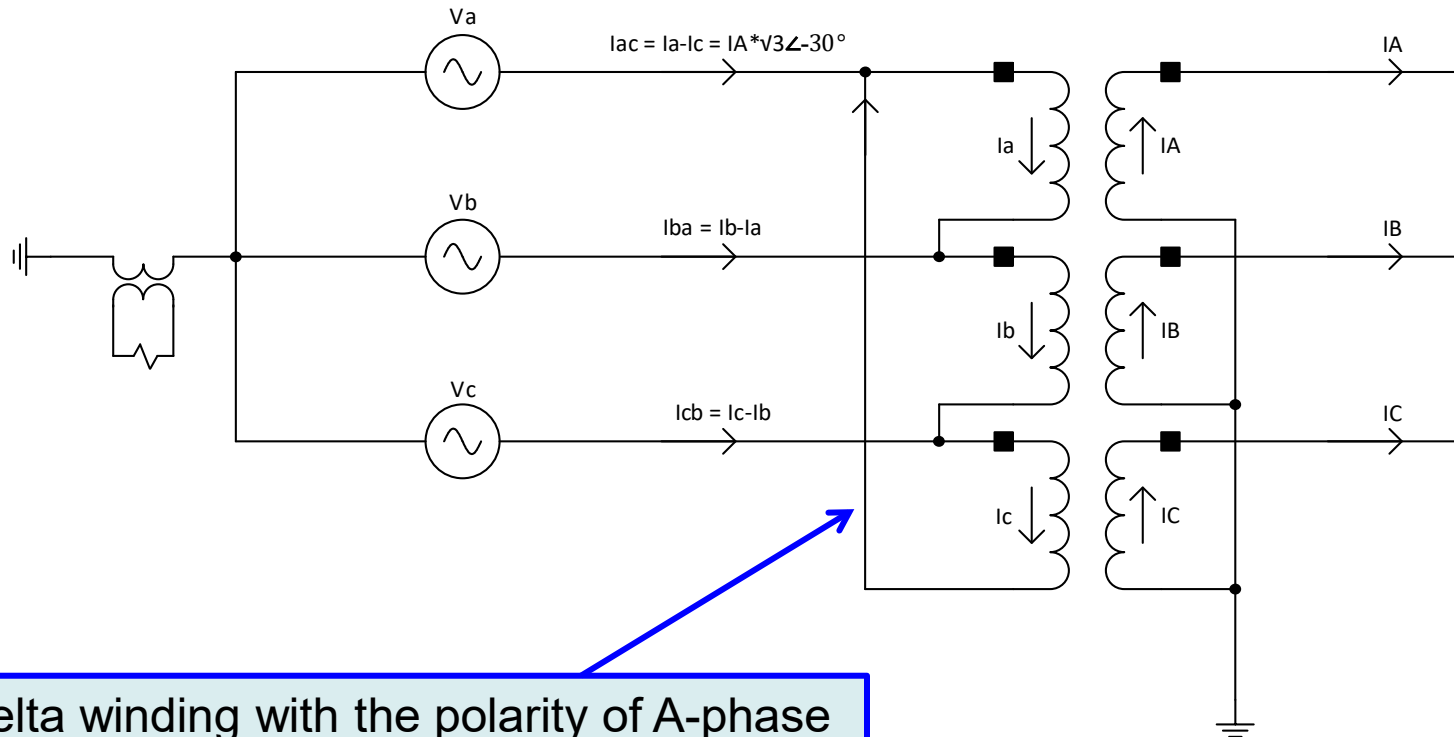
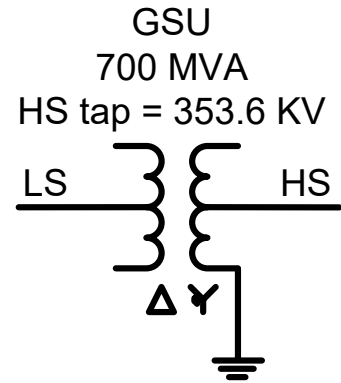
- *Provides 87T sensitive differential protection*
- *and 87H high-set differential protection for high magnitude internal faults*

Trip Characteristic – 87T



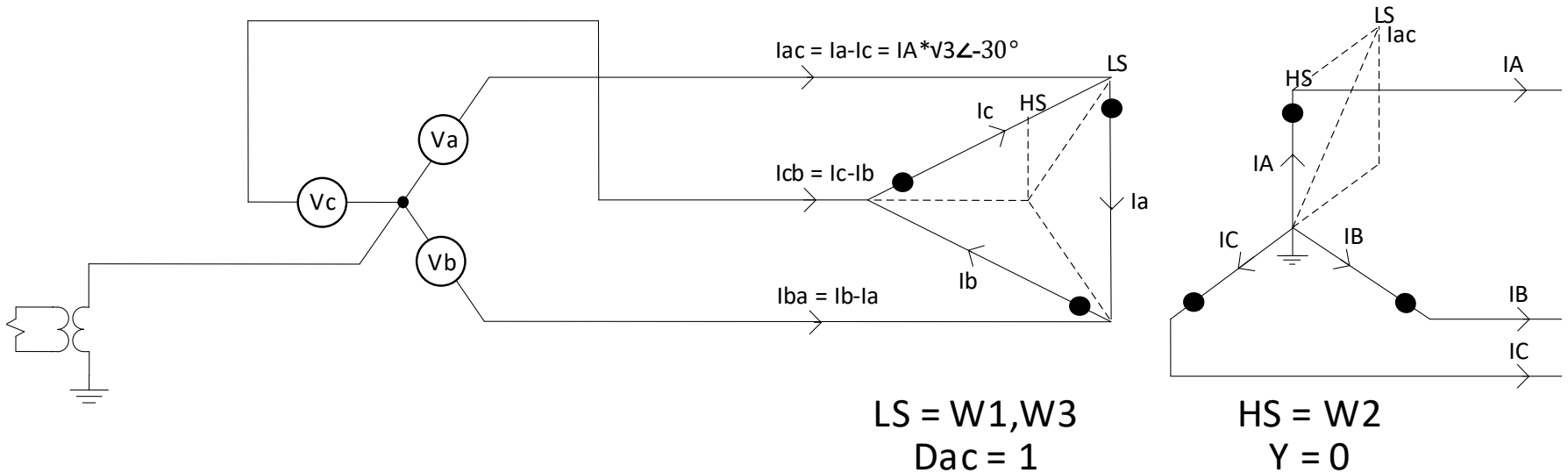
$$I_R = \frac{\sum |I_{AW1}| + |I_{AW2}| + |I_{AW3}|}{2}$$

XFMR Phase Shift Compensation



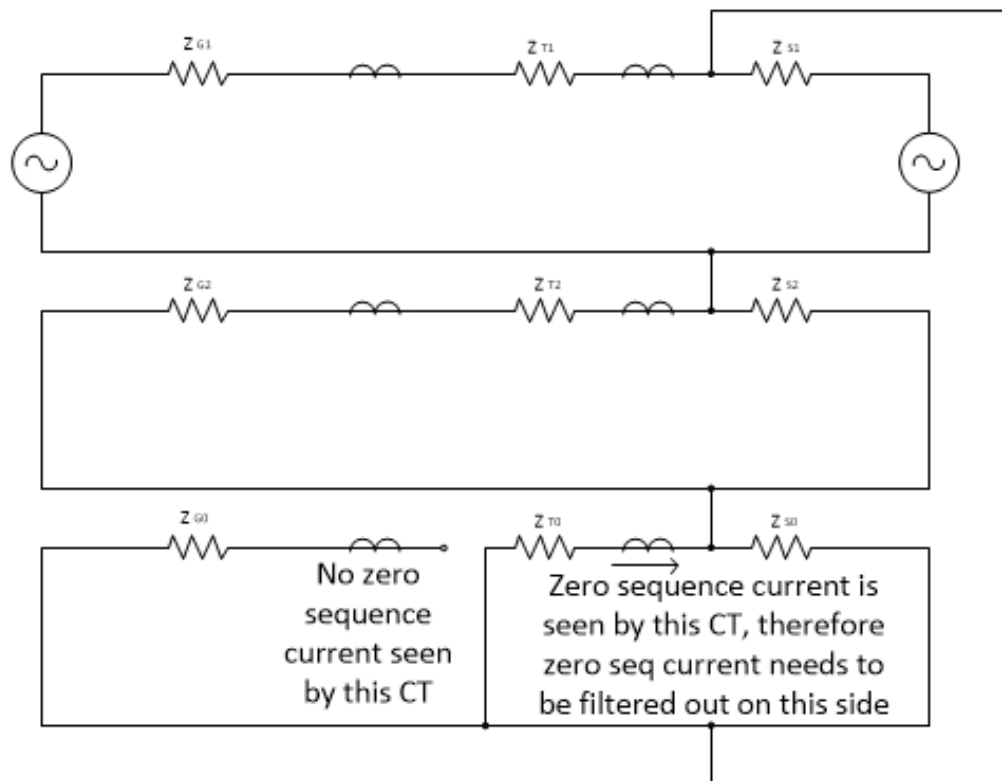
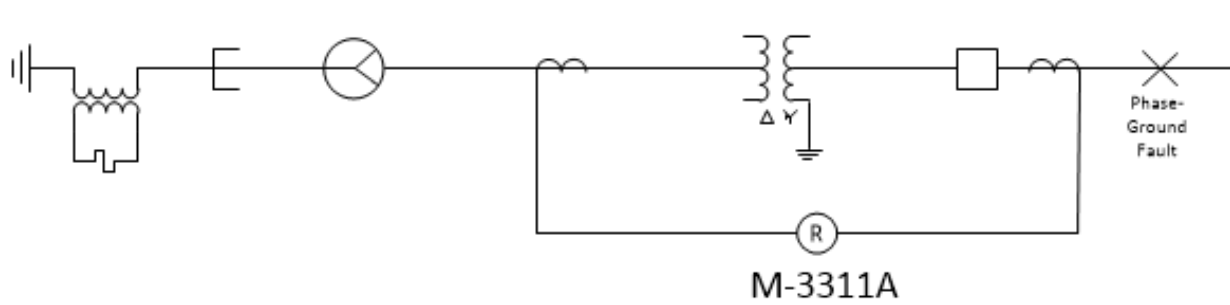
I_{ac} = Delta winding with the polarity of A-phase connected to the non-polarity of C-phase

XFMR Phase Shift Compensation



- The compensation matrix is a discrete number representing the number of 30° increments ($1 = 30^\circ$) a balanced set of currents with ABC phase rotation will be rotated in a CCW direction.
- All current inputs are compensated against a reference vector of 0° (they are not compensated against a particular winding that is designated as the reference quantity like some other relay mfgs).

Zero Sequence Filtering



Zero Sequence Filter

- The M-3311A 87 algorithm automatically filters out the zero sequence quantities on uncompensated (e.g. $Y = 0$) or ungrounded windings that do not have an external ground source introduced; therefore the zero sequence filter should not be enabled for these cases (other mfgs may do it differently).
- Therefore, for the M-3311A relay, the zero sequence filter should only be enabled if an external ground source exists on an ungrounded winding e.g. if a zigzag grounding transformer were connected on a Delta winding.
- For example, in the M-3311A relay, any Y windings should have a compensation setting of “0” and the algorithm will **automatically filter out the zero sequence currents** (unless an external ground source exists), whereas for some other mfgs Y windings with Y CTs cannot be left uncompensated (“0” compensation setting) or zero sequence currents will appear in those relay inputs but in no others resulting in a possible false trip for external ground faults.

