

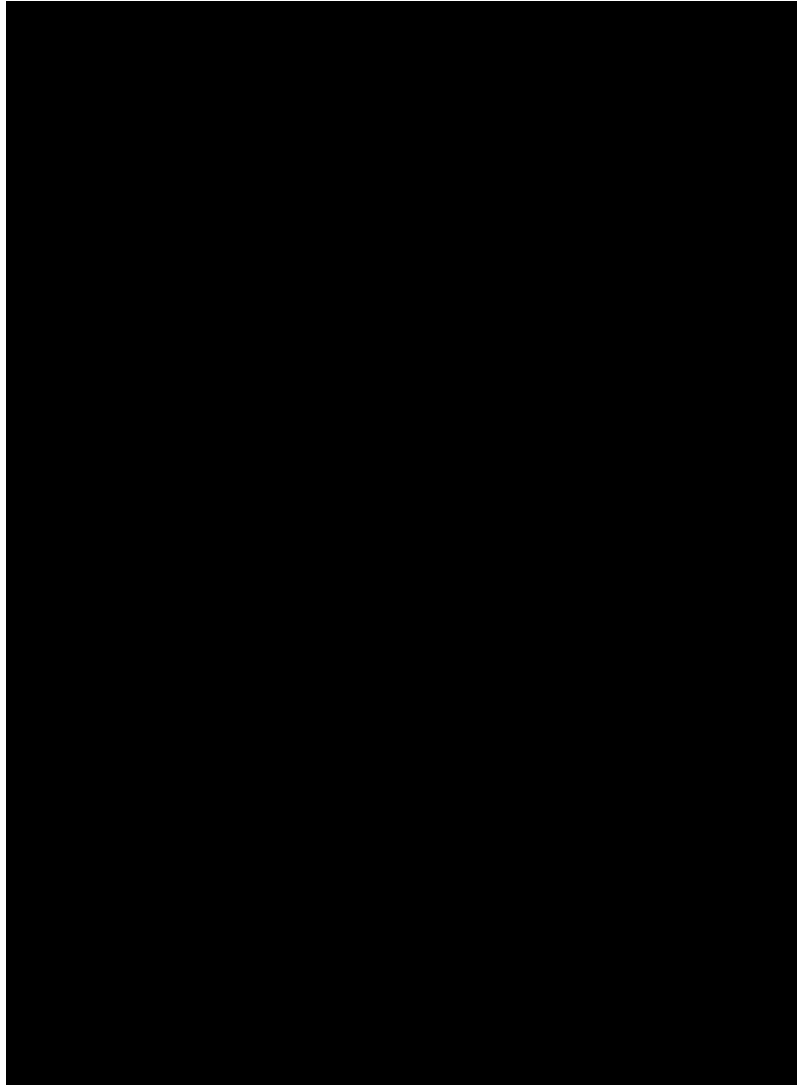
Catastrophic Relay Misoperations and Successful Relay Operation

**Presenter: David Aldrich
IEEE Senior Member
Beckwith Electric Company**

- Detailed technical analysis of several catastrophic relay misoperations
- How to prevent them from occurring
 - Overall differential relay operation occurred at hydro power plant during an external fault on the auxiliary transformer low side
 - Generator breaker failure operation tripped large load center

- Transformer differential trip due to sympathetic inrush when nearby large GSU energized via interconnecting high-voltage transmission line
- Intermittent arcing ground fault quickly cleared by high-speed arcing ground fault protection scheme

Overall Differential Relay Operation at Hydro Power Plant - External Fault on Auxiliary Transformer Low Side



Overall Differential Relay Operation

Transformer/CT Phase Compensation — Standard Custom

Transformer W1	Transformer W2	Transformer W3	Transformer W4
7 (Inverse Dac)	0 (Y)	0 (Y)	6 (Inverse Y)
C.T. W1	C.T. W2	C.T. W3	C.T. W4
0 (Y)	0 (Y)	0 (Y)	0 (Y)
W1 Zero Sequence Filter: <input type="radio"/> Disable <input checked="" type="radio"/> Enable	W2 Zero Sequence Filter: <input checked="" type="radio"/> Disable <input type="radio"/> Enable	W3 Zero Sequence Filter: <input checked="" type="radio"/> Disable <input type="radio"/> Enable	W4 Zero Sequence Filter: <input checked="" type="radio"/> Disable <input type="radio"/> Enable

Existing Settings

Transformer/CT Phase Compensation — Standard Custom

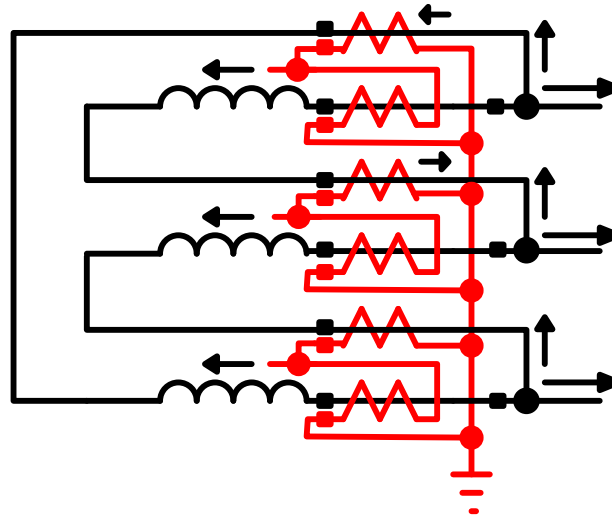
Transformer W1	Transformer W2	Transformer W3	Transformer W4
7 (Inverse Dac)	0 (Y)	0 (Y)	0 (Y)
C.T. W1	C.T. W2	C.T. W3	C.T. W4
0 (Y)	0 (Y)	0 (Y)	0 (Y)
W1 Zero Sequence Filter: <input type="radio"/> Disable <input checked="" type="radio"/> Enable	W2 Zero Sequence Filter: <input checked="" type="radio"/> Disable <input type="radio"/> Enable	W3 Zero Sequence Filter: <input checked="" type="radio"/> Disable <input type="radio"/> Enable	W4 Zero Sequence Filter: <input checked="" type="radio"/> Disable <input type="radio"/> Enable

Corrected Settings

IT'S ALWAYS EASY WHEN YOU KNOW THE ANSWER.

