Event Analysis

Douglas L. Weisz, PE

Power Plant Protection Track
Thursday, August 7, 2025

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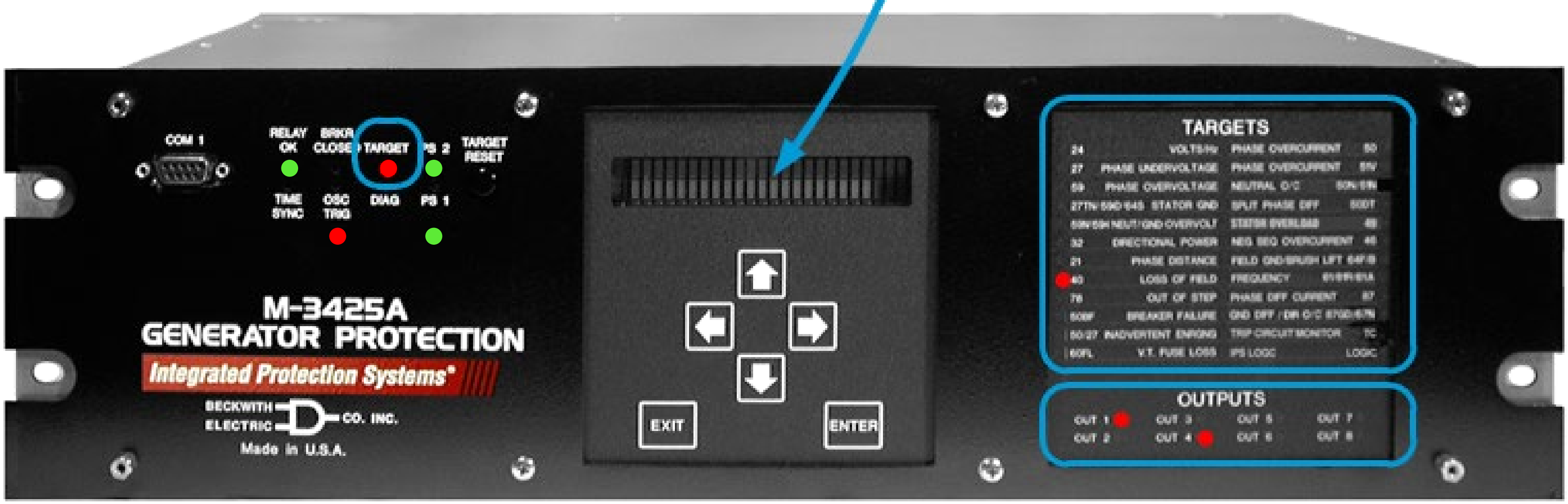
Information to gather after a relay trip

- First - LEDs/HMI from front of relay

Target, Time, Outputs, Function, Phase



Information to gather after a relay trip (continued)

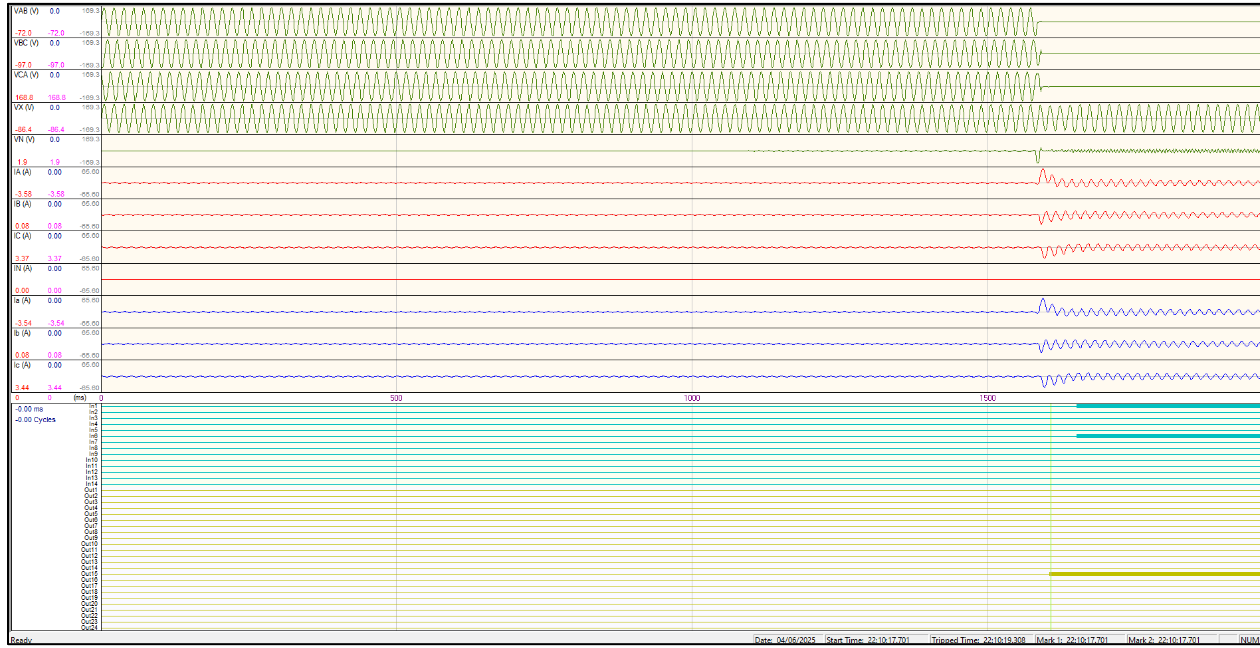
- Next, get information from the relay via the software:
  - ✓ Target List
  - ✓ SOE aka SER
  - ✓ Oscillograph aka event files (native and comtrade format)
  - ✓ native relay setting file from relay, instead of just a pdf of the settings or screenshots of certain settings, etc