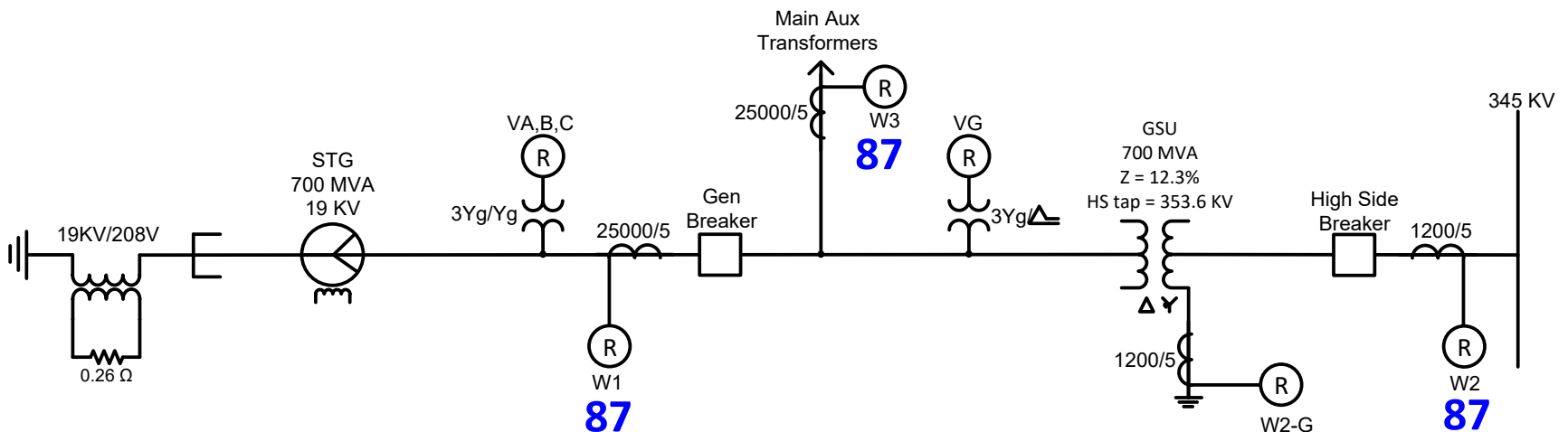
Enter 87 Compensation settings into relay

- The transformer can be compensated with types 0-11 using **Custom** selection, while the CTs can be compensated with types 0-23:
 - ✓ Types 0-11 correspond to phase shifts of 0° to 330° CCW with a magnitude gain of 1.
 - ✓ Types 13-23 is phase shifts of 0° to 330° CCW with a magnitude gain of $1/\sqrt{3}$.

Transformer/CT Connection

Standard Custom

Transformer W1	Transformer W2	Transformer W3
Dac	Y	Dac
C.T. W1	C.T. W2	C.T. W3
Y	Y	Y
W1 Zero Sequence Filter:	W2 Zero Sequence Filter:	W3 Zero Sequence Filter:
<input checked="" type="radio"/> Disable <input type="radio"/> Enable	<input checked="" type="radio"/> Disable <input type="radio"/> Enable	<input checked="" type="radio"/> Disable <input type="radio"/> Enable



Calculate Tap settings

Use the max rating of the GSU (700 MVA) to calculate Tap settings:

$$LS\ W1\ CT\ Tap = \frac{S_{gsu}}{\sqrt{3} * V_{LL}} * \frac{1}{CTR} = \frac{700M}{\sqrt{3} * 19K} * \frac{5}{25000} = 4.25\ sec\ amps$$

$$HS\ W2\ CT\ Tap = \frac{S_{gsu}}{\sqrt{3} * V_{LL}} * \frac{1}{CTR} = \frac{700M}{\sqrt{3} * 353.6K} * \frac{5}{1200} = 4.76\ sec\ amps$$

$$LS\ W3\ CT\ Tap = \frac{S_{gsu}}{\sqrt{3} * V_{LL}} * \frac{1}{CTR} = \frac{700M}{\sqrt{3} * 19K} * \frac{5}{25000} = 4.25\ sec\ amps$$

Check: $\frac{\max\ Tap}{\min\ Tap} = \frac{4.76}{4.25} = 1.12 < 8$ so CT Taps and CTRs are OK

87: Phase Differential Current

Enter 87 Tap settings into relay:

F87T | F87H | C.T. Tap

Winding 1 C.T. Tap:	<input type="text" value="4.25"/>	1.00	◀	▶	100.00
Winding 2 C.T. Tap:	<input type="text" value="4.76"/>	1.00	◀	▶	100.00
Winding 3 C.T. Tap:	<input type="text" value="4.25"/>	1.00	◀	▶	100.00

Calculate 87T Pickup

Set the 87T Pickup \geq 10% CT error and $<$ the min internal fault current with plenty of margin. First, calculate the minimum internal phase fault:

$$\text{internal HS } \Phi\Phi \text{ fault as seen by HS W2} = \frac{0.866 * \frac{1}{0.1043} * \frac{700 M}{\sqrt{3} * 353.6 K * 240}}{4.76} = 8.3 pu$$

$$\text{internal HS } \Phi\Phi \text{ fault as seen by LS W1} = \frac{0.866 * \frac{1}{0.295 + 0.123} * \frac{700 M}{\sqrt{3} * 19 K * 5000}}{4.25} = 2.1 pu$$

$$\text{Idiff from internal HS } \Phi\Phi \text{ fault} = 8.3 + 2.1 = 10.4 pu$$

$$\text{internal LS } \Phi\Phi \text{ fault as seen by HS W2} = \frac{0.866 * \frac{1}{0.1043 + 0.123} * \frac{700 M}{\sqrt{3} * 353.6 K * 240}}{4.76} = 3.8 pu$$

$$\text{internal LS } \Phi\Phi \text{ fault as seen by LS W1} = \frac{0.866 * \frac{1}{0.295} * \frac{700 M}{\sqrt{3} * 19 K * 5000}}{4.25} = 2.9 pu$$

$$\text{Idiff from internal LS } \Phi\Phi \text{ fault} = 3.8 + 2.9 = 6.7 pu$$

Calculate 87T Pickup

Set 87T Pickup \geq 10% CT error and $<$ the min internal fault current with margin:

$$\frac{(0.10 * CT \text{ Secondary Rating})}{\text{min Tap}} \leq 87T \text{ Pickup} < \text{min amps from HS } \Phi\Phi \text{ fault seen by W1, HS open}$$

$$\frac{(0.10 * 5)}{4.25} \leq 87T \text{ Pickup} < 2.1$$

$$0.12 \leq 87T \text{ Pickup} < 2.1$$

Set 87T Pickup = 0.12 pu

			87T Pickup = 0.12 pu	
			Pickup*Tap	Asec*CTR
			Asec	Apri
	Tap			
LS	W1	4.25	0.51	2550
HS	W2	4.76	0.57	137
LS	W3	4.25	0.51	2550

Calculate Slope 1

- Set the first slope more sensitive to detect low fault currents.
- Look at all the possible error currents in order to develop secure and sensitive slope settings.
- As there is no LTC on this GSU, the voltage ratio variation factor does not need to be considered here.
- In addition, use worst-case values of a 5% relay measurement error and a 3% transformer excitation current.
- For the first, sensitive slope region, Slope 1, assume a CT error of only $\pm 1\%$ because the CT error will usually be less at these low current levels.

$$\begin{aligned} \text{Slope 1} &> 2 * \text{CT error} + \text{relay accuracy} + \text{transformer excitation current} \\ &> 2 * 1\% + 5\% + 3\% \\ &> 10\% \end{aligned}$$

Set Percent Slope 1 = 20% (secure for CT errors up to $(20-8)/2 = 6\%$)

Calculate Slope 2

- Set the second, secure slope region, Slope 2, less sensitive to increase security in the high current region where the CT error is higher from CT saturation to correctly restrain for heavy external faults.
- Assume a CT error of $\pm 10\%$:

$$\begin{aligned} \text{Slope 2} &> 2 * \text{CT error} + \text{relay accuracy} + \text{transformer excitation current} \\ &> 2 * 10\% + 5\% + 3\% \\ &> 28\% \end{aligned}$$

Set Percent Slope 2 = 60% (secure for CT errors up to $(60-8)/2 = 26\%$)

Calculate the Break Point

- For the Slope Break Point between Slope 1 and Slope 2, use the following criteria:

$$87T \text{ Pickup} * \frac{100}{\text{Slope 1}} < \text{Break Point} < \frac{\text{max range of Tap settings}}{\text{max Tap}}$$

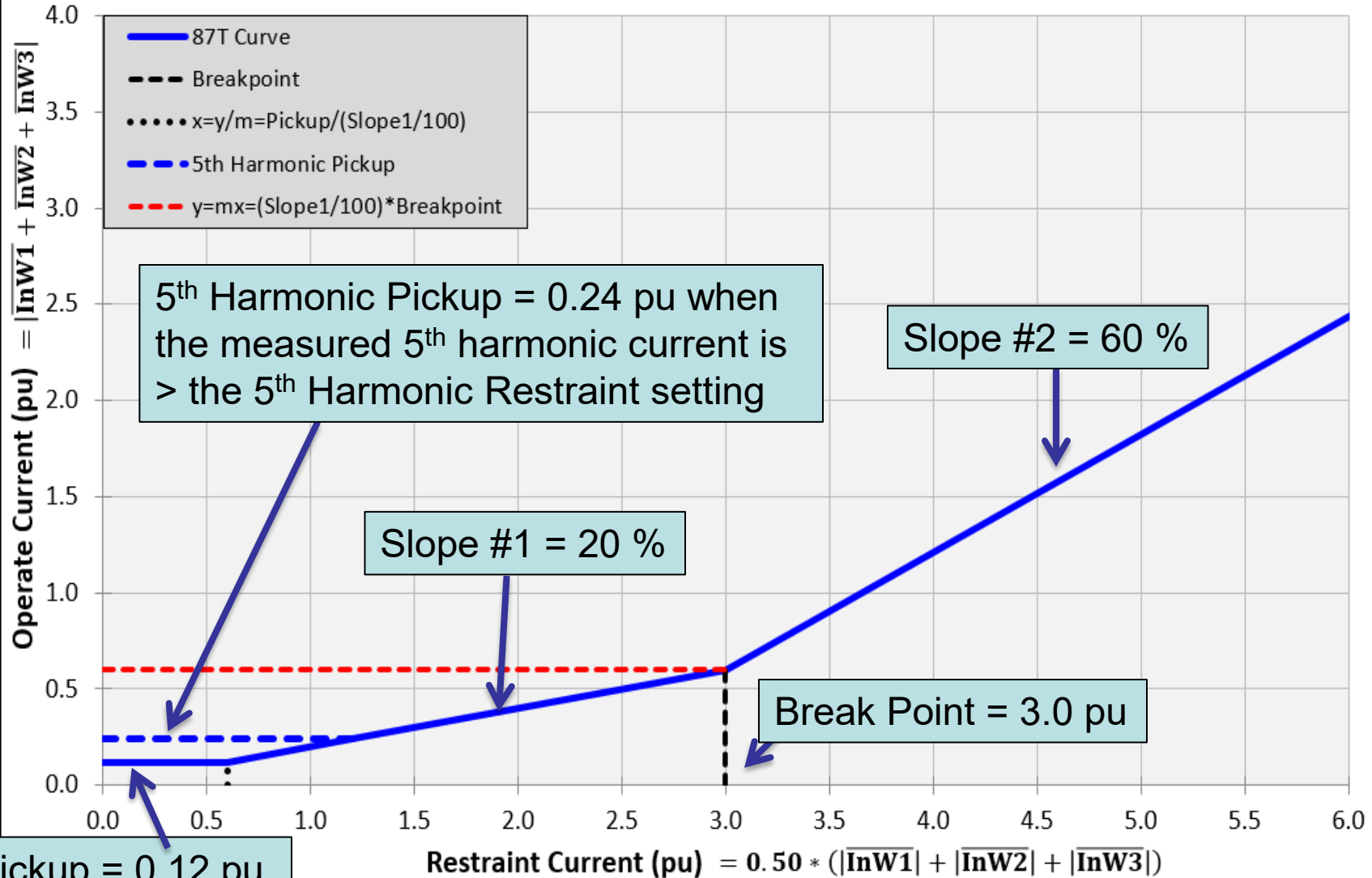
$$0.12 * \frac{100}{20} < \text{Break Point} < \frac{100}{4.76}$$