Overall Differential Relay Operation

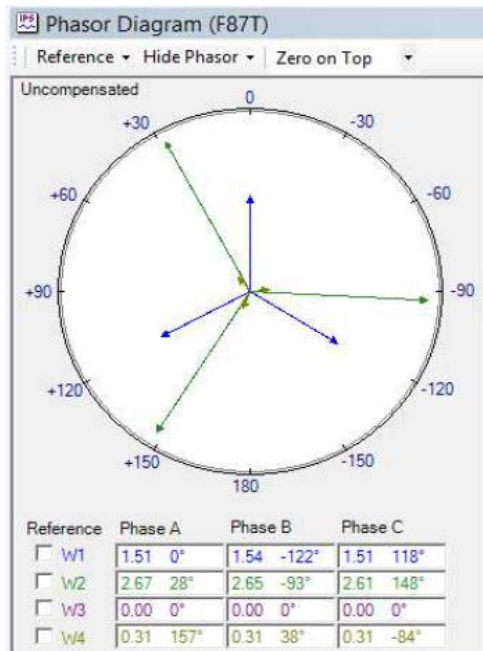
- Why the event was difficult to analyze
 - Lack of adequate three-line diagram



Actual Winding 1 Internal CT Connections

Overall Differential Relay Operation

- Correct transformer winding and CT connections were verified by through load injection simulation



**Load
Current**

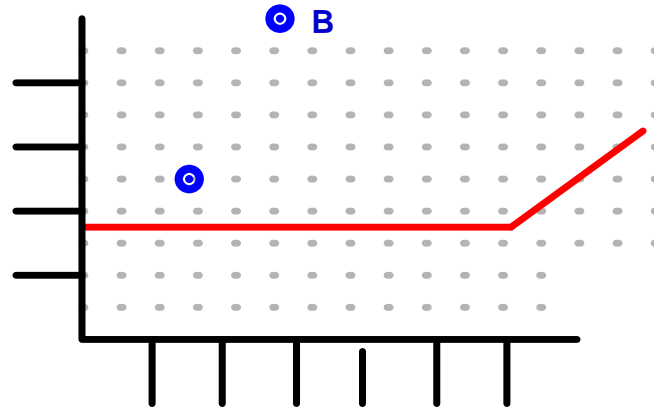
$$\begin{aligned}
 I_{AW1cc} &:= \frac{I_{AW1c}}{TAP1} & I_{BW1cc} &:= \frac{I_{BW1c}}{TAP1} & I_{CW1cc} &:= \frac{I_{CW1c}}{TAP1} \\
 I_{AW2c} &:= \frac{I_{CW2} - I_{AW2}}{TAP2 \cdot \sqrt{3}} & I_{BW2c} &:= \frac{I_{AW2} - I_{BW2}}{TAP2 \cdot \sqrt{3}} & I_{CW2c} &:= \frac{I_{BW2} - I_{CW2}}{TAP2 \cdot \sqrt{3}} \\
 I_{AW3c} &:= \frac{I_{CW3} - I_{AW3}}{TAP3 \cdot \sqrt{3}} & I_{BW3c} &:= \frac{I_{AW3} - I_{BW3}}{TAP3 \cdot \sqrt{3}} & I_{CW3c} &:= \frac{I_{BW3} - I_{CW3}}{TAP3 \cdot \sqrt{3}} \\
 I_{AW4c} &:= \frac{I_{AW4} - I_{CW4}}{TAP4 \cdot \sqrt{3}} & I_{BW4c} &:= \frac{I_{BW4} - I_{AW4}}{TAP4 \cdot \sqrt{3}} & I_{CW4c} &:= \frac{I_{CW4} - I_{BW4}}{TAP4 \cdot \sqrt{3}}
 \end{aligned}$$

Current Compensation

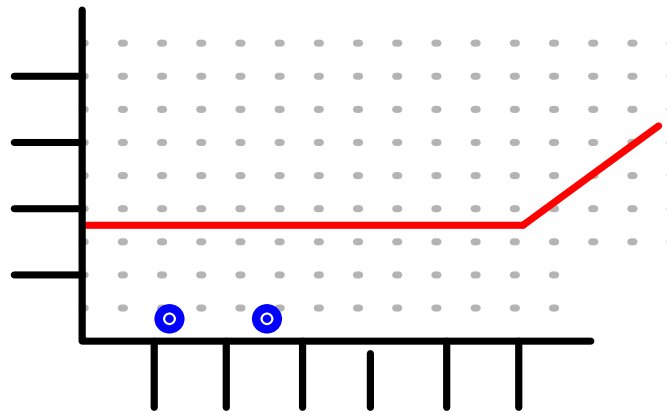
$$\begin{aligned}
 DIFF_A &:= |I_{AW1cc} + I_{AW2c} + I_{AW3c} + I_{AW4c}| & DIFF_B &:= |I_{BW1cc} + I_{BW2c} + I_{BW3c} + I_{BW4c}| & DIFF_C &:= |I_{CW1cc} + I_{CW2c} + I_{CW3c} + I_{CW4c}| \\
 BIAS_A &:= \frac{|I_{AW1cc}| + |I_{AW2c}| + |I_{AW3c}| + |I_{AW4c}|}{2} & BIAS_B &:= \frac{|I_{BW1cc}| + |I_{BW2c}| + |I_{BW3c}| + |I_{BW4c}|}{2} & BIAS_C &:= \frac{|I_{CW1cc}| + |I_{CW2c}| + |I_{CW3c}| + |I_{CW4c}|}{2}
 \end{aligned}$$

Differential Current Equations

Overall Differential Relay Operation



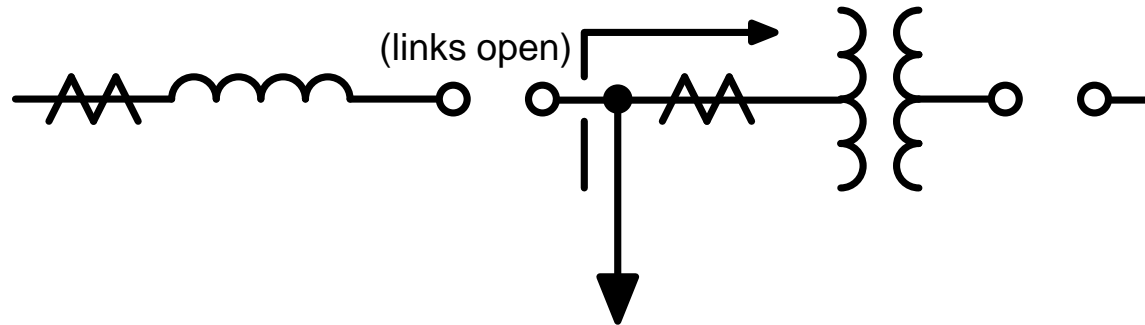
Differential Operating Characteristic (Misoperation)