- Information from redundant relay (Targets, SOE, OSC, settings)

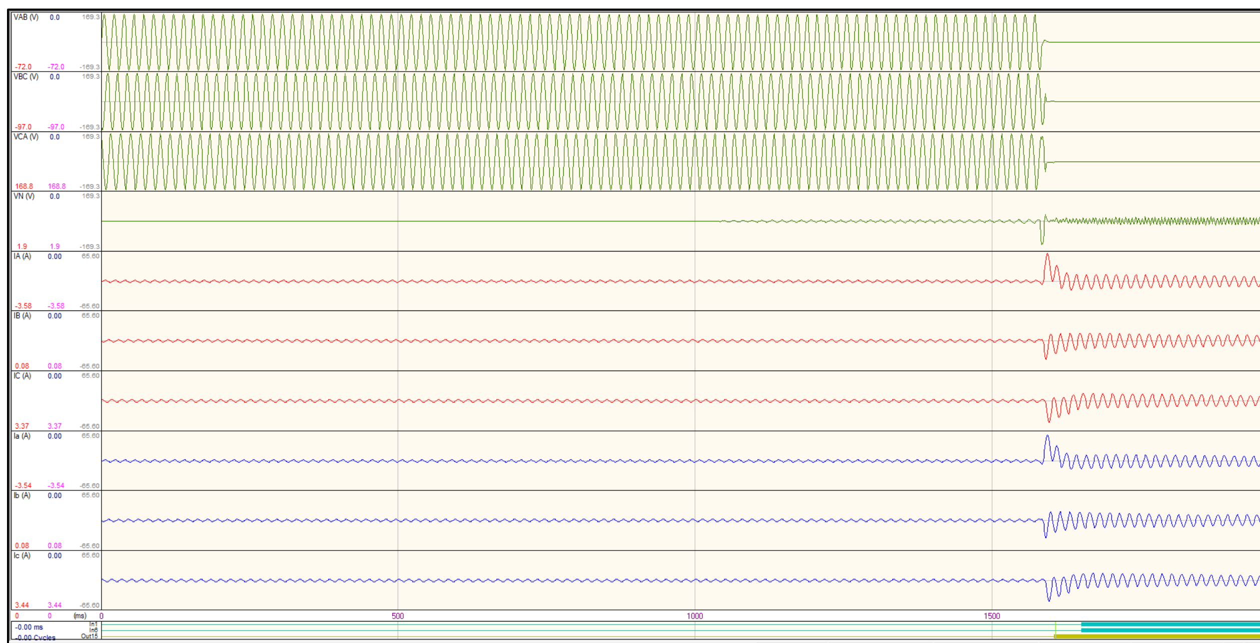
- DCS/RTU/SCADA digital information
- DCS/RTU/SCADA analog historian data
- Are all relays and DCS time synced?
- 1-line, 3-lines (AC Schematics)
- DC Schematics (tripping schemes, relay I/O)
- Talk to the plant operators on duty at the time of the trip
- System conditions at the time of the event
- Plant conditions (any work going on, switching, etc?)