$$0.60 < \text{Break Point} < 21$$

Set Slope Break Point = 3.0 pu

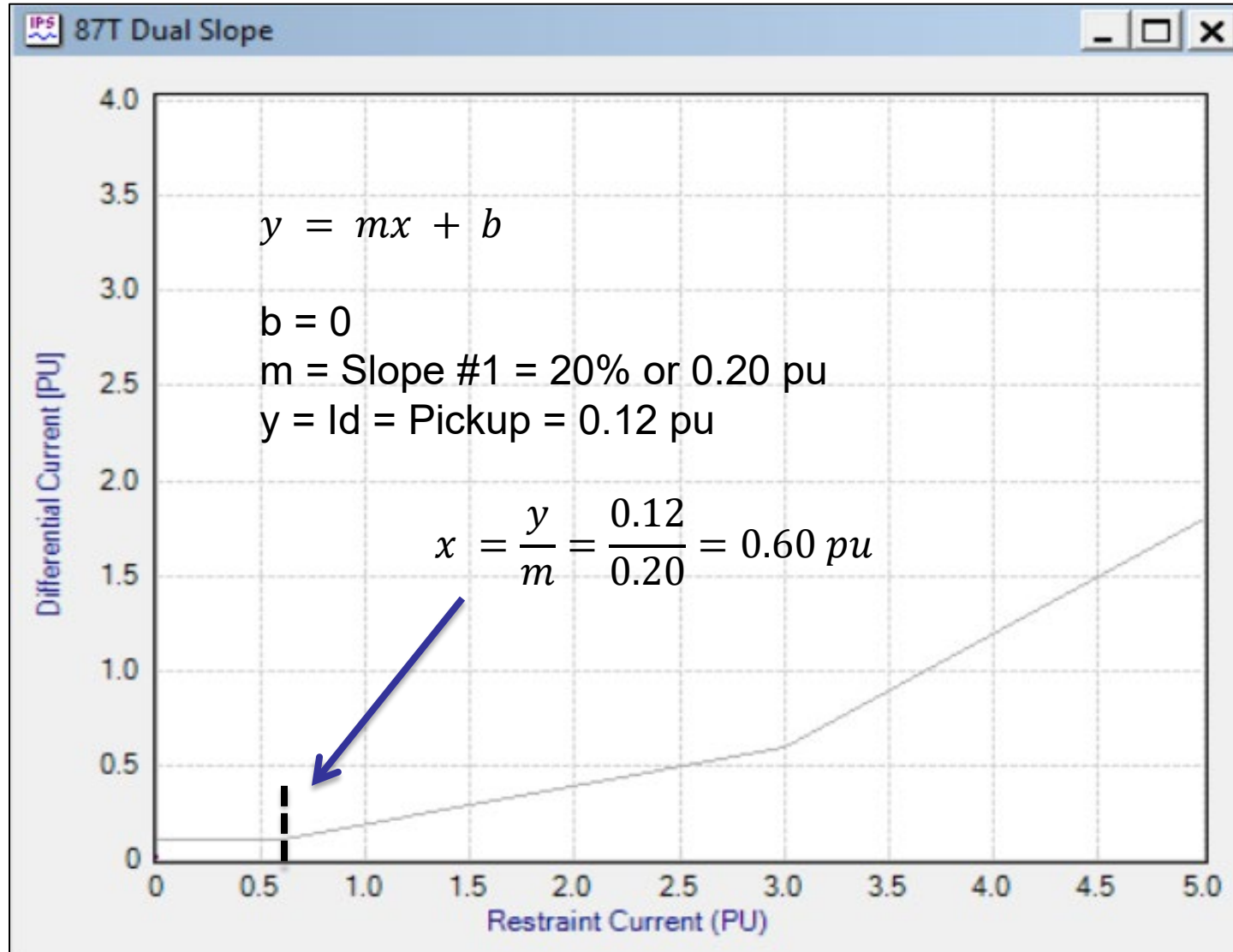
How to plot the 87T Characteristic

87T Characteristic Curve



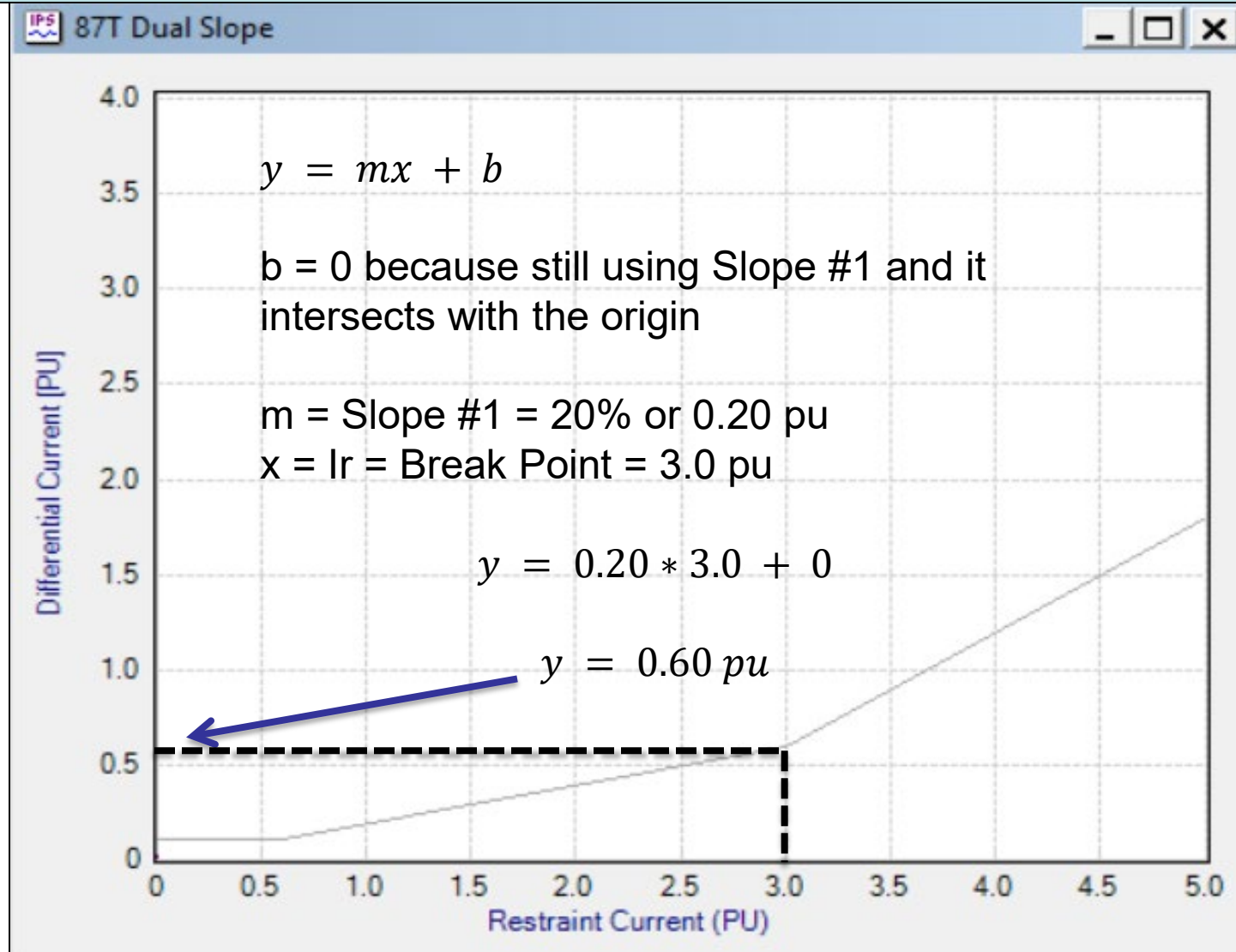
How to plot the 87T Characteristic

Step 1 – calc the pt on the x-axis where the Pickup intersects with Slope #1



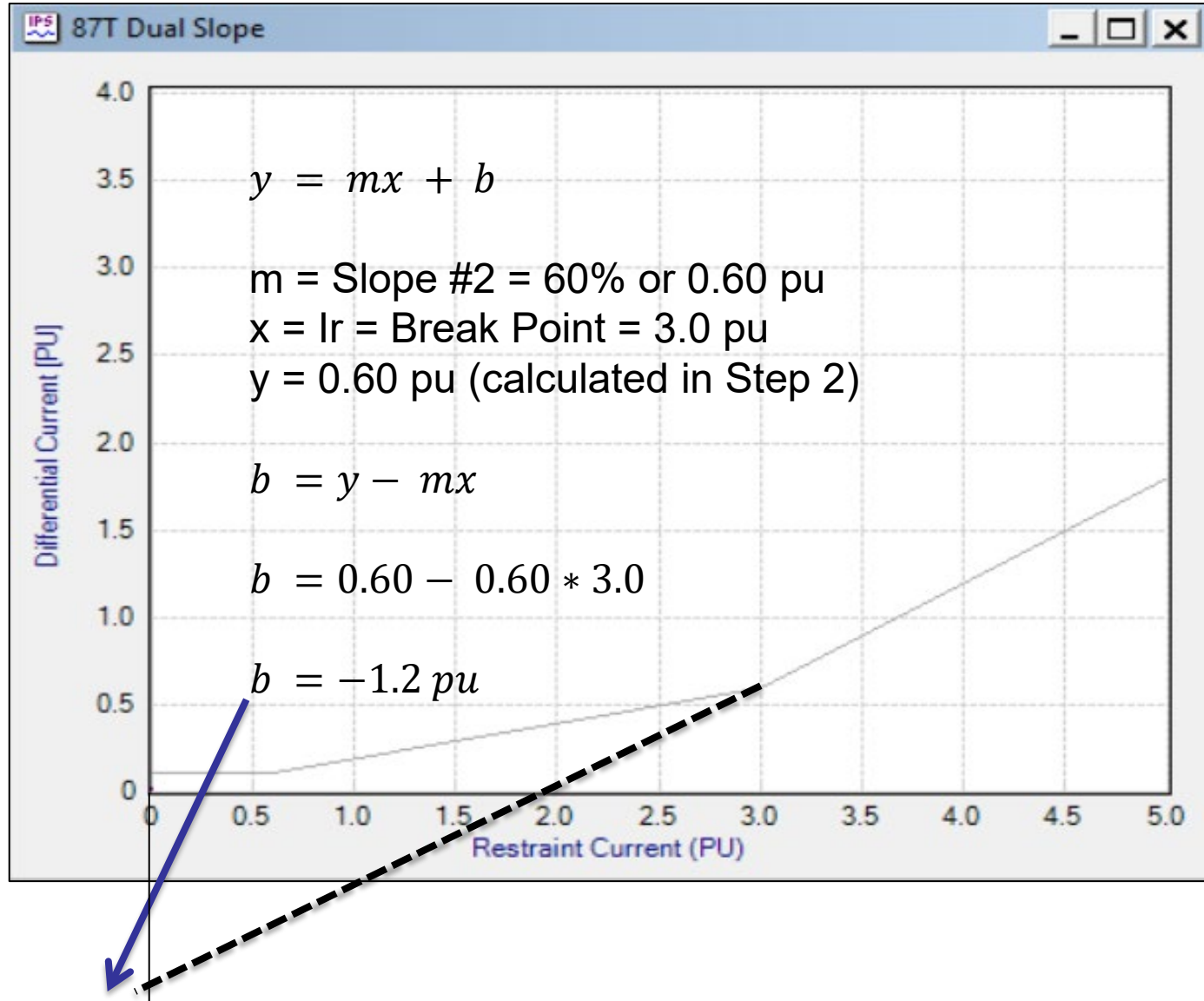
How to plot the 87T Characteristic

Step 2 – calculate the point on the y-axis (I_d) at which Slope #1 intersects with the Break Point (I_r on x-axis)