Differential Operating Characteristic (Corrected)

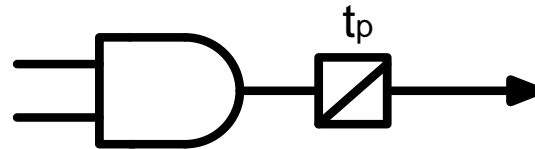
Breaker Failure Operation

- Tripped during high load
- Outage in the adjoining downtown area of a large city



System Topology

Breaker Failure Operation



Original Scheme Logic

50BF: Breaker Failure

Phase Current: 0.10 10.00 (A)

Phase Current Select: Disable Enable

Neutral Current: 0.10 10.00 (A)

Neutral Current Select: Disable Enable

Time Delay: 1 8160 (Cycles)

Output Initiate

<input checked="" 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 type="checkbox"/> 17	<input type="checkbox"/> 18	<input type="checkbox"/> 19	<input type="checkbox"/> 20	<input type="checkbox"/> 21	<input type="checkbox"/> 22	<input type="checkbox"/> 23	

Input Initiate

<input type="checkbox"/> 1	<input checked="" type="checkbox"/> 2	<input type="checkbox"/> 3	<input checked="" 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		

Outputs

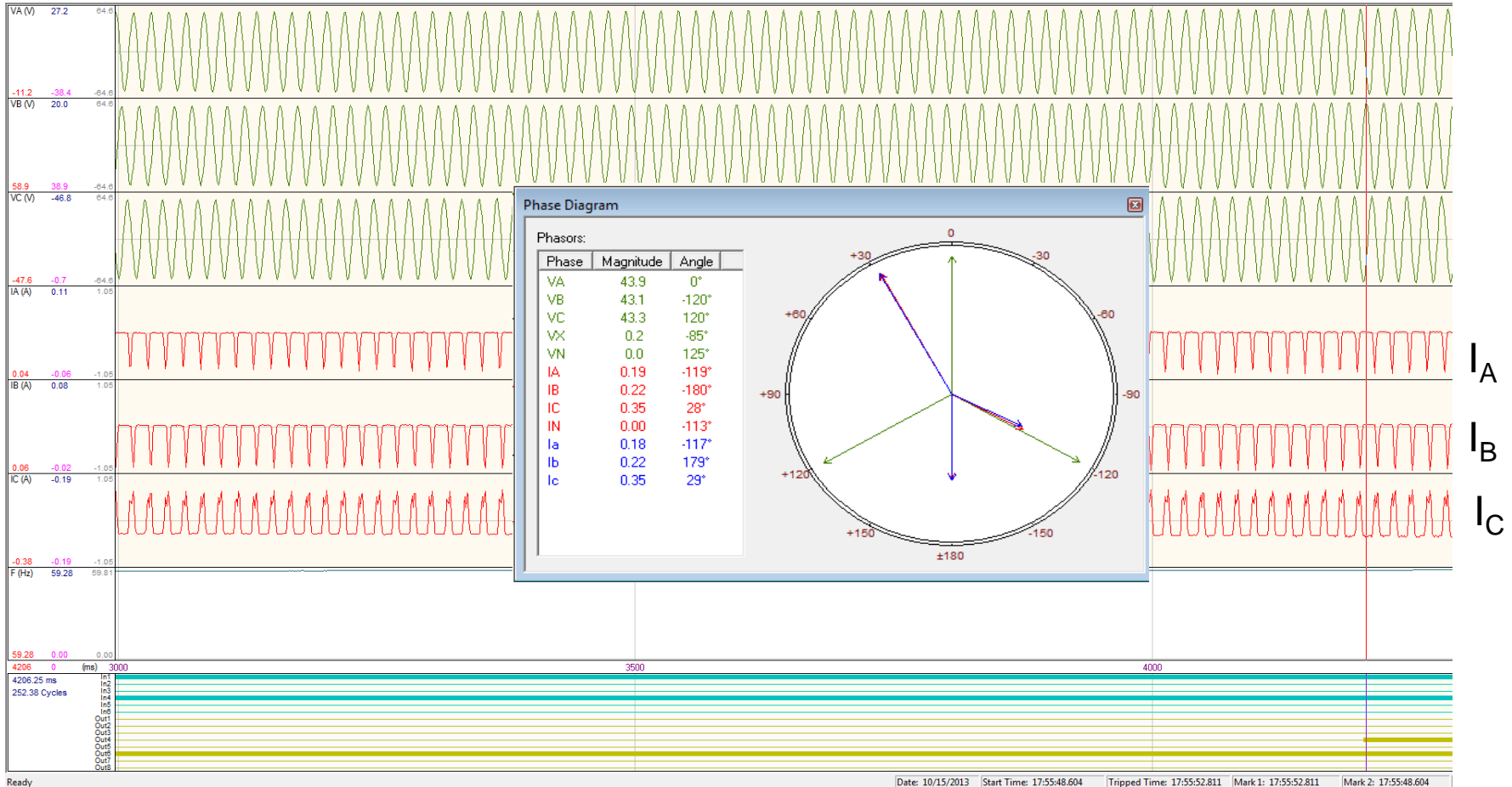
<input type="checkbox"/> 1	<input type="checkbox"/> 2	<input type="checkbox"/> 3	<input checked="" type="checkbox"/> 4	<input type="checkbox"/> 5	<input type="checkbox"/> 6	<input type="checkbox"/> 7	<input type="checkbox"/> 8
<input type="checkbox"/> 9	<input type="checkbox"/> 10	<input type="checkbox"/> 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	<input type="checkbox"/> 19	<input type="checkbox"/> 20	<input type="checkbox"/> 21	<input type="checkbox"/> 22	<input type="checkbox"/> 23	

Blocking Inputs

<input type="checkbox"/> FL	<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

Original Protection Settings

Breaker Failure Operation



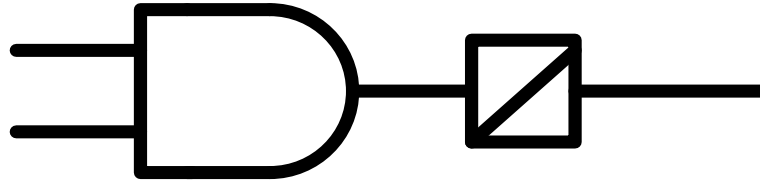
Transformer Excitation Current due to Backfeed