Event Analysis Steps

Oscillography "big picture":
- ✓ Display all V & I
- ✓ Display all Digital I/O



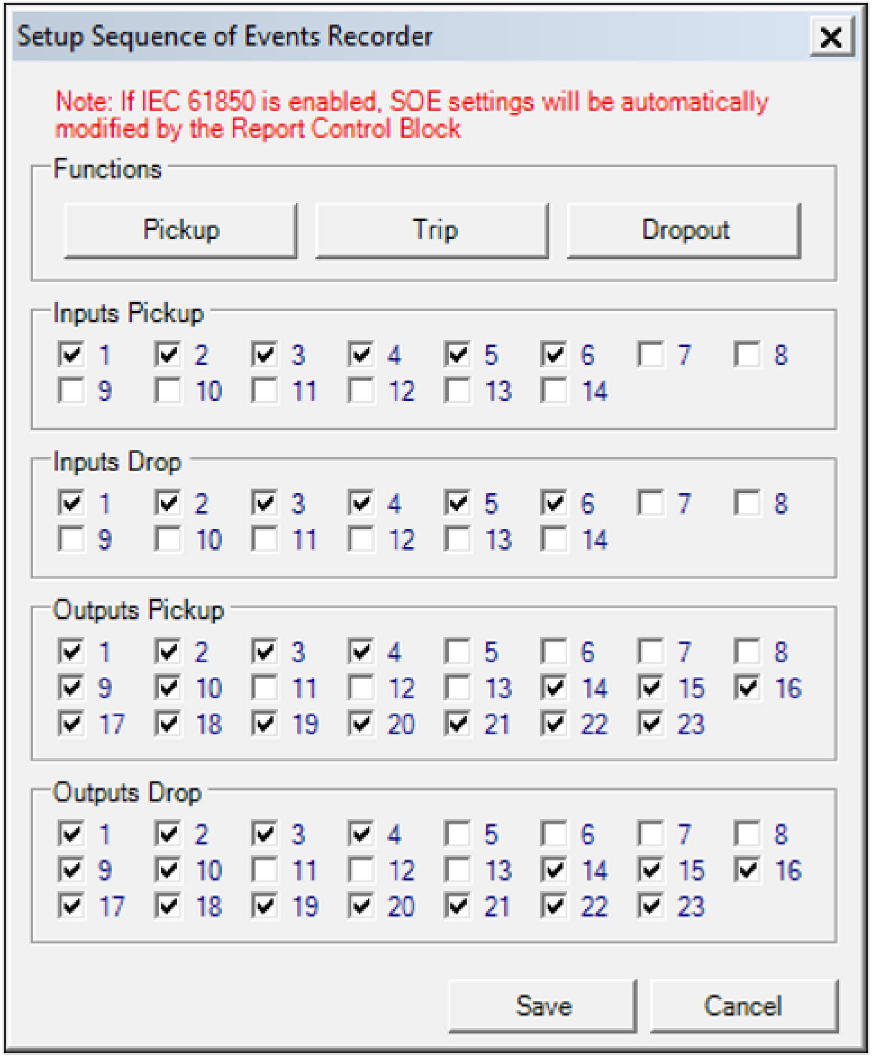
- ✓ Get rid of clutter

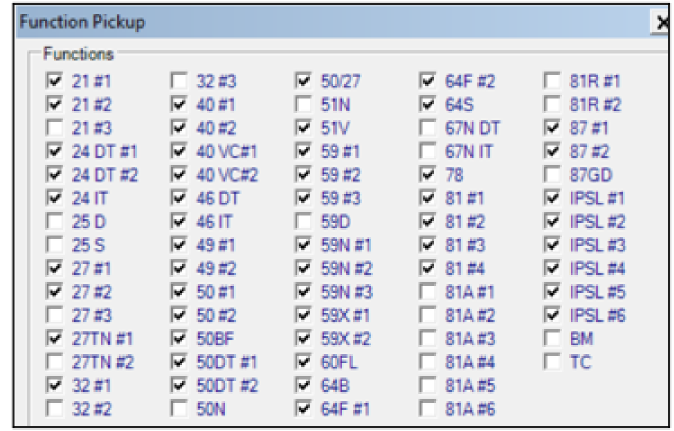


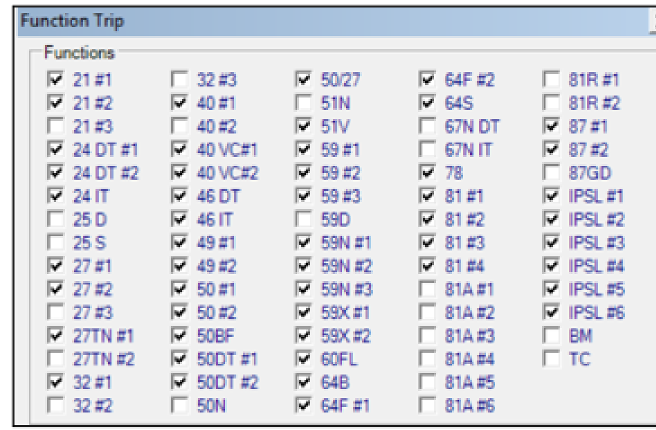
Event Analysis Steps (continued)

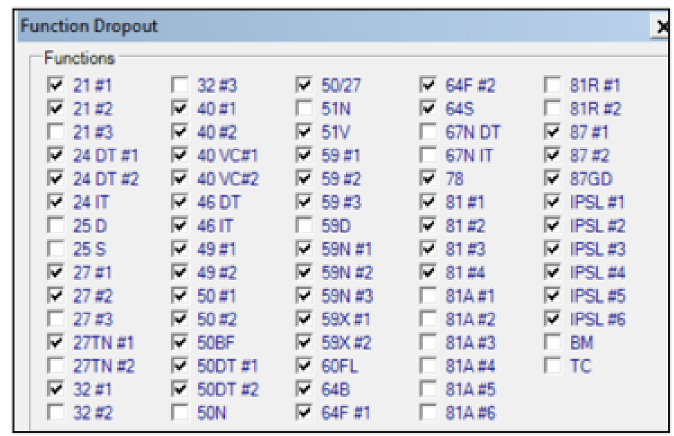
- Review 1-lines, 3-lines, DC Schematics to ensure the relay tripped all required equipment as intended (any wiring changes needed?)
- Check relay settings to ensure incorrect settings (or too sensitive of settings) are not the cause of event
- Compare OSC, SOE, Targets, relay settings, dwgs, & DCS alarms to understand event and answer questions:
  - ✓ Do phase voltages dip and currents increase, which phases?
  - ✓ Are the V & I phasors rotating in the "Phase Rotation" setting direction?
  - ✓ Is any I2 or V2 present and what does it mean?
  - ✓ Is any IN, IG, 3Io, VG, VN, 3Vo present and what does it mean?
- **Are the OSC/SOE Setup trigger settings OK?** →