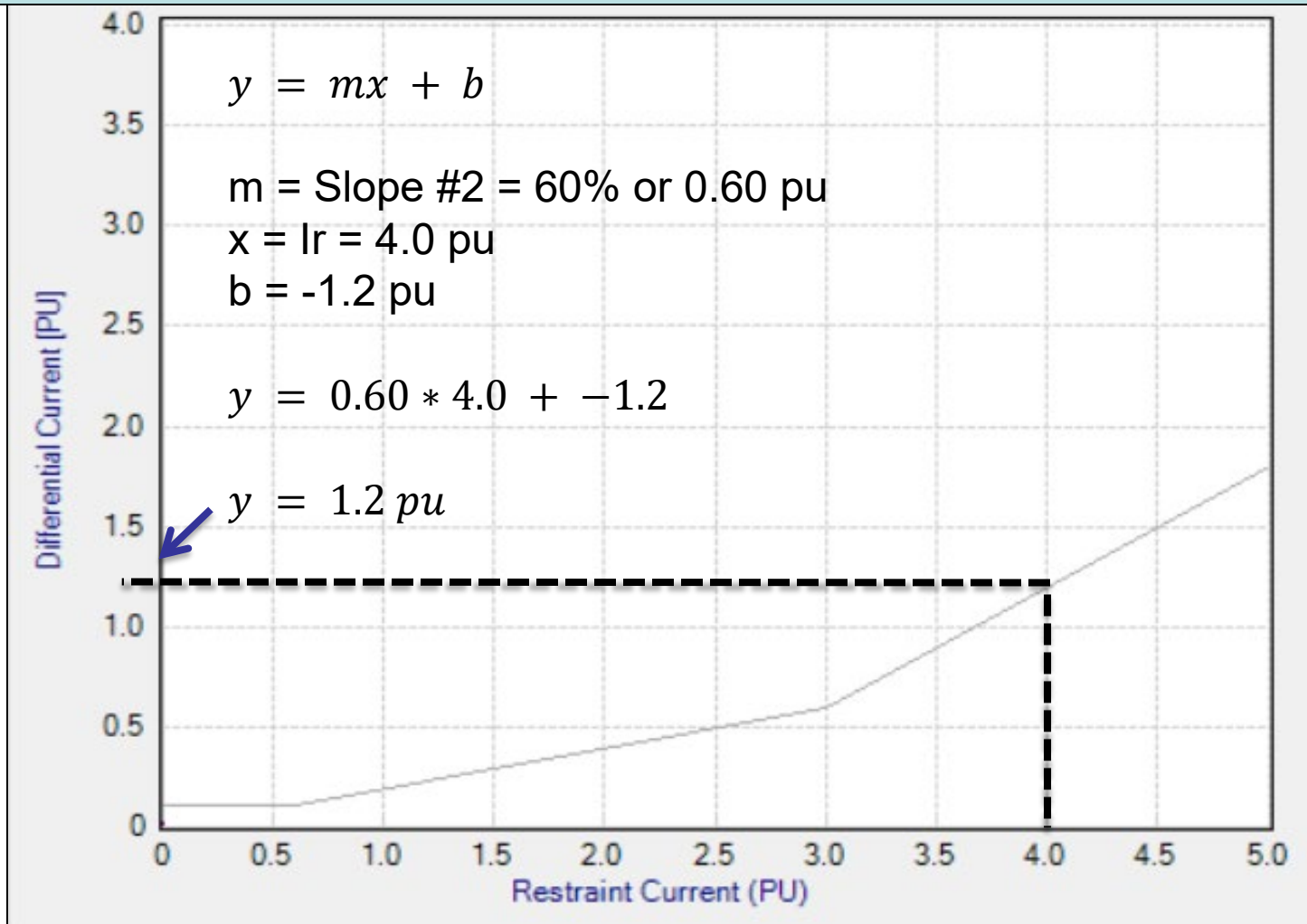
How to plot the 87T Characteristic

Step 3 – calculate the y-intercept for Slope #2



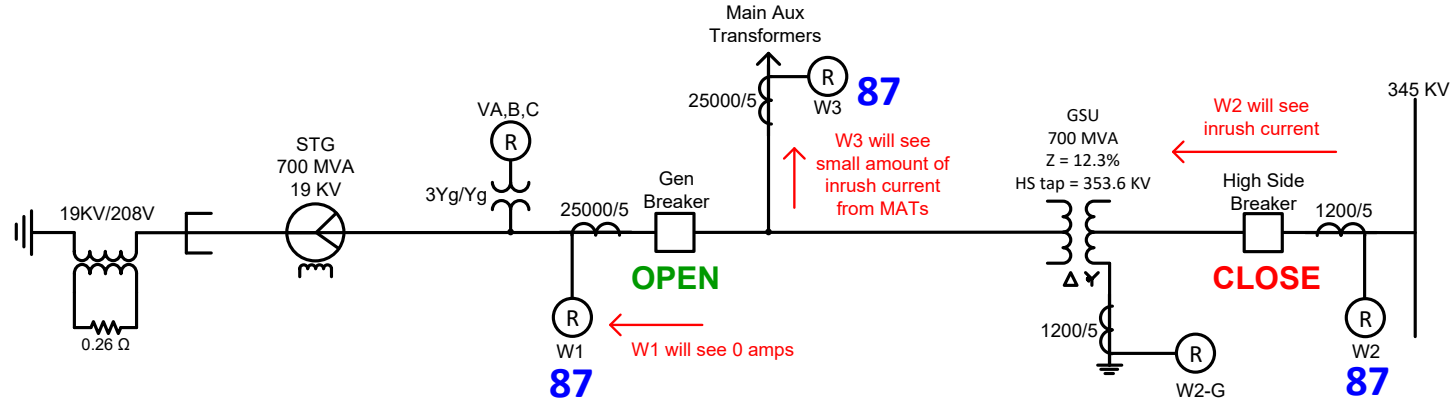
How to plot the 87T Characteristic

Now that the y-intercept is known, any point along Slope #2 can be calculated e.g. if you want to know the differential current (I_d) point on Slope #2 that corresponds to a restraint current (I_r) of 4.0 pu:



Even Harmonic Restraint

- Energization of a transformer causes a temporary large flow of magnetizing inrush current into one terminal of a transformer, without other terminals seeing this current.



- Thus, it appears as a differential current that could cause improper relay operation.
- Magnetizing inrush currents contain greater amounts of 2nd and 4th harmonic currents than do fault currents.
- This even-harmonic current can be used to identify the inrush phenomenon and to prevent relay mis-operation.
- The M-3311A relay measures the amount of 2nd and 4th harmonic currents flowing in the transformer and can restrain or block the relay from operating if the measured even harmonic current > even harmonic restrain pickup setting.

- The Even Harmonic restraint averages the 2nd and 4th harmonics for better security compared to only looking at the 2nd harmonic:

$$Ind(24) = \sqrt{Ind2^2 + Ind4^2} \quad \text{where } n = A, B, C$$

- It is recommended to enable Cross Phase Averaging (CPA) on the Even Harmonic Restraint.
- CPA takes the average of the 3 phases and evaluates it against your Even Harmonic Restraint setpoint:

$$Id(CPA, 24) = \sqrt{IAd24^2 + IBd24^2 + ICd24^2}$$

$$\frac{Id(CPA, 24)}{Ind(1)} > \text{Even Harmonic Restraint} * Ind \quad \text{where } n = A, B, C$$

- If CPA is enabled and this equation evaluates true for any phase, it will restrain 87T i.e. it will not trip even if one or more of the phases of differential current exceed the 87T pickup setting.
- If CPA is not enabled, it does not use the average value instead it evaluates each phase and if any phase evaluates false (measured even harmonic value is not $>$ the even harmonic setpoint), then it will not restrain or it will allow a trip if other criteria are met i.e. it will not restrain if one or more of the phases of differential current exceeds the 87T pickup setting.

Even Harmonic Restraint (2nd and 4th) = Enable w/ cross average
Restraint = 15%

- For example, with Even Harmonic Restraint = 15% and if the measured even harmonic values for A, B, and C are 10%, 20%, and 30% respectively and if CPA is Enabled, then it will correctly restrain because:

$$Id(CPA, 24) = \sqrt{10^2 + 20^2 + 30^2} = 37\%, \quad \text{and } 37\% > 15\%$$

- Conversely, if CPA is not enabled then the relay will not restrain because phase A at 10% is not > the 15% restraint setting, so it will allow a trip if other criteria are met.

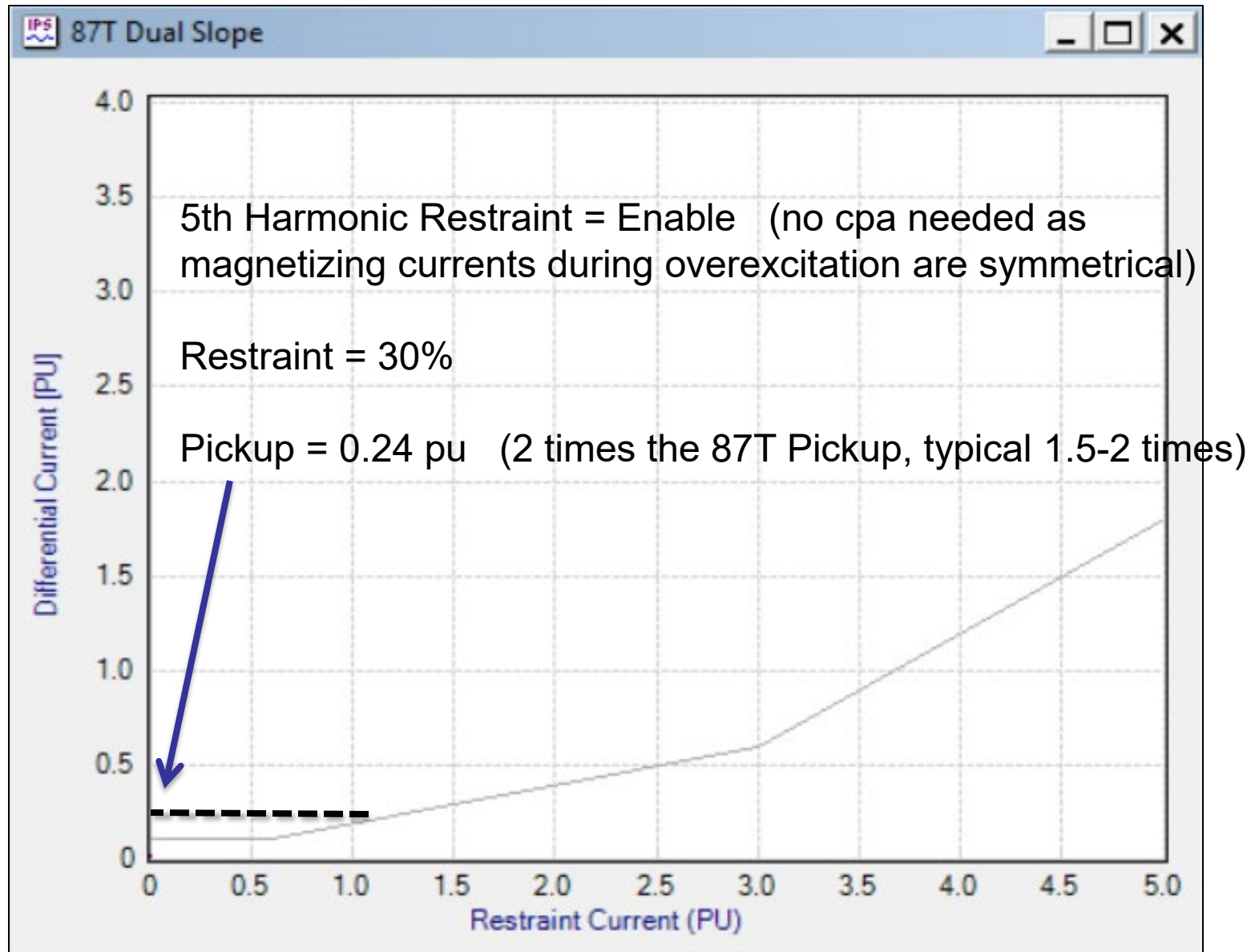
- Transformer simulations show that magnetizing inrush current usually yields more than 30% of IF_2/IF_1 in the first cycle of the inrush so a setting of 15% usually provides a margin of security for older transformers that have higher amounts of even harmonics present during magnetization.
- This could be decreased for newer transformers as typically, modern transformers tend to have low core losses and very steep magnetizing characteristics.
- An even harmonic setting of 10% or even lower may be appropriate for some of these modern transformers; although be aware that a setting $\leq 10\%$ risks blocking for internal faults.