**$I_C >$ Phase Current Level Detector
Input 4 asserted**

Breaker Failure Operation

- Breaker failure function may be used for a unit breaker rather than a generator breaker
- It is limited - no fault detector associated with the unit breaker
- Trip if any of the initiate contacts close and the 52b contact indicated a closed breaker after set time delay

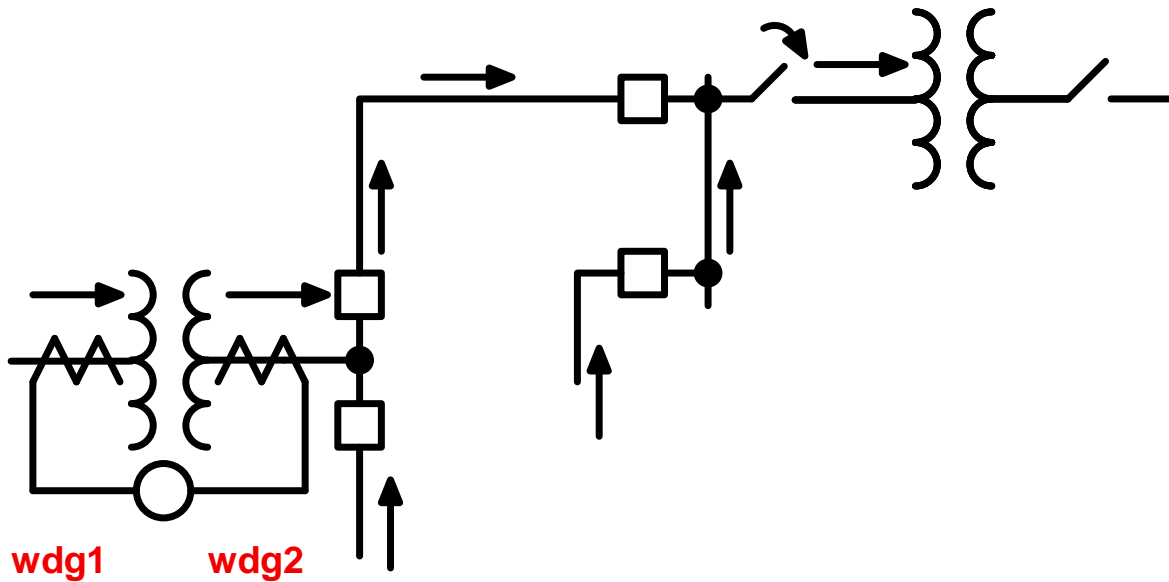
Breaker Failure Operation



Correct Scheme Logic

Transformer Differential Trip

Sympathetic Inrush when nearby Large GSU Energized via Interconnecting High-Voltage Transmission Line



Arrows depict flow of inrush current

Transformer Differential Trip

87: Phase Differential Current

F87T | F87H | C.T. Tap

Pickup:	<input type="text" value="0.30"/>	0.10	<input type="button" value="◀"/>	<input type="checkbox"/>	<input type="button" value="▶"/>	1.00 (PU)	<input type="button" value="Disable"/>
Percent Slope #1:	<input type="text" value="30"/>	5	<input type="button" value="◀"/>	<input type="checkbox"/>	<input type="button" value="▶"/>	100 (%)	
Percent Slope #2:	<input type="text" value="60"/>	5	<input type="button" value="◀"/>	<input type="checkbox"/>	<input type="button" value="▶"/>	200 (%)	
Slope Break Point:	<input type="text" value="3.0"/>	1.0	<input type="button" value="◀"/>	<input type="checkbox"/>	<input type="button" value="▶"/>	4.0 (PU)	

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

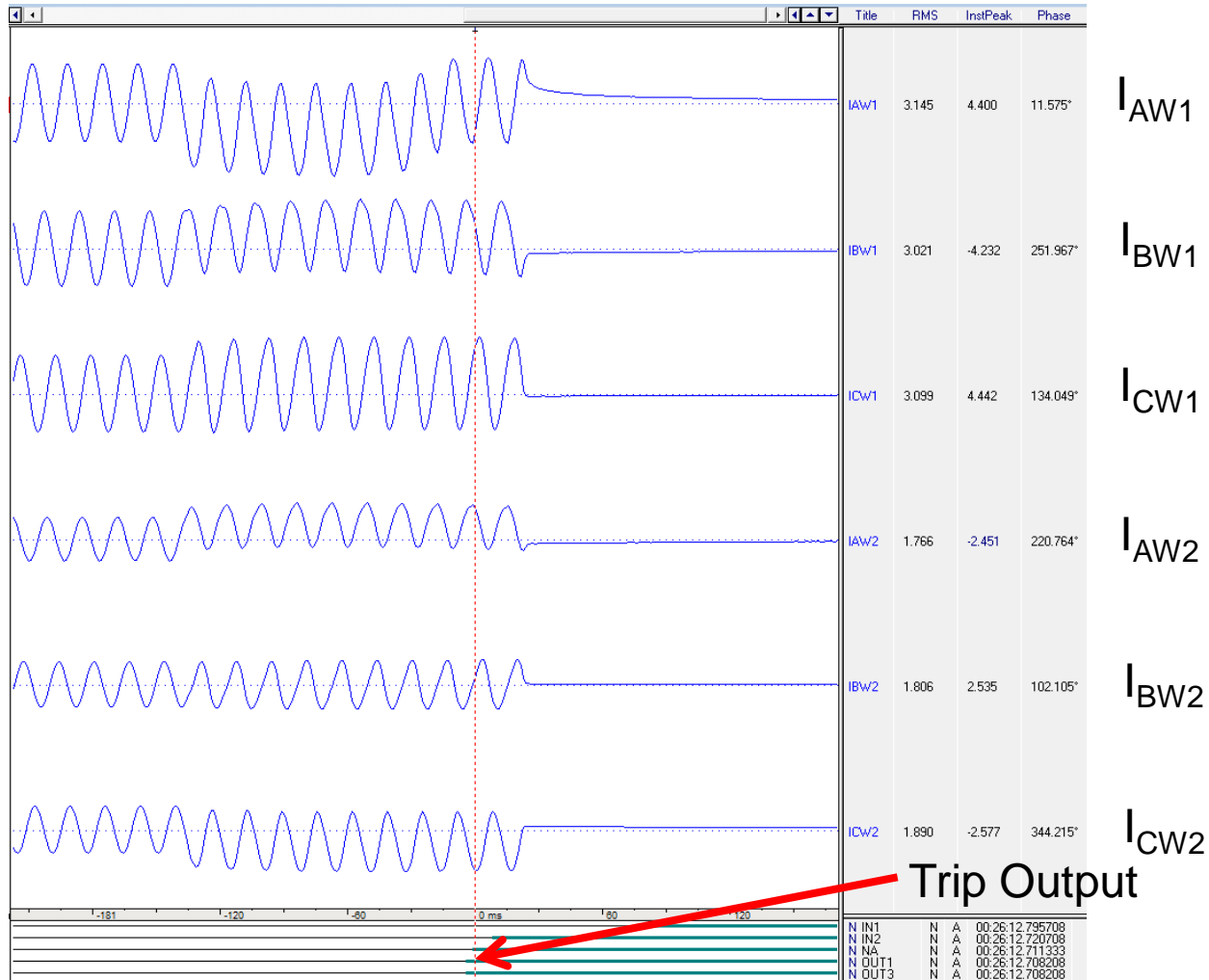
Restraint:	<input type="text" value="20"/>	5	<input type="button" value="◀"/>	<input type="checkbox"/>	<input type="button" value="▶"/>	50 (%)
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5th Harmonic Restraint Disable Enable Enable w/cross average