SOE Setup





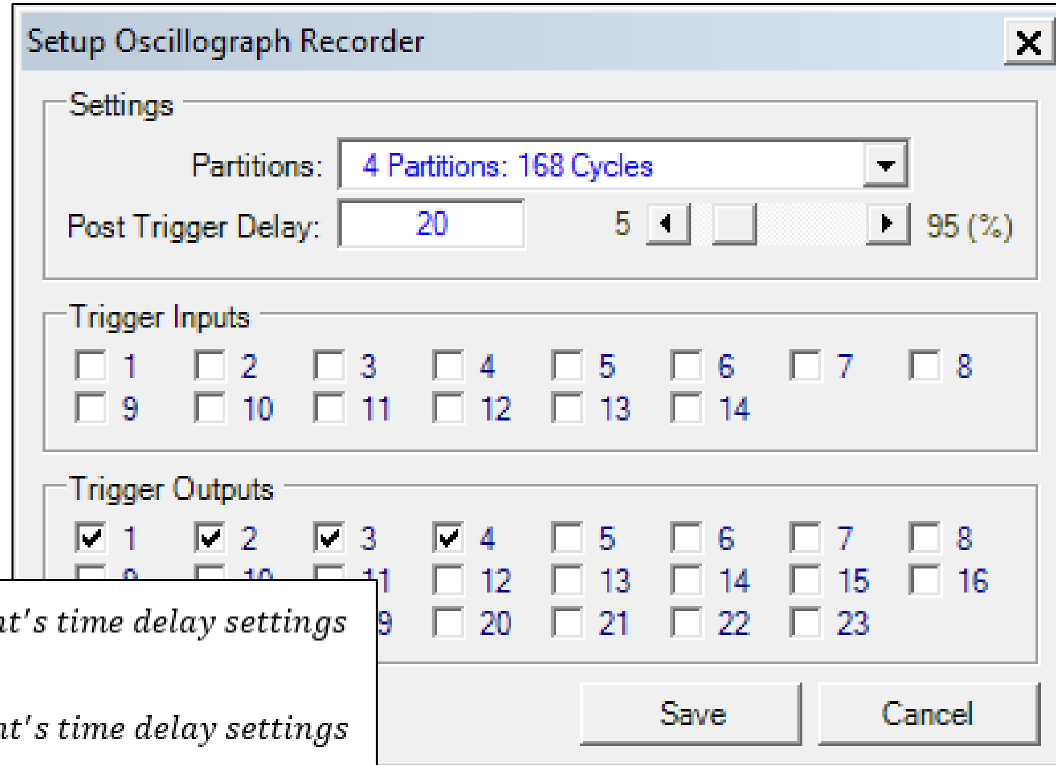




The Pickup, Trip, and Dropout of all the trip and alarm functions used may typically be checked to trigger SOE records.

Also, the Pickup and Dropout of the used I/O may typically be selected to trigger SOE records.

Oscillograph Setup



$$prefault\ length > element's\ time\ delay\ settings$$

$$\left(1 - \frac{Post\ Trigger\ Delay}{100\%}\right) * record\ length > element's\ time\ delay\ settings$$

$$\left(1 - \frac{20\%}{100\%}\right) * 168\ cycles > element's\ time\ delay\ settings$$

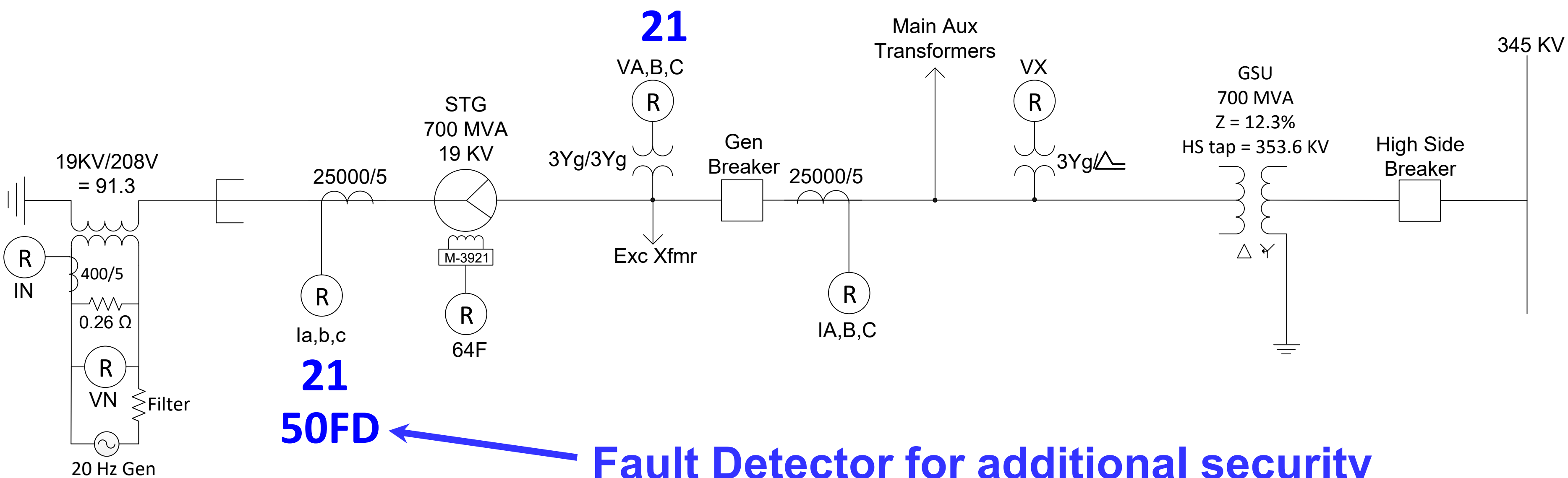
$$134.4\ cycles > element's\ time\ delay\ settings$$

$$\frac{Post\ Trigger\ Delay}{100\%} * record\ length > gen\ breaker\ interrup\ time * margin$$

$$\frac{20\%}{100\%} * 168\ cycles > 5\ cycles * 2$$

$$33.6\ cycles > 10\ cycles$$

21 – Phase Distance



Fault Detector for additional security

Blocking Inputs = FL, 1

(block for blown fuse and open breaker)