5th Harmonic Restraint

- Transformer overexcitation produces 5th harmonics which can appear as an internal fault i.e. differential current to a transformer differential relay.
- The M-3311A relay just **desensitizes** the 87T element during overexcitation conditions, **rather than blocking** the 87T element (like some relay mfgs) as it is important to have differential protection during an overexcitation condition to protect the transformer from insulation breakdown that may be caused by the overfluxing.
- Fourier analysis of transformer currents during overexcitation indicates that a 30% to 35% 5th harmonic restraint setting is adequate to desensitize the differential element.
- The 5th Harmonic Pickup setting will be used as the 87T characteristic minimum pickup if the measured 5th Harmonic current is > the 5th Harmonic Restraint setting:

$$\frac{Ind(5)}{Ind(1)} > 5th \text{ Harmonic Restraint} * Ind \quad \text{where } n = A, B, C$$

5th Harmonic Restraint



Enter 87T settings into relay

87: Phase Differential Current

F87T | F87H | C.T. Tap

Pickup: 0.10 1.00 (PU)

Percent Slope #1: 5 100 (%)

Percent Slope #2: 5 200 (%)

Slope Break Point: 1.0 4.0 (PU)

Even Harmonics Restraint (2nd and 4th) Disable Enable Enable w/cross average

Restraint: 5 50 (%)

5th Harmonic Restraint Disable Enable Enable w/cross average

Restraint: 5 50 (%)

Pickup: 0.10 2.00 (PU)

Outputs

1 2 3 4 5 6 7 8
 9 10 11 12 13 14 15 16

Blocking Inputs

1 2 3 4 5 6 7 8 9
 10 11 12 13 14 15 16 17 18

Calculate 87H Pickup

- Set the unrestrained high set differential overcurrent function to detect high magnitude internal winding faults.
- The 87H function is not blocked by harmonic restraint.
- The 87H Pickup should be set above the worst-case, first peak of the inrush current to prevent mis-operation due to magnetizing inrush during energizing of the transformer.
- Note, a worst-case inrush of 12 times the self-cooled rating (not max rating) rating of the GSU will be used for this example:

$$\frac{(\text{inrush} * \text{xfmr self cooled rating}) / \text{CTR}}{\text{high side TAP}} < 87H \text{ Pickup} < \text{max internal fault}$$

$$\frac{12 * \frac{420}{\sqrt{3} * 0.3536} * \frac{5}{1200}}{4.76} < 87H \text{ Pickup} < \frac{1}{0.1043} * \frac{700 M}{\sqrt{3} * 353.6 K * 240} / 4.76$$

$$7.2 < 87H \text{ Pickup} < 9.6$$

Set 87H Pickup = 8.0 pu

Set 87H Time Delay = 1 cycle

Enter 87H settings into relay

The screenshot shows a software interface for configuring a relay. At the top, a blue header reads "87: Phase Differential Current". Below this, there are three tabs: "F87T", "F87H" (which is selected), and "C.T. Tap". The main configuration area contains two rows of settings. The first row is for "Pickup", with a text box containing "8.0", a range selector from "5.0" to "20.0 (PU)", and a "Disable" button. The second row is for "Time Delay", with a text box containing "1", a range selector from "1" to "8160 (Cycles)", and no button. Below these settings are two sections: "Outputs" and "Blocking Inputs". The "Outputs" section has a grid of checkboxes for 16 channels, with checkboxes 1 through 8 checked. The "Blocking Inputs" section has a grid of checkboxes for 18 channels, all of which are unchecked.

Section	Channel	Status
Outputs	1	Checked
	2	Checked
	3	Checked
	4	Checked
	5	Checked
	6	Unchecked
	7	Checked
	8	Checked
	9	Checked
	10	Checked
	11	Unchecked
	12	Unchecked
	13	Unchecked
	14	Unchecked
	15	Unchecked
	16	Unchecked
Blocking Inputs	1	Unchecked
	2	Unchecked
	3	Unchecked
	4	Unchecked
	5	Unchecked
	6	Unchecked
	7	Unchecked
	8	Unchecked
	9	Unchecked
	10	Unchecked
	11	Unchecked
	12	Unchecked
	13	Unchecked
	14	Unchecked
	15	Unchecked
	16	Unchecked
	17	Unchecked
	18	Unchecked

CT Saturation/Modelling/Dimensioning Calculations:

- To ensure the selected 87 settings (primarily the slope settings) are secure especially for severe, close-in, external faults or fault currents with high DC offset content which can cause severe saturation.
- These CT saturation calculations would ideally have been done during the design stage of the plant, substation, etc.
- This is so that the optimal CT relay classes could be specified to the mfg – for GSUs, the CTs may be provided by the GСУ mfg; however, for this example application, the CTs were provided by the gen breaker mfg, GСУ HS breaker mfg, and UAT mfg (UAT HS CTs).
- If the CT saturation calcs were not done, or even if they were, may want to re-run them to ensure the 87 settings are secure (or they may show that the 87 settings should be desensitized a bit for added security, etc).
- The CT saturation calcs may also determine the CT secondary wire gauge that is chosen to be installed, and any other burdens, etc.

Class “C” CTs

- Class “C” CTs are designed to “faithfully” replicate primary currents to within +/- 10%
- Class designations designate maximum secondary CT circuit voltage at standard burden (Z_{rated}) that can be applied to maintain accuracy

$Z_{\text{rated}} \Rightarrow$ Voltage Class , $20 * \text{Rated Secondary Current (5A)} * \text{Burden}$

$Z_{\text{rated}} \Rightarrow$ C800 , $20 * 5\text{A} * 8 \Omega$, \therefore 800V at 8 Ω burden

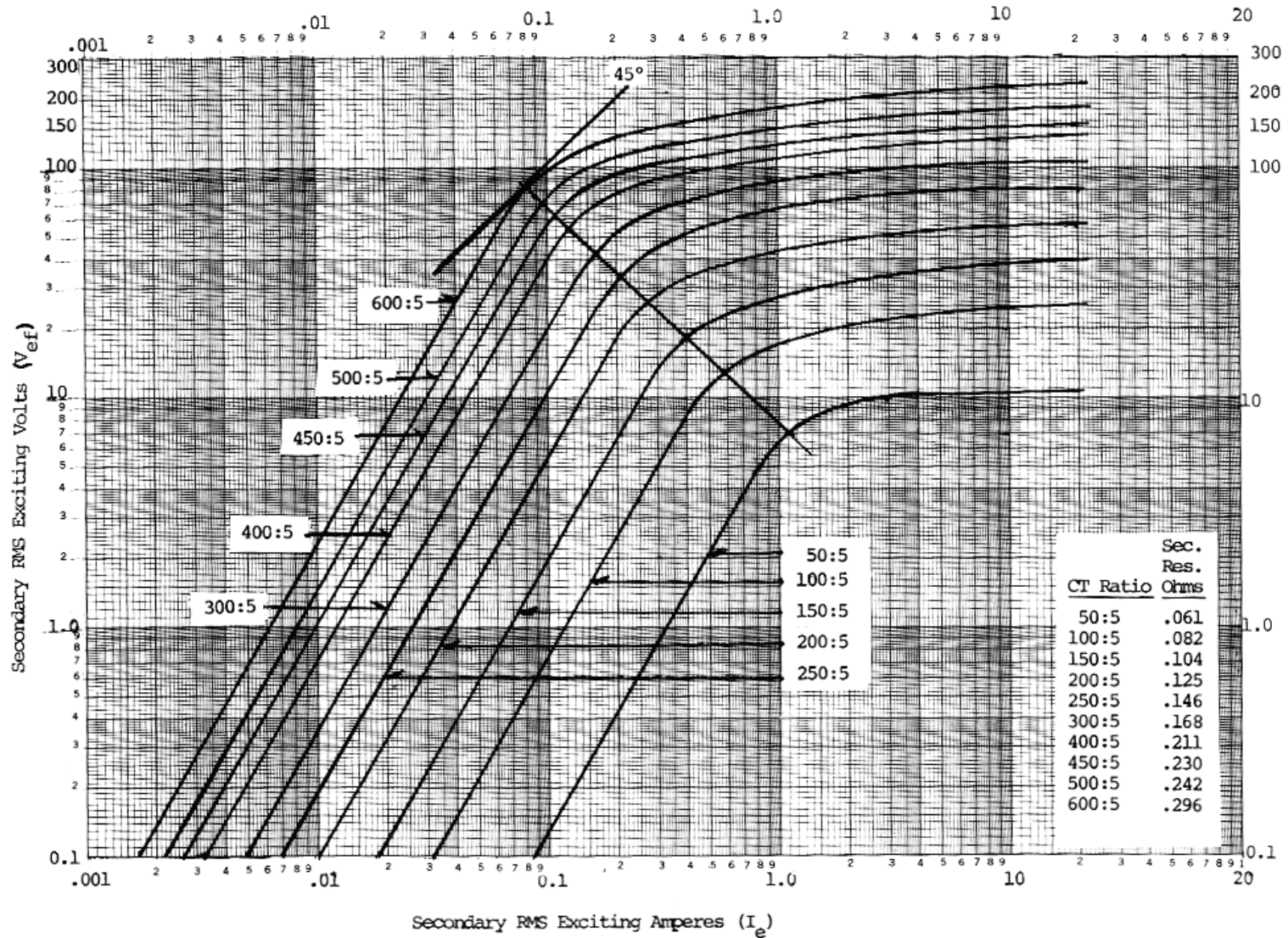
$Z_{\text{rated}} \Rightarrow$ C200 , $20 * 5\text{A} * 2 \Omega$, \therefore 200V at 2 Ω burden

The higher the C rating the greater the burden the CT can maintain its accuracy.

CT Performance

- Class “C” CTs have established secondary voltage/burden curves that are used to predict linear performance
- Operating a CT at values above the “kneepoint” on the curve invite unfaithful replication of the primary waveform and saturation
- Unfaithful replication (including saturation) between two CTs in a differential protection causes misoperation

Class "C" CT Performance Curve



Typical excitation curves for a 600:5 multiratio class C100 current transformer.