Restraint:	<input type="text" value="25"/>	5	<input type="button" value="◀"/>	<input type="checkbox"/>	<input type="button" value="▶"/>	50 (%)
Pickup:	<input type="text" value="1.00"/>	0.10	<input type="button" value="◀"/>	<input type="checkbox"/>	<input type="button" value="▶"/>	2.00 (PU)

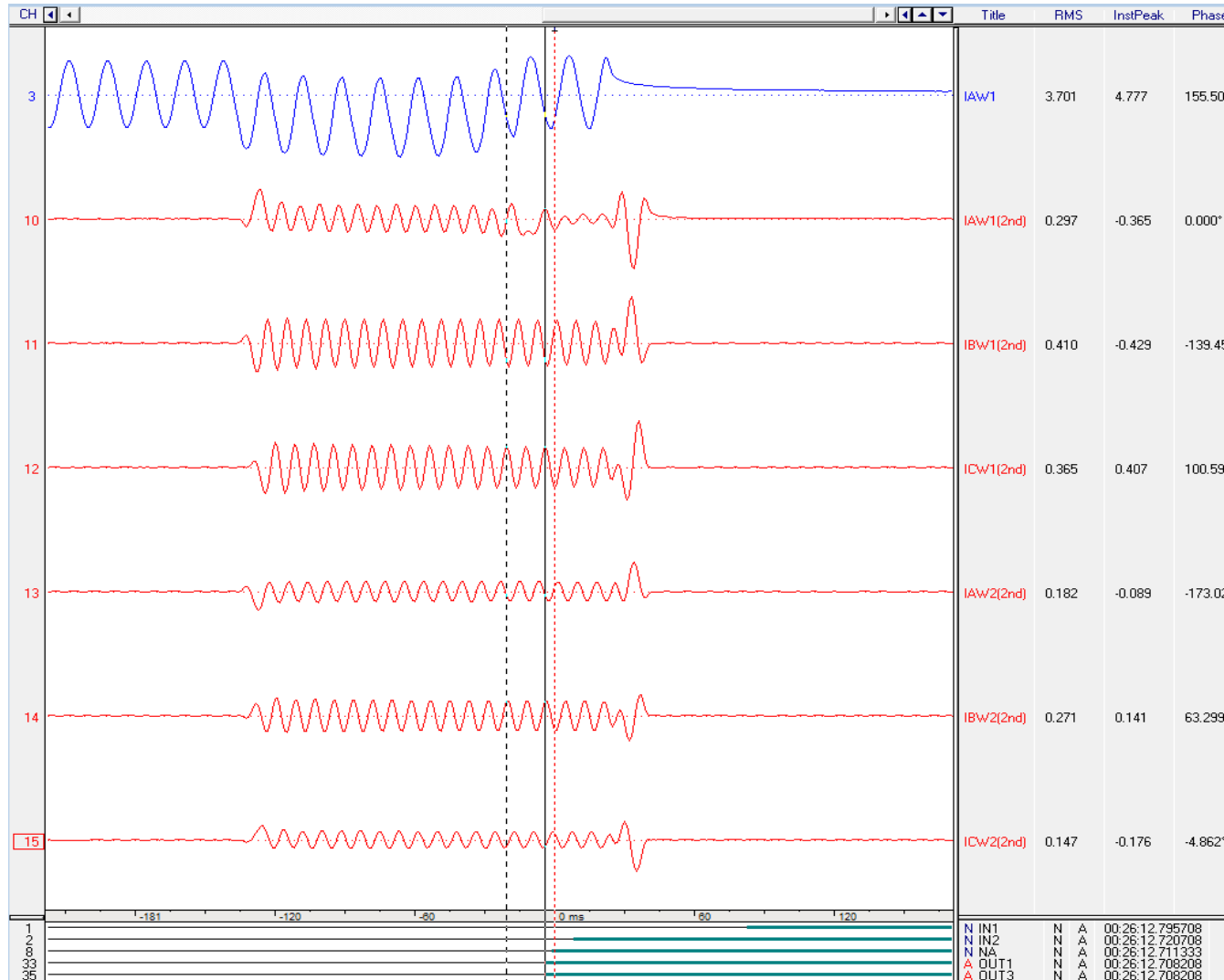
Original Protection Settings

Transformer Differential Trip



Event Oscillography (Raw waveforms)

Transformer Differential Trip



I_{AW1} (raw)

I_{AW1}^{2nd}

I_{BW1}^{2nd}

I_{CW1}^{2nd}

I_{AW2}^{2nd}

I_{BW2}^{2nd}

I_{CW2}^{2nd}

Event Oscillography (2nd Harmonic Content)

Transformer Differential Trip

The 2nd harmonic **differential** current present when the trip occurred was as follows:

A-Phase = 17%

B-Phase = 13%

C-Phase = 13%

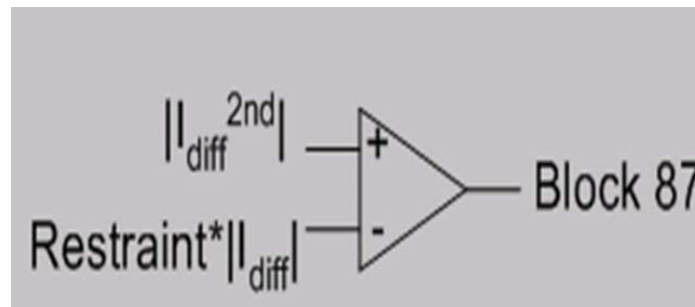
The original 2nd harmonic restraint setting was **20%** for the electro-mechanical transformer differential relay.