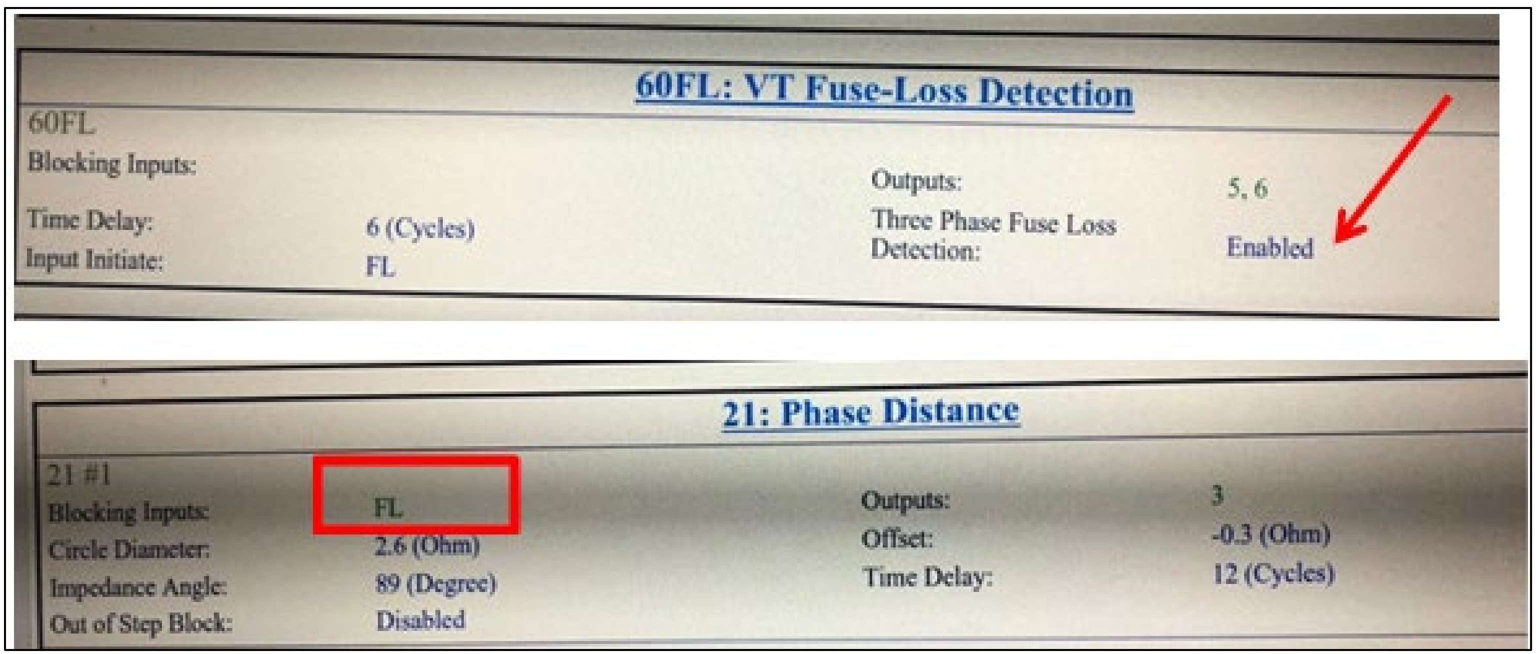
$$Z = \frac{V}{I}$$

Typically used for system backup phase fault protection.