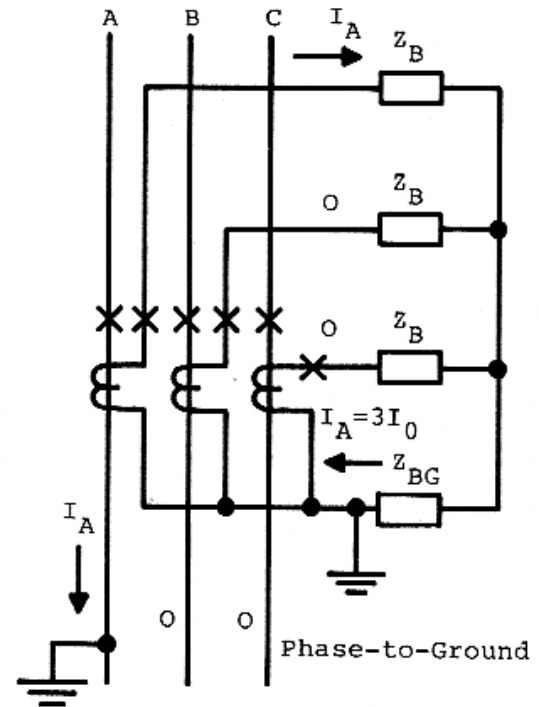
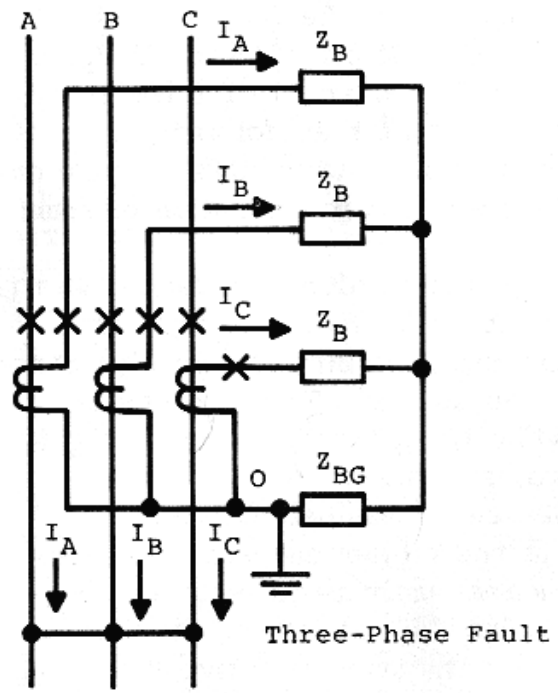
More than 100V secondary and you're in trouble

CT Performance Calculation

Use with Class “C” CTs

- Determine maximum primary phase and ground fault current
- Calculate secondary current based on CTR and CT connection type (wye or delta)
- Determine secondary CT circuit burden
- Determine maximum secondary voltage produced from burden with secondary fault currents
- Check maximum secondary voltage against CT capability

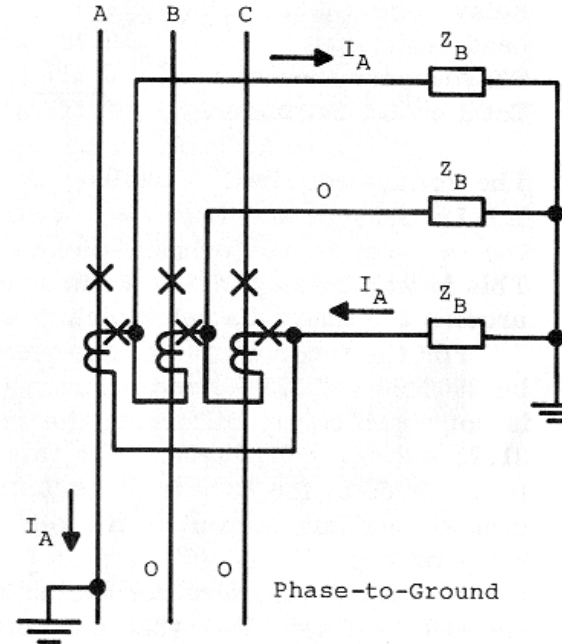
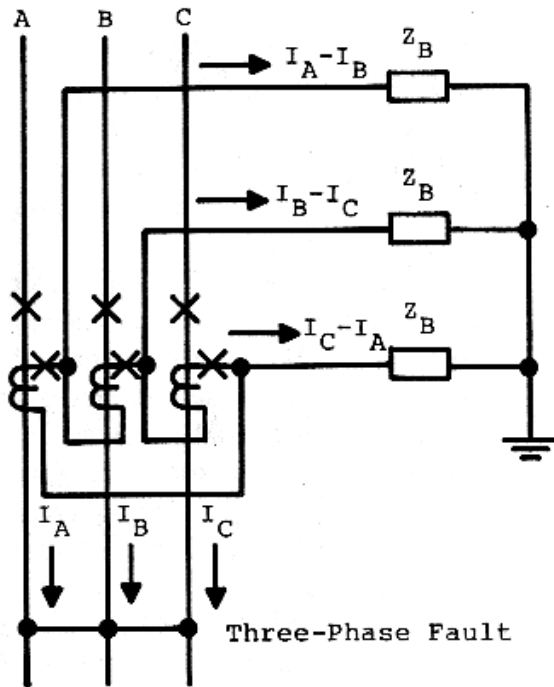
Fault Types and Currents in Secondary Circuits



For WYE connected CTs, to obtain secondary current, use:

$$I_{PRI} / CTR = I_{SEC}$$

Fault Types and Currents in Secondary Circuits



For Delta connected CTs, to obtain secondary current, use $\sqrt{3}$ factor as for a 3-phase fault
 $I_A - I_B = \sqrt{3} I_A$

$$\sqrt{3} I_{PRI} / CTR = I_{SEC}$$

Burden Calculation

- Determine all series burdens in secondary circuit
 - Relays, meters, instrumentation
- Determine lead burden
 - Use wire tables (AWG @ ohms/ft)
- Determine CT impedance
- Use CT data sheet (typ. 0.4 ohm or less)

AWG	Dia-mils	TPI	Dia-mm	Circ-mils	Ohms/Kft	Ft/Ohm	Ft/Lb	Ohms/Lb	Lb/Kft	*Amps	MaxAmps
0000	459.99	2.1740	11.684	211592	0.0490	20402	1.5613	0.0001	640.48	282.12	423.18
000	409.63	2.4412	10.405	167800	0.0618	16180	1.9688	0.0001	507.93	223.73	335.60
00	364.79	2.7413	9.2657	133072	0.0779	12831	2.4826	0.0002	402.80	177.43	266.14

AWG	Dia-mils	TPI	Dia-mm	Circ-mils	Ohms/Kft	Ft/Ohm	Ft/Lb	Ohms/Lb	Lb/Kft	*Amps	MaxAmps
0	324.85	3.0783	8.2513	105531	0.0983	10175	3.1305	0.0003	319.44	140.71	211.06
1	289.29	3.4567	7.3480	83690	0.1239	8069.5	3.9475	0.0005	253.33	111.59	167.38
2	257.62	3.8817	6.5436	66369	0.1563	6399.4	4.9777	0.0008	200.90	88.492	132.74
3	229.42	4.3588	5.8272	52633	0.1970	5075.0	6.2767	0.0012	159.32	70.177	105.27
4	204.30	4.8947	5.1893	41740	0.2485	4024.7	7.9148	0.0020	126.35	55.653	83.480
5	181.94	5.4964	4.6212	33101	0.3133	3191.7	9.9804	0.0031	100.20	44.135	66.203
6	162.02	6.1721	4.1153	26251	0.3951	2531.1	12.585	0.0050	79.460	35.001	52.501
7	144.28	6.9308	3.6648	20818	0.4982	2007.3	15.869	0.0079	63.014	27.757	41.635
8	128.49	7.7828	3.2636	16509	0.6282	1591.8	20.011	0.0126	49.973	22.012	33.018
9	114.42	8.7396	2.9063	13092	0.7921	1262.4	25.233	0.0200	39.630	17.456	26.185

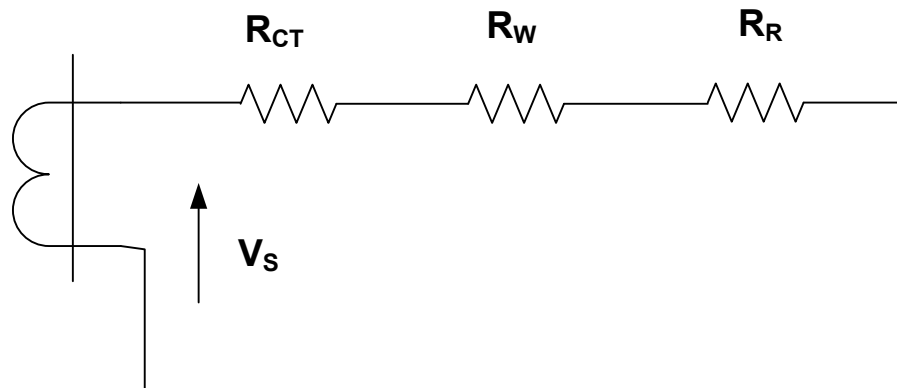
AWG	Dia-mils	TPI	Dia-mm	Circ-mils	Ohms/Kft	Ft/Ohm	Ft/Lb	Ohms/Lb	Lb/Kft	*Amps	MaxAmps
10	101.90	9.8140	2.5881	10383	0.9989	1001.1	31.819	0.0318	31.428	13.844	20.765
11	90.741	11.020	2.3048	8233.9	1.2596	793.93	40.122	0.0505	24.924	10.978	16.468
12	80.807	12.375	2.0525	6529.8	1.5883	629.61	50.593	0.0804	19.765	8.7064	13.060
13	71.961	13.896	1.8278	5178.3	2.0028	499.31	63.797	0.1278	15.675	6.9045	10.357
14	64.083	15.605	1.6277	4106.6	2.5255	395.97	80.447	0.2031	12.431	5.4755	8.2132
15	57.067	17.523	1.4495	3256.7	3.1845	314.02	101.44	0.3230	9.8579	4.3423	6.5134
16	50.820	19.677	1.2908	2582.7	4.0156	249.03	127.91	0.5136	7.8177	3.4436	5.1654
17	45.257	22.096	1.1495	2048.2	5.0636	197.49	161.30	0.8167	6.1997	2.7309	4.0963
18	40.302	24.813	1.0237	1624.3	6.3851	156.62	203.39	1.2986	4.9166	2.1657	3.2485
19	35.890	27.863	0.9116	1288.1	8.0514	124.20	256.47	2.0648	3.8991	1.7175	2.5762

Equivalent Circuit of the CT Secondary Wiring

Where R_{CT} is CT burden (internal)
 R_W total resistance of the ct secondary wiring.
 R_R is relay burden

$$V_S = I (R_{CT} + R_W + R_R)$$

I is the fault current and V_S is the CT secondary voltage. In order to make sure that the CT is in the linear range (to avoid ac saturation of the CTs), V_S should be less than the knee-point voltage of the ct excitation characteristics. (See IEEE Guide for the Application of Current Transformers Used for Protective Relaying Purposes C37.110).



Burden Calculation

Example

- Relay burden is specified as = 0.5 VA @ 5 A
 $R_R = VA/A^2$, $R_R = 0.5/25 = 0.02 \Omega$
- $R_W = 2 \Omega$ (round trip resistance of the CT wiring)
- $R_{CT} = 0.20 \Omega$ (CT internal burden)
- Total burden = 2.22 Ω


Secondary CT Circuit Voltage

- Assume maximum secondary current of 90 Amps and wye connected CTs
- $V_S = I (R_{CT} + R_W + R_R) * (F_{\Delta-Y})$
 - $(F_{\Delta-Y})$ = delta or wye CT factor
 - Use 1 for wye; use $\sqrt{3}$ for delta
- $V_S = 90 \times 2.22 * (1) = 199.8 \text{ V}$
- $V_S * 2 = 199.8 * 2 = 399.6 \text{ V}$ (Use at least a C400 rated CT)
 - *The 2x factor accounts for full DC offset*

- To also account for remanence:

$$V_{sat} := \frac{(|X_{overR}| + 1) \cdot \frac{I_{fmax}}{CT_{conntap}} \cdot \left(\frac{(Z_{relay} + 2 \cdot Z_{leads} + Z_{ctwdg})}{Z_{ctburden} \cdot \frac{CT_{conntap}}{CT_{maxtap}}} \right)}{1 - remanence}$$

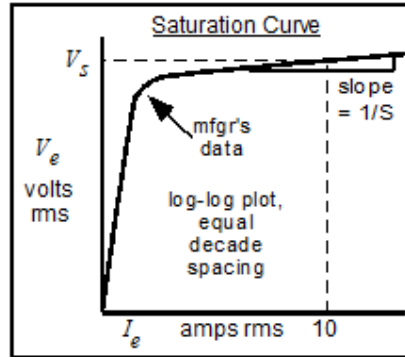
if $V_{sat} < 20$, then CTs will not saturate