Customer used the same setting for the multifunction numerical relay that replaced the original electro-mechanical relay.

Transformer Differential Trip

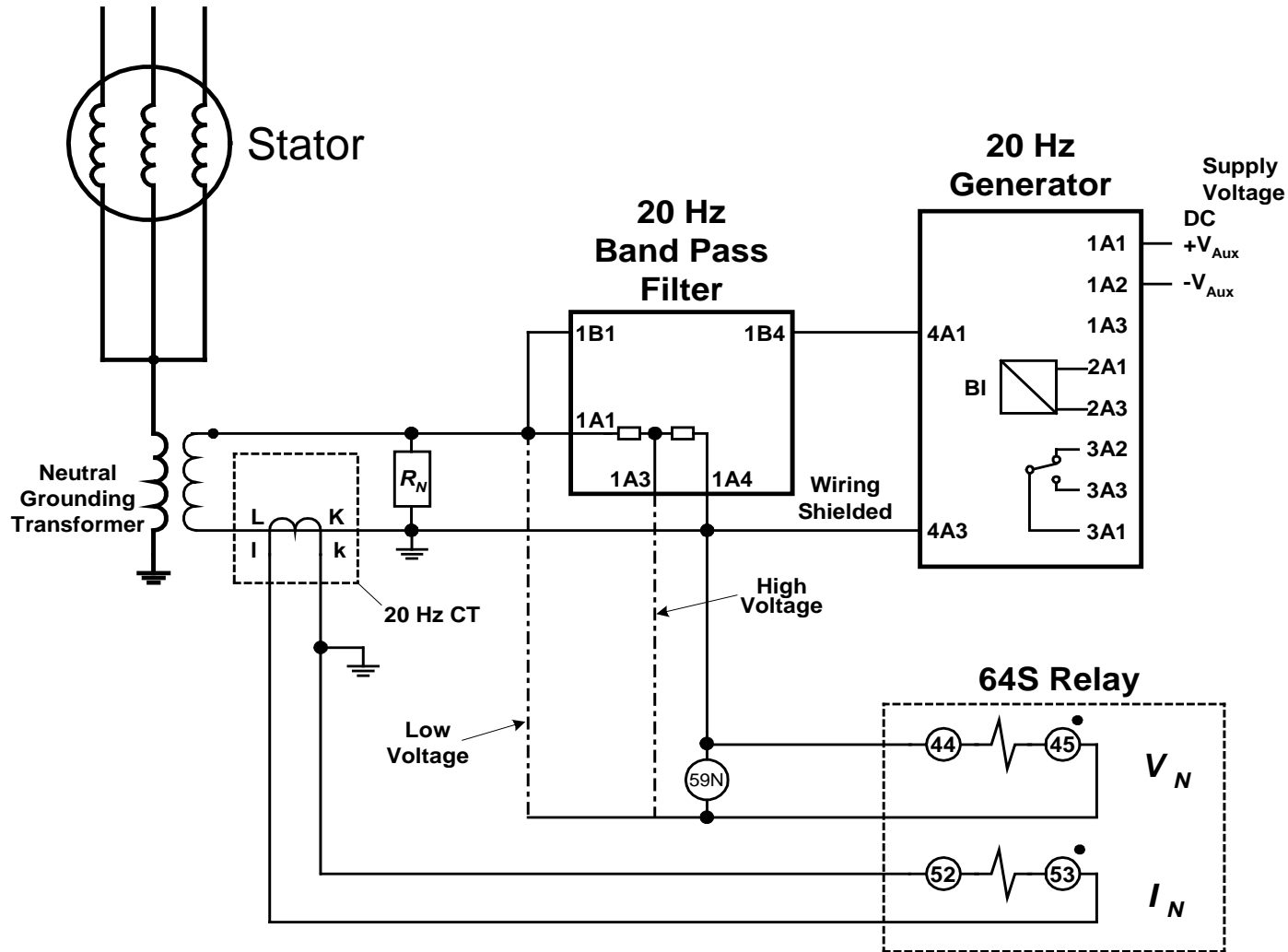
Harmonic Restraint

$$\text{Ratio} = \frac{|I_{diff}^{2nd}|}{|I_{diff}|} \cdot 100\%$$



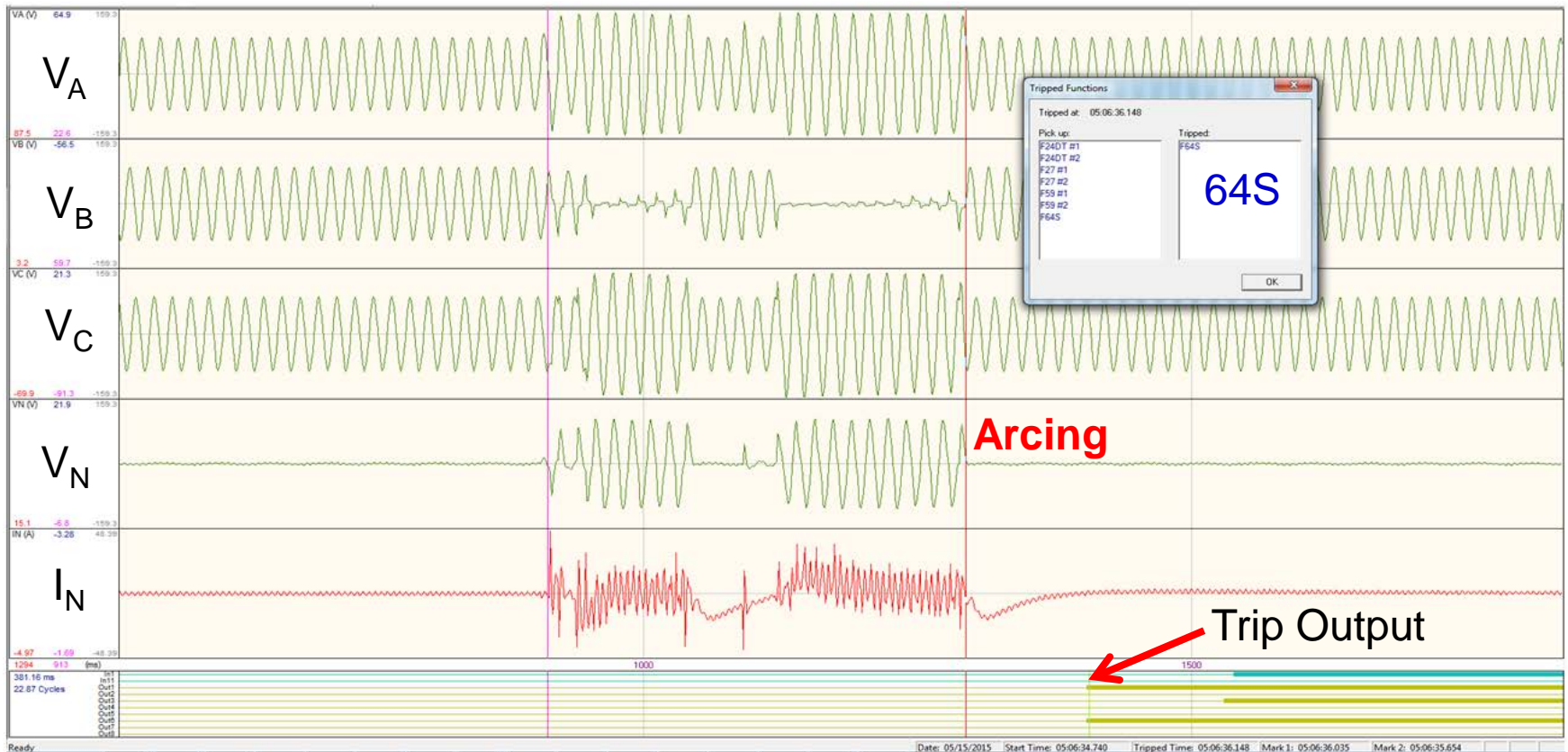
Setting of 11% for the 2nd harmonic restraint would be the most reliable for this particular application.

Intermittent Arcing Ground Fault



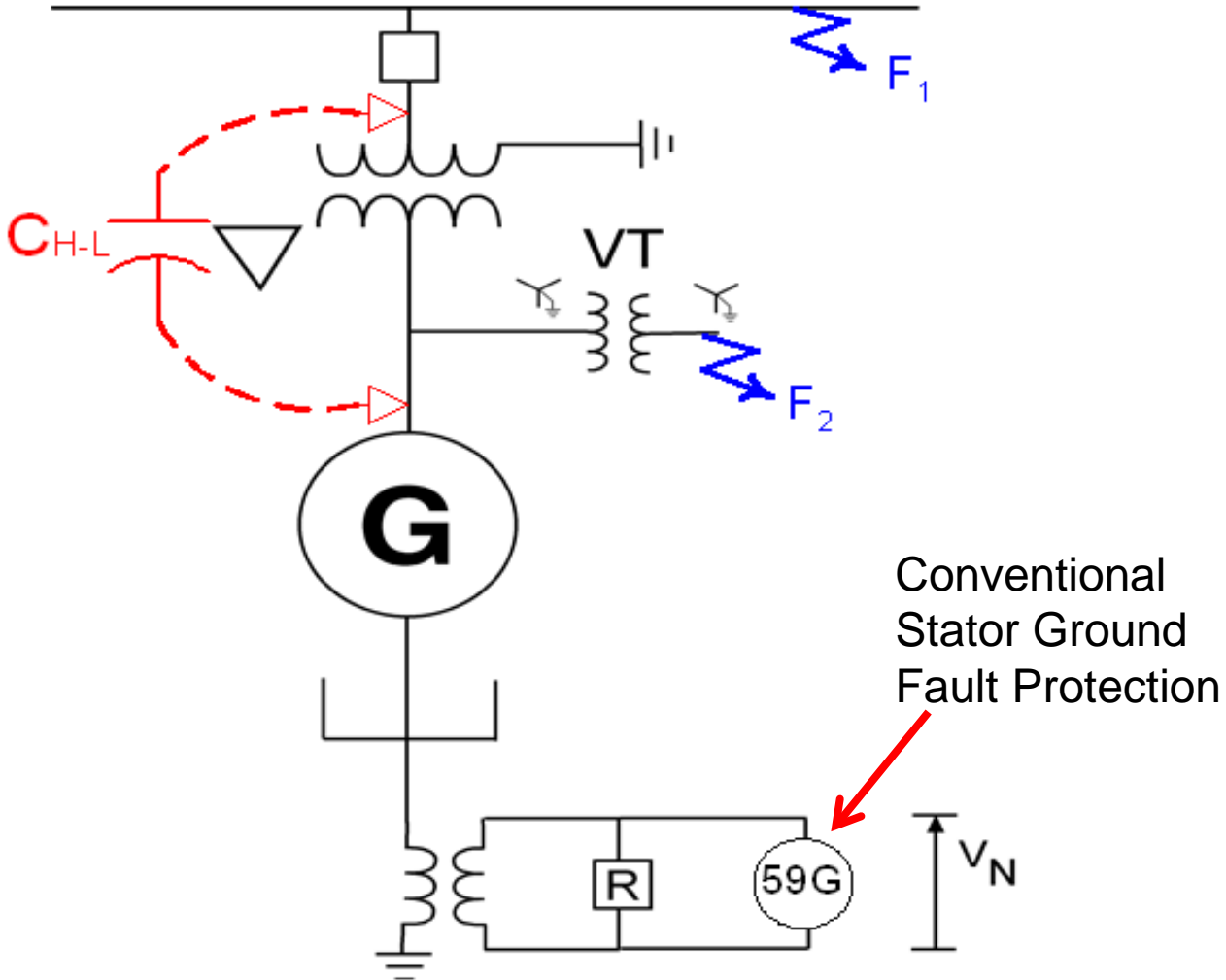
20 Hz Injection Grounding Network

Intermittent Arcing Ground Fault Quickly Cleared by High-Speed Arcing Ground Fault Protection Scheme