- However, this is still just a spot check of the CT saturation at a single point in time i.e. it does not tell the full story of the CT saturation with respect to time.
- We may want a picture of how/when the CTs on each side of the transformer enter in to and exit out of saturation.
- e.g. If the CTs on one side of the transformer come out of saturation at a different rate than the other side's CTs, then there may be sufficient differential current to cause a nuisance 87 trip for some external faults.
- To calculate CT saturation with respect to time, may use 

CT Performance: 200:5, C200, R=0.5, Offset = 0.5, 1000A

INPUT PARAMETERS:

		ENTER:	
Inverse of sat. curve slope =	S =	22	---
RMS voltage at 10A exc. current =	Vs =	200	volts rms
Turns ratio = n2/1=	N =	40	---
Winding resistance =	Rw =	0.300	ohms
Burden resistance =	Rb =	0.500	ohms
Burden reactance =	Xb =	0.500	ohms
System X/R ratio =	XoverR =	12.0	---
Per unit offset in primary current =	Off =	0.50	-1<Off<1
Per unit remanence (based on Vs) =	λrem	0.50	---
Symmetrical primary fault current =	Ip =	1,000	amps rms

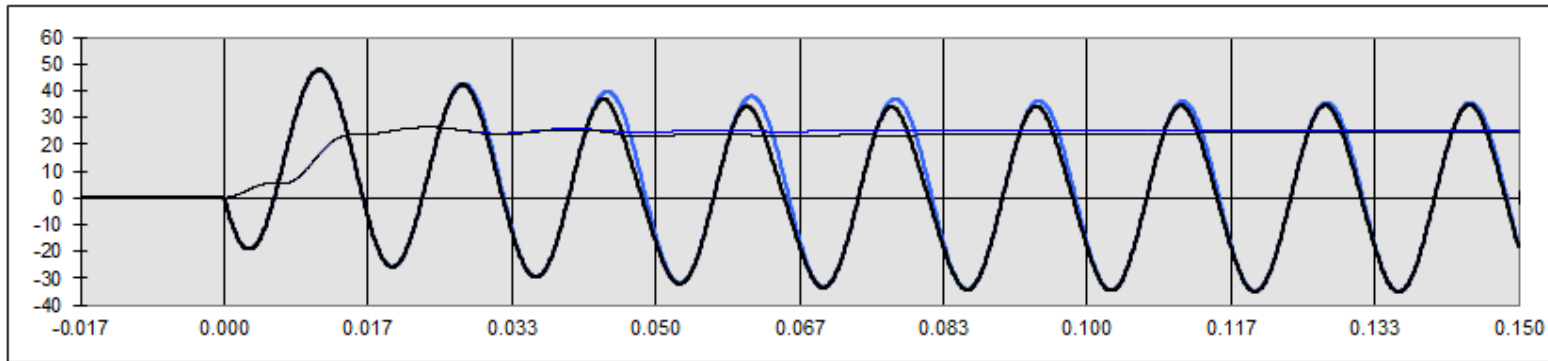


CALCULATED:

Rt = Total burden resistance = $R_w + R_b =$	0.800	ohms
pf = Total burden power factor =	0.848	---
Zb = Total burden impedance =	0.943	ohms
Tau1 = System time constant =	0.032	seconds
Lamsat = Peak flux-linkages corresponding to Vs	0.750	Wb-turns
ω = Radian freq =	376.99	rad/s
RP = Rms-to-peak ratio =	0.34584	
A = Coefficient in instantaneous ie versus lambda curve: ie = A * I ^S :	1.61E+04	---
dt = Time step =	0.000083	seconds
Lb = Burden inductance =	0.00133	henries

Thick lines: Ideal (blue) and actual (black) secondary current in amps vs time in seconds.

Thin lines: Ideal (blue) and actual (black) secondary current extracted fundamental rms value, using a simple DFT with a one-cycle window.



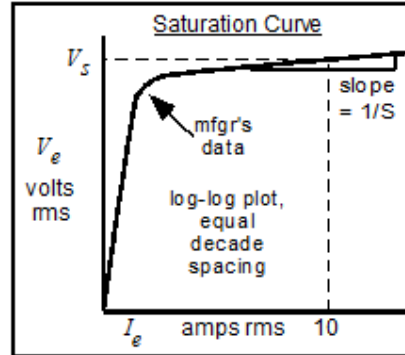
Source: http://www.pes-psrc.org/kb/published/reports/CT_SAT%2010-01-03.zip

CT Performance:

200:5, C200, R=0.75, Offset = 0.75, 2000A

INPUT PARAMETERS:

		ENTER:		
Inverse of sat. curve slope =	S =	22	---	
RMS voltage at 10A exc. current =	Vs =	200	volts rms	
Turns ratio = n2/1 =	N =	40	---	
Winding resistance =	Rw =	0.300	ohms	
Burden resistance =	Rb =	0.500	ohms	
Burden reactance =	Xb =	0.500	ohms	
System X/R ratio =	XoverR =	12.0	---	
Per unit offset in primary current =	Off =	0.75	-1<Off<1	
Per unit remance (based on Vs) =	λrem =	0.75	---	
Symmetrical primary fault current =	Ip =	2,000	amps rms	

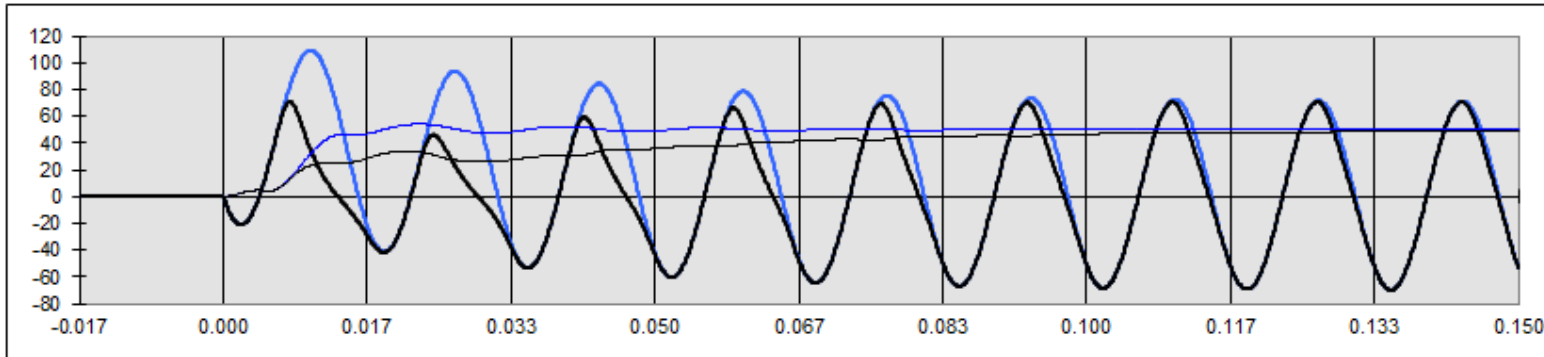


CALCULATED:

Rt = Total burden resistance = $R_w + R_b =$	0.800	ohms
pf = Total burden power factor =	0.848	---
Zb = Total burden impedance =	0.943	ohms
Tau1 = System time constant =	0.032	seconds
Lamsat = Peak flux-linkages corresponding to Vs	0.750	Wb-turns
ω = Radian freq =	376.99	rad/s
RP = Rms-to-peak ratio =	0.34584	
A = Coefficient in instantaneous ie versus lambda curve: $i_e = A * I^S$:	1.61E+04	---
dt = Time step =	0.000083	seconds
Lb = Burden inductance =	0.00133	henries

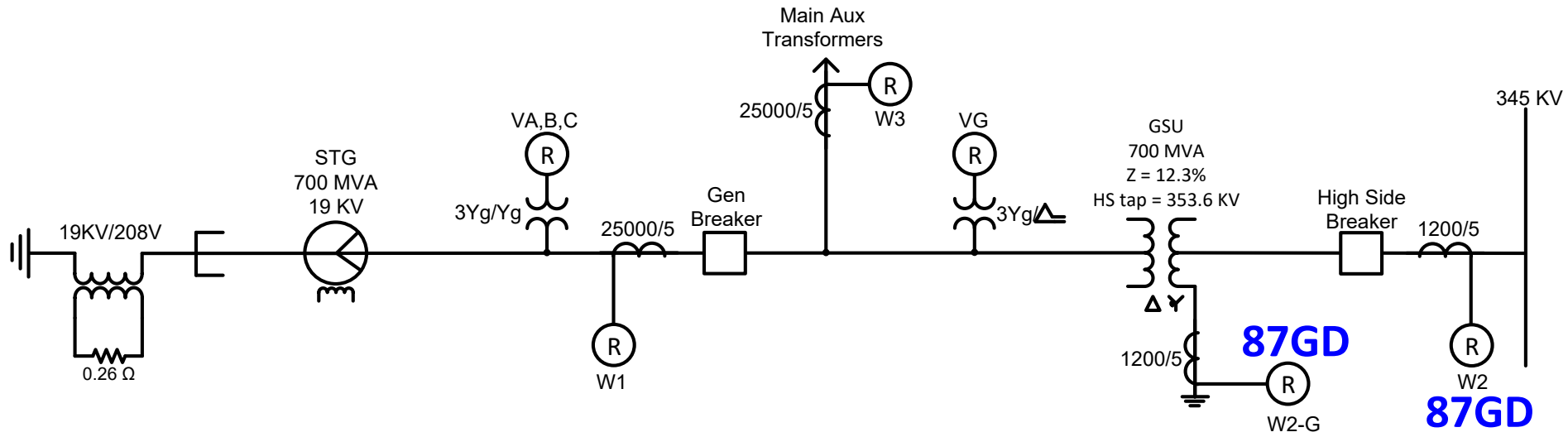
Thick lines: **Ideal (blue)** and **actual (black)** secondary current in amps vs time in seconds.

Thin lines: **Ideal (blue)** and **actual (black)** secondary current extracted fundamental rms value, using a simple DFT with a one-cycle window.