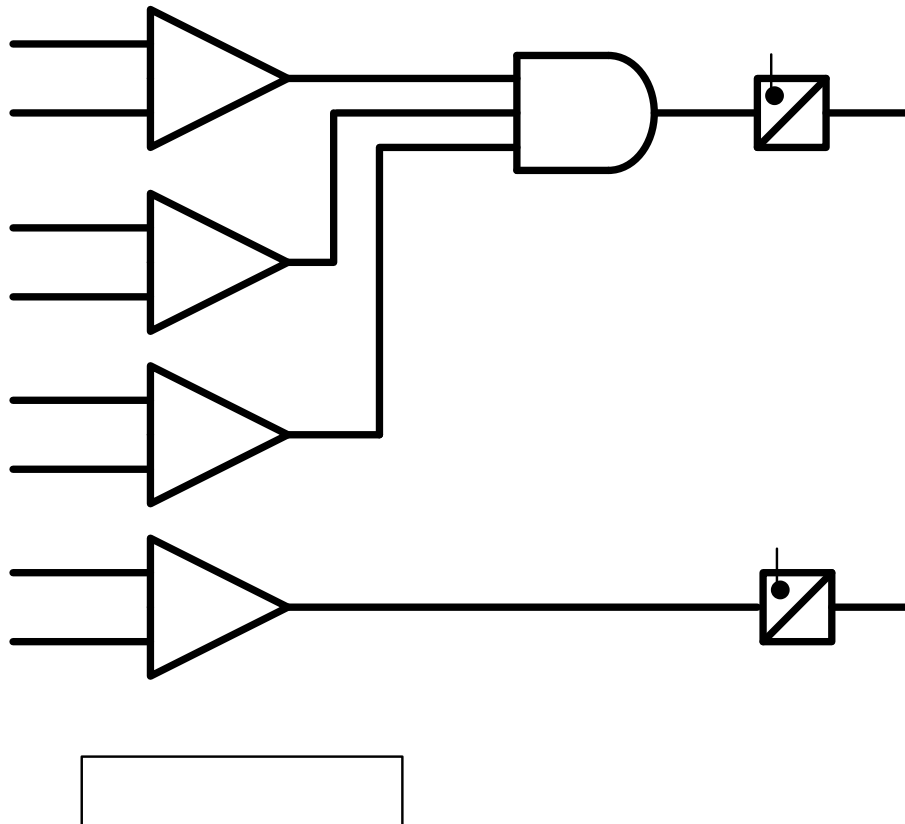
Trip time from initial fault inception = 27 cycles

Intermittent Arcing Ground Fault



Neutral Voltage Induced due to Capacitive Coupling across GSU

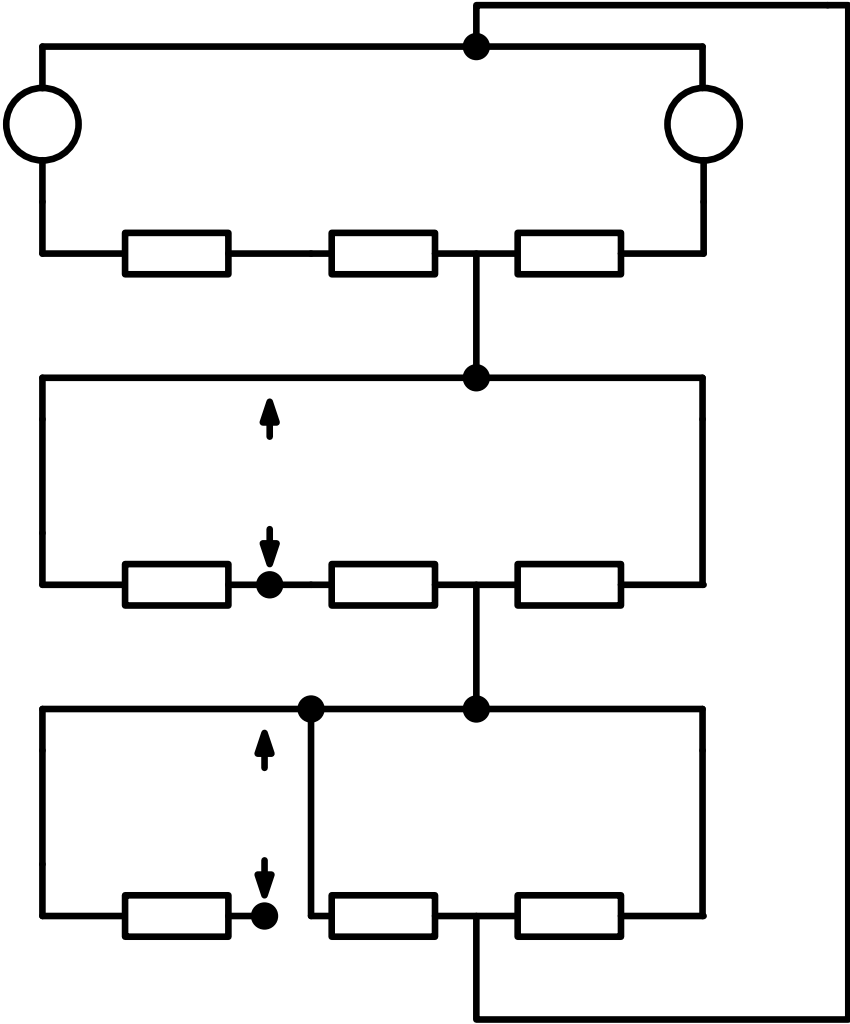
Intermittent Arcing Ground Fault



Accelerated Stator Ground Fault Tripping Scheme Logic

59N1P - pickup setting should cover at least 90% of stator windings

Intermittent Arcing Ground Fault



There is ample negative-sequence voltage at the machine terminal while no zero-sequence voltage present since there is an open circuit on the generator side of GSU.

Therefore, 59N1 is blocked from tripping.

External Ground Fault

Intermittent Arcing Ground Fault

59N1

59N: Neutral Overvoltage

#1 #2 #3

Pickup: 5.0 180.0 (V)

Time Delay: 1 8160 (Cycles)

Neg. Seq. Voltage Inhibit (>): 1.0 100.0 (%) Disable Enable

Zero Seq. Voltage Inhibit (<): 1.0 100.0 (%) Disable Enable

Zero Seq. Voltage Selection: 3V0 VX

Outputs

<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 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	<input type="checkbox"/> 19	<input type="checkbox"/> 20	<input type="checkbox"/> 21	<input type="checkbox"/> 22	<input type="checkbox"/> 23	

Blocking Inputs

<input checked="" type="checkbox"/> FL	<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

59N2

59N: Neutral Overvoltage

#1 #2 #3

Pickup: 5.0 180.0 (V)

Time Delay: 1 8160 (Cycles)

Neg. Seq. Voltage Inhibit (>): 1.0 100.0 (%) Disable Enable

Zero Seq. Voltage Inhibit (<): 1.0 100.0 (%) Disable Enable

Zero Seq. Voltage Selection: 3V0 VX

Outputs

<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 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	<input type="checkbox"/> 19	<input type="checkbox"/> 20	<input type="checkbox"/> 21	<input type="checkbox"/> 22	<input type="checkbox"/> 23	

Blocking Inputs

<input type="checkbox"/> FL	<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

Conclusions

- Analyzed technical details of two relay misoperations:
 - due to an incorrect relay setting
 - due to an incorrect application
- Demonstrated how to prevent misoperations from occurring
- Recommended best practice for each particular application
- Careful assessment of initial settings is necessary as mistakes often occur at design stage.