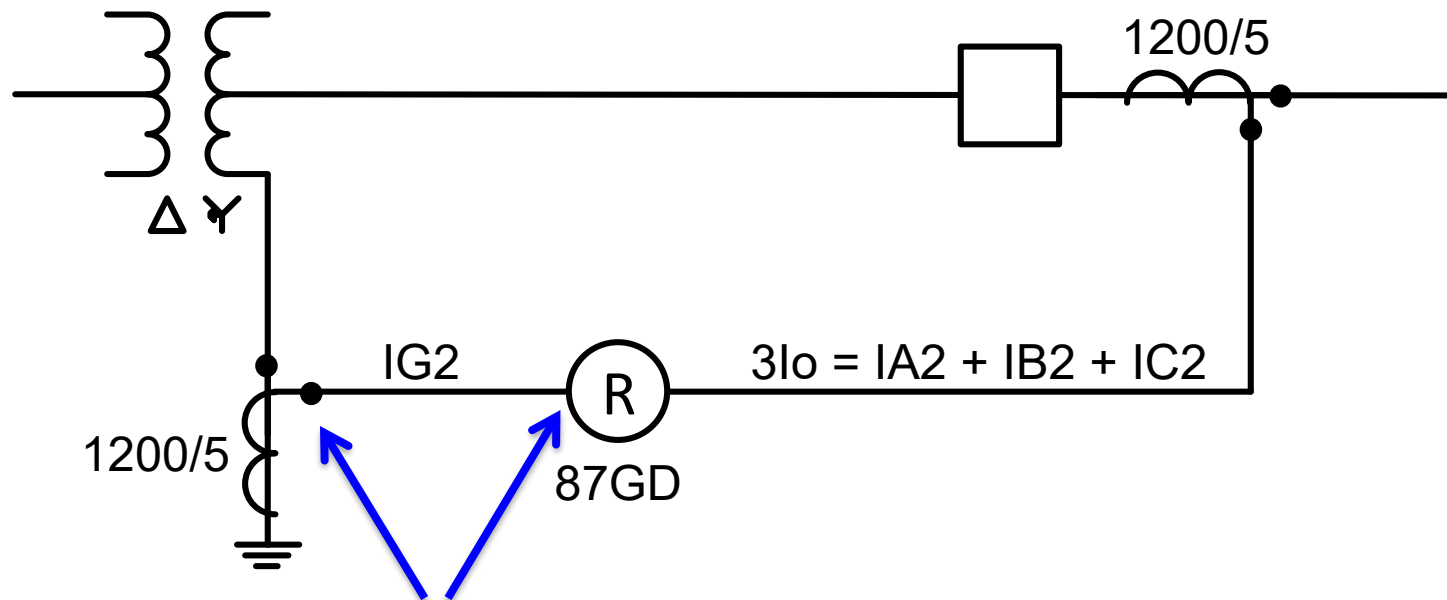


Source: http://www.pes-psrc.org/kb/published/reports/CT_SAT%2010-01-03.zip

87GD – Ground Different Current

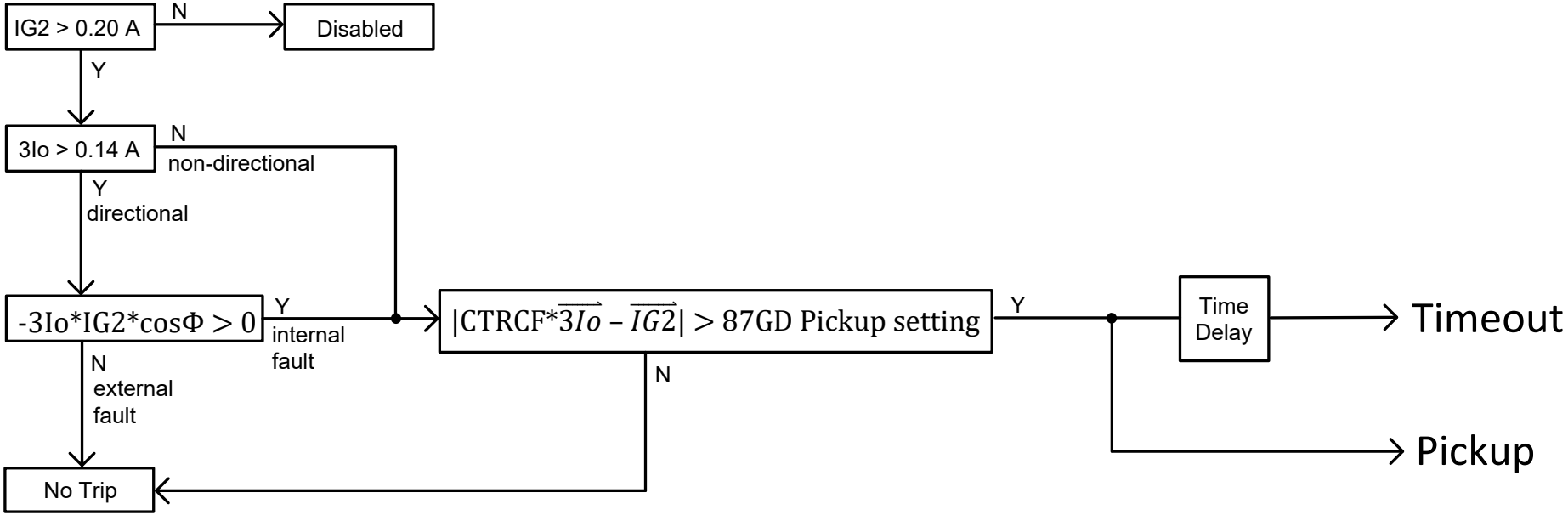


- Use the 87GD on Winding 2 for sensitive ground fault detection in the zone between the Winding 2 phase CTs and the Winding 2 ground CT i.e. for the restricted zone from the GSU high side grounded wye winding out to the high side breaker:



- PRO TIP:** ensure ground CT polarity is connected correctly to the relay IG current input polarity or may trip for external ground faults out on the transmission system.

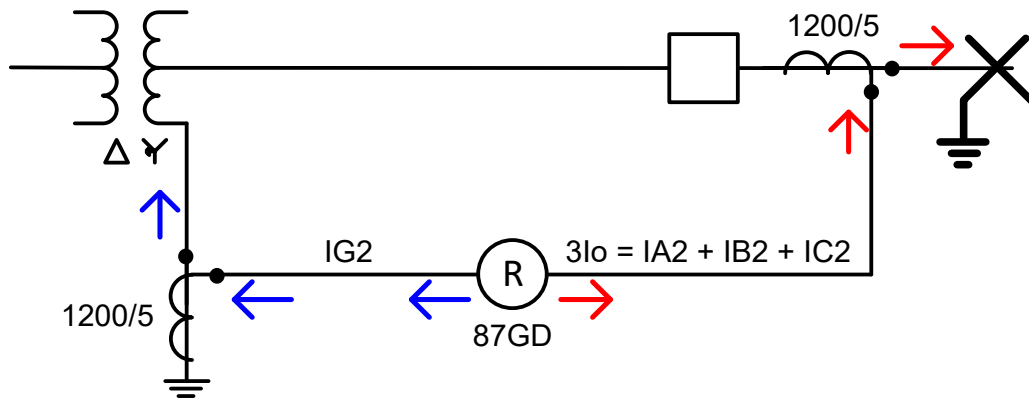
87GD algorithm operates as such:



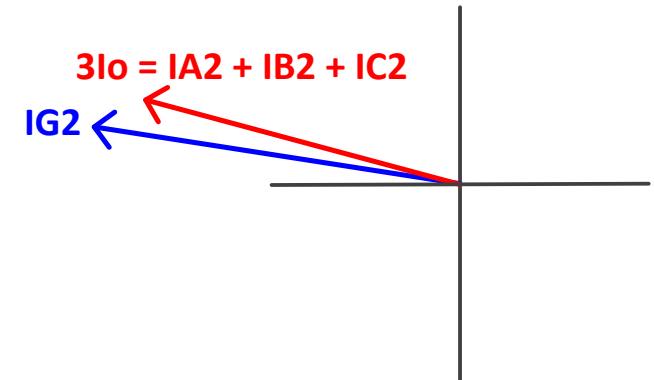
- $\Phi = \Phi_{3I_o} - \Phi_{IG2}$

External Fault:

- $3I_o$ is out of relay polarity, I_{G2} is out of relay polarity
- Therefore $3I_o$ & I_{G2} are in phase
- $-3I_o * I_{G2} * \cos(\Phi_{3I_o} - \Phi_{I_{G2}}) = -3I_o * I_{G2} * \cos 0^\circ = -3I_o * I_{G2} * 1 = -3I_o * I_{G2} < 0$

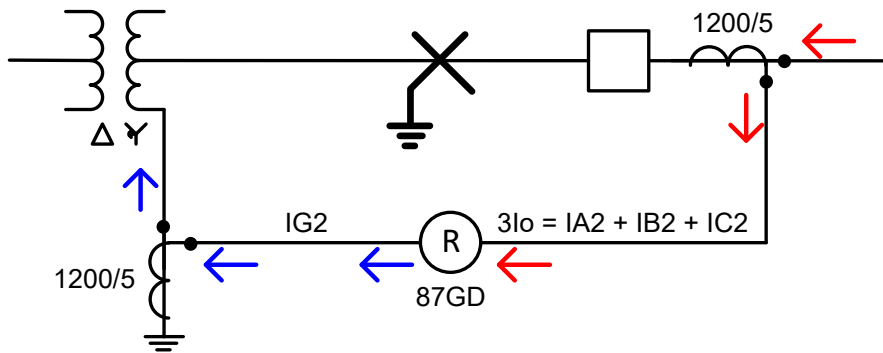


External Fault = In-Phase

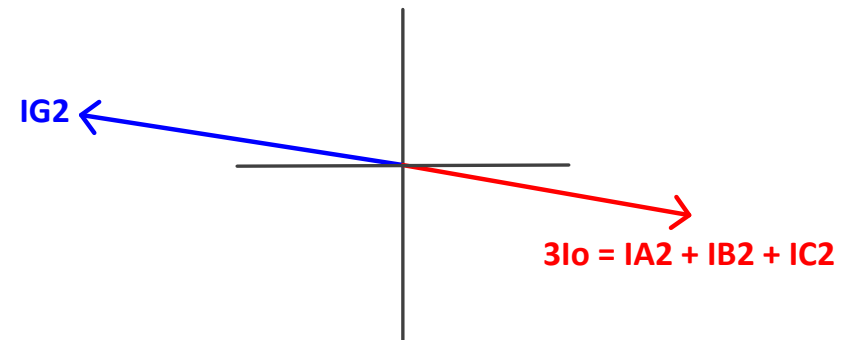


Internal Fault:

- $3I_o$ is into relay polarity, $IG2$ is out of relay polarity
- Therefore $3I_o$ & $IG2$ are 180° out of phase
- $-3I_o * IG2 * \cos(\Phi_{3I_o} - \Phi_{IG2}) = -3I_o * IG2 * \cos 180^\circ = -3I_o * IG2 * -1 = 3I_o * IG2 > 0$



Internal Fault = 180° Out-of-Phase



Calculate 87GD Pickup

- Set > highest unbalance expected, assume it is 10% of max output of generator. Does not absolutely need to meet this criterion as this is for security against a thru event so it would not see this condition anyway; however, still try to meet this criteria if possible as it may reduce confusion if this element could not even be picked up during worst case load unbalance. On HS of GSU, the phase CT would see $0.10 \cdot 4.88 = 0.488$ sec amps. The ground CT would see $0.10 \cdot 4.88 = 0.488$ sec amps.
- Set > 5% of the relative sensitivity of the phase CT compared to the neutral CT i.e. the pickup needs to be increased (and likely the time delay as well) to account for noise amplification due to high CT Ratio Correction settings which can cause substantial differential current:

$$0.05 * \left(\frac{\text{phase CTR}}{\text{ground CTR}} \right) = 0.05 * \frac{240}{240} = 0.05 \text{ sec amps}$$

- Set < 25% of the max internal ground fault current. The W2 ground CT will see $(0.25 \cdot 2343 / 240) = 2.44$ sec amps. The W2 phase CTs will see $(0.25 \cdot 16,517 / 240) = 17.2$ sec amps.

$$0.488; 0.488; 0.05 \leq 87GD \text{ Pickup} \leq 2.44; 17.2$$

- The selected Time delay settings may typically be driven from the CT saturation calculations. Sans detailed CT saturation modelling and calculations, a more sensitive element will be chosen with a 6 cycle delay and a less sensitive element with a 3 cycle delay. If a high CT Ratio Correction setting is necessary, then typically more time delay (and possibly a higher pickup setting as well) may be necessary where the detailed CT saturation calculations can help inform such.
- 87GD #1: Pickup = 0.50 A, Time Delay = 6 cycles (provide security against mis-operations during external ground faults with CT saturation)
- 87GD #2: Pickup = 1.00 A, Time Delay = 3 cycles
- 3I_o Current Selection = Winding 2
- Directional Element = Enable (provides security against ratio errors and CT saturation during external faults)
- $CT\ Ratio\ Correction = \frac{Phase\ CTR}{Ground\ CTR} = \frac{240}{240} = 1.00$

Enter 87GD settings into relay

87GD: Ground Differential

Winding 2 | Winding 3 | Winding 4

#1

Pickup: 0.20 10.00 (A)

Time Delay: 1 8160 (Cycles)

Outputs: 1 2 3 4 5 6 7 8
 9 10 11 12 13 14 15 16

Blocking Inputs: 1 2 3 4 5 6 7 8 9
 10 11 12 13 14 15 16 17 18

#2

Pickup: 0.20 10.00 (A)

Time Delay: 1 8160 (Cycles)

Outputs: 1 2 3 4 5 6 7 8
 9 10 11 12 13 14 15 16

Blocking Inputs: 1 2 3 4 5 6 7 8 9
 10 11 12 13 14 15 16 17 18

Settings

3I0 Current Selection: Summing 1 Summing 2 Winding 2

Directional Element: Disable Enable

CT Ratio Correction: 0.10 7.99



Questions?



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