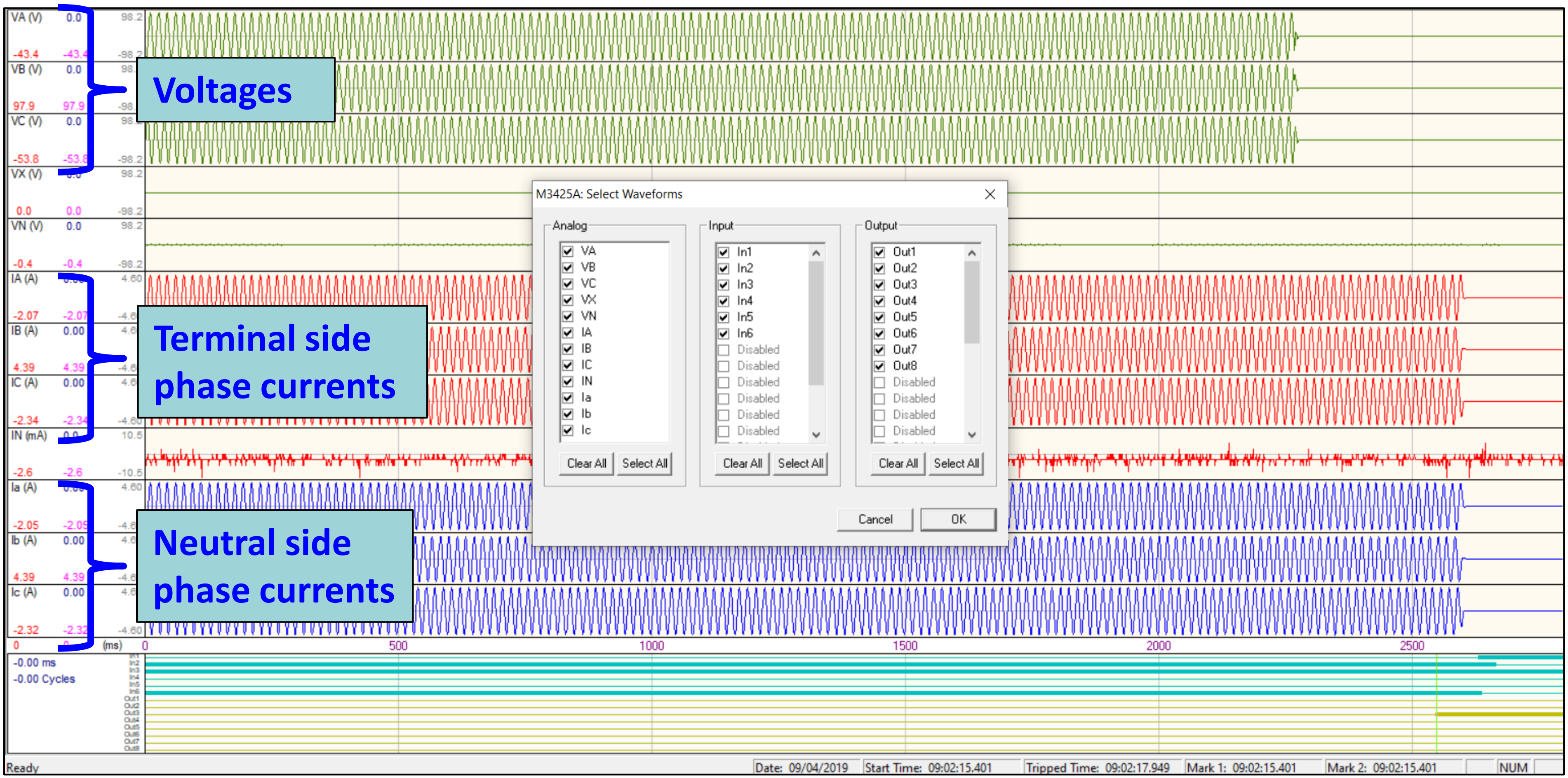
21 Event Analysis

- Customer reported 21 trip and voltage loss on all 3 phases from “thermal” breaker operation (VT secondary fused breaker)
- They asked, “why didn’t the relay’s blown fuse logic prevent the 21 trip?”

- All the typical information was requested; however, only part of the story was provided which can make the analysis a bit more challenging.
- OSC was provided, but only screenshots of some SOE and some relay settings:

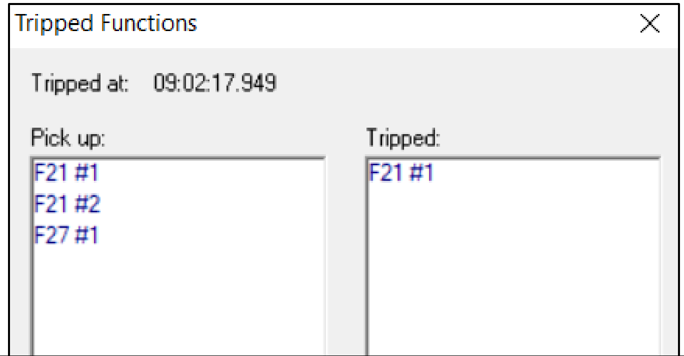


- Show step by step for this first event analysis.
- First, look at the “big picture” from the oscillograph record:

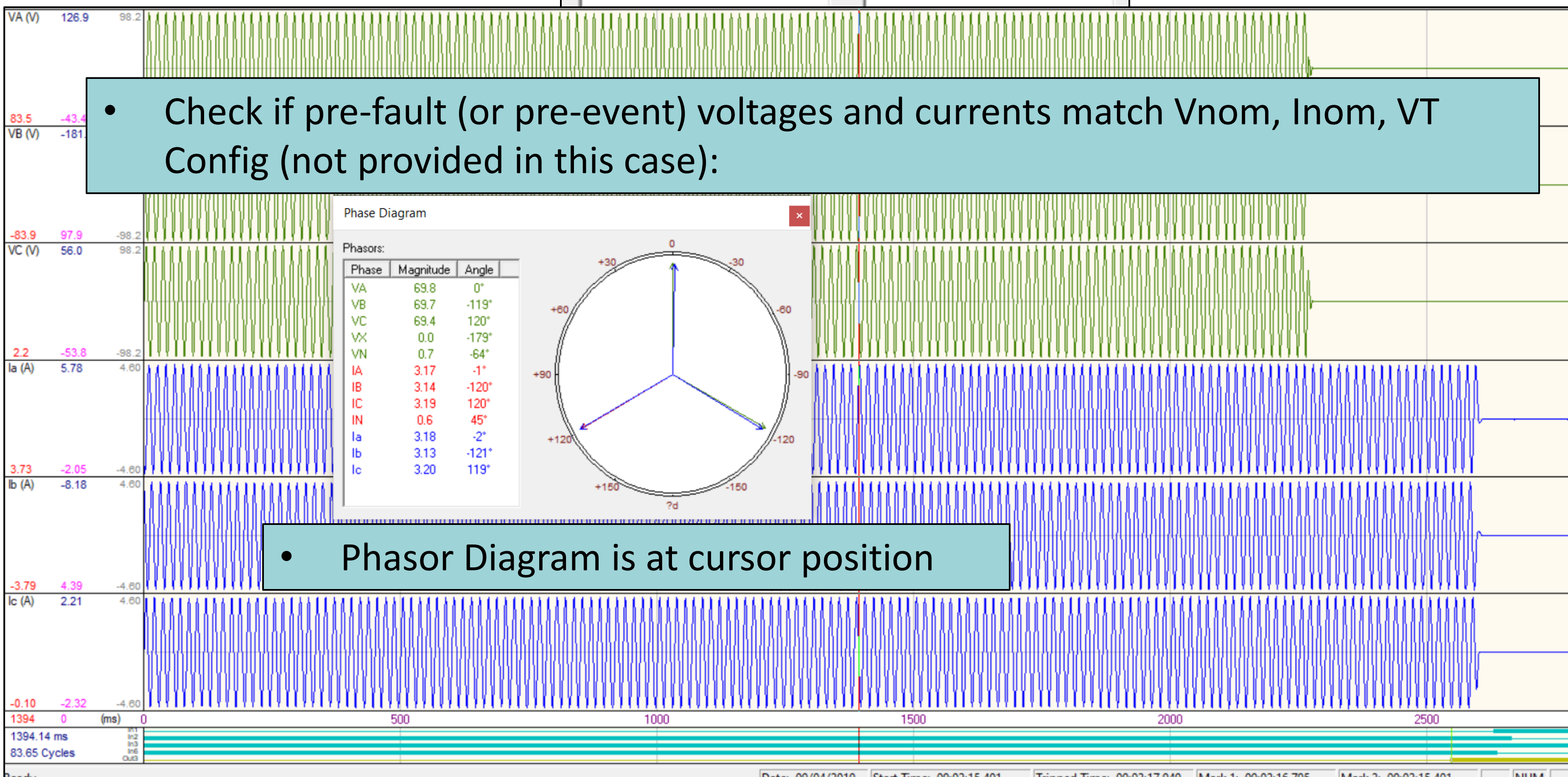


- The 21 function is made up by Z = V/I where the currents are from the neutral side phase CTs (Ia, Ib, and Ic) so we can clear the terminal side currents and other non-essential info.

- Check Tripped Functions:

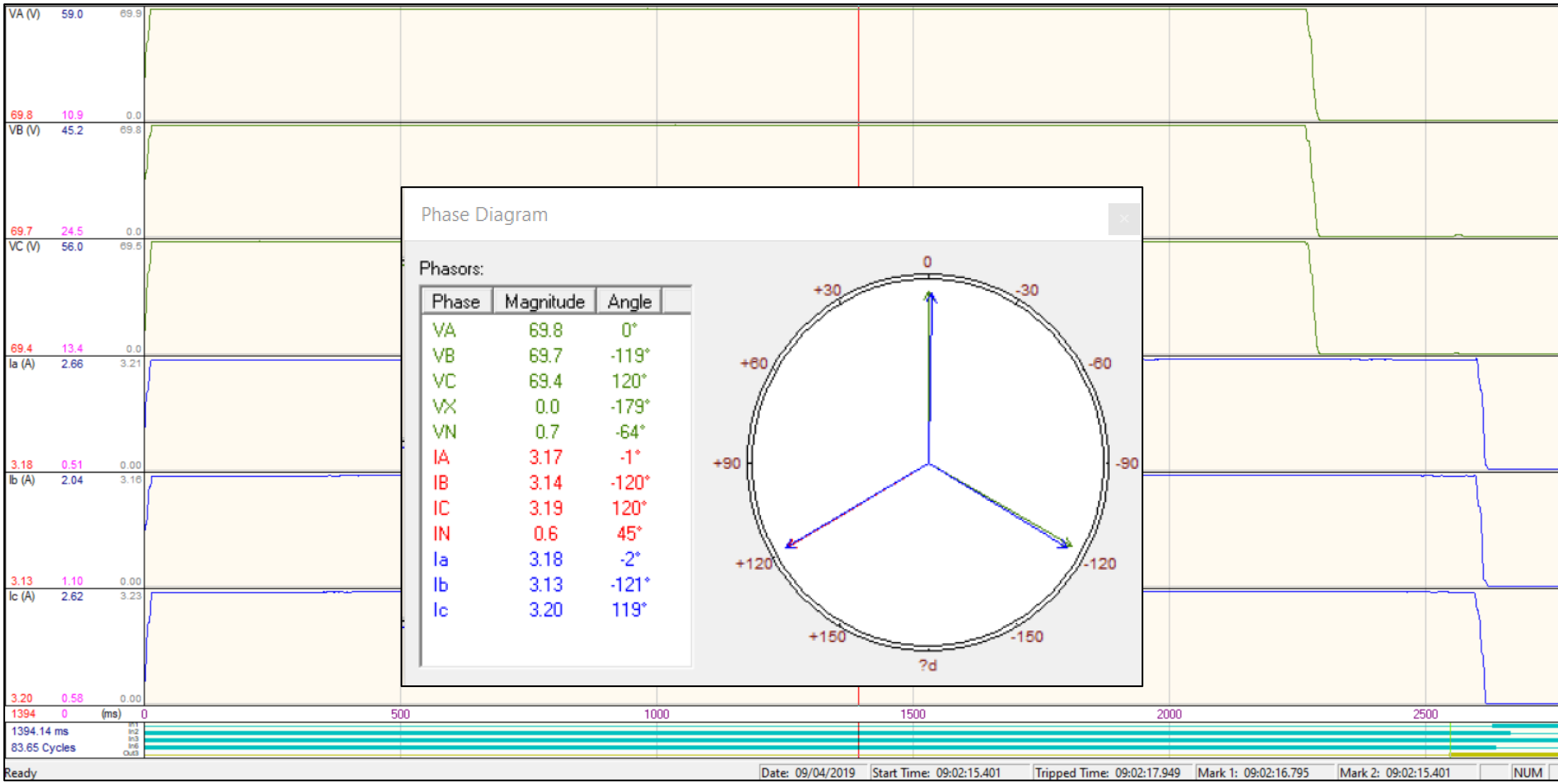


- Check if pre-fault (or pre-event) voltages and currents match Vnom, Inom, VT Config (not provided in this case):



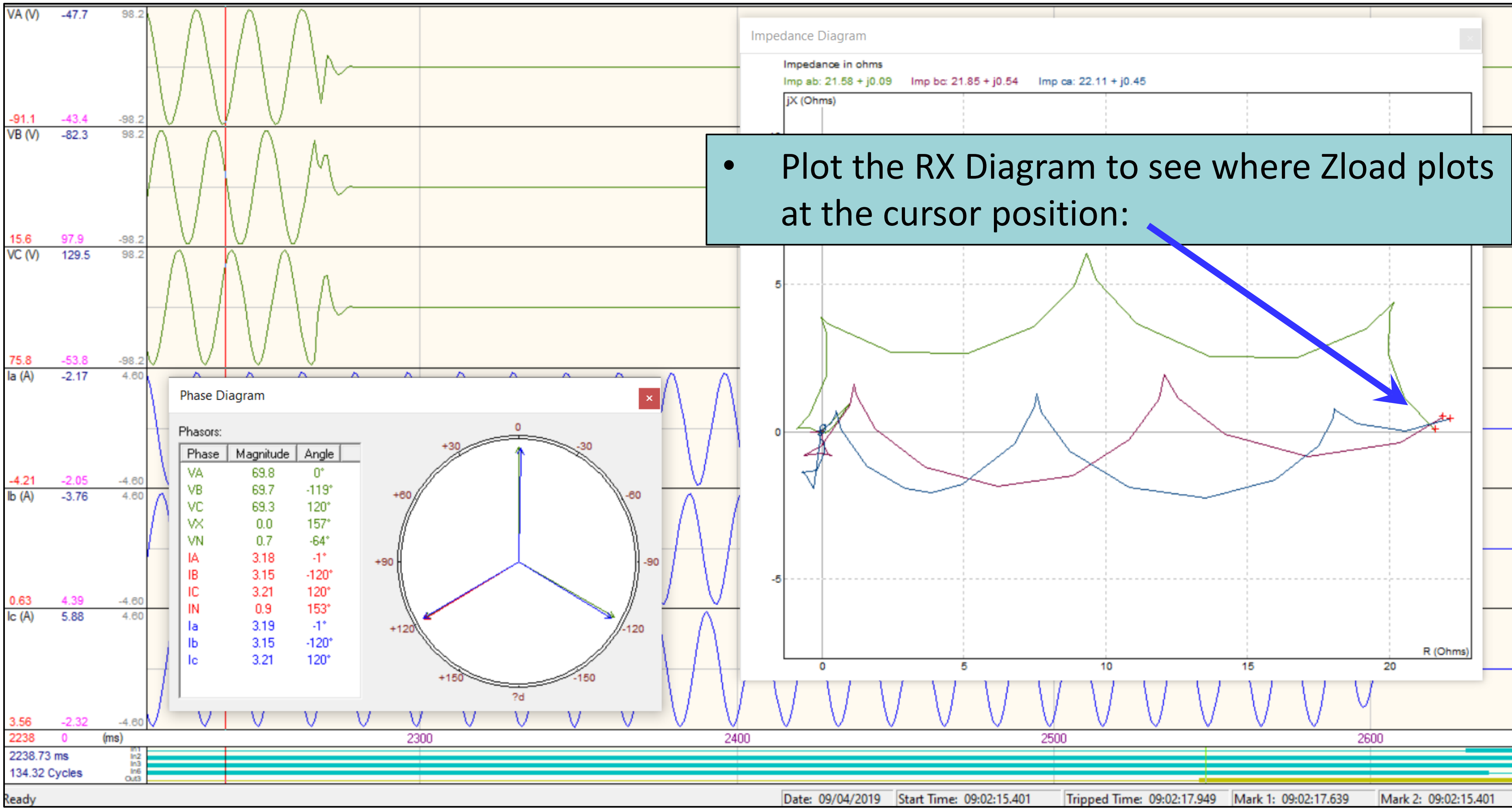
- Phasor Diagram is at cursor position

- Although customer reported that the trip was not from a fault, do a quick RMS visual check to see if there are any dips in voltage or increase in the currents.
- Or could move cursor thru all the pre-fault period to see if phasors rotate or change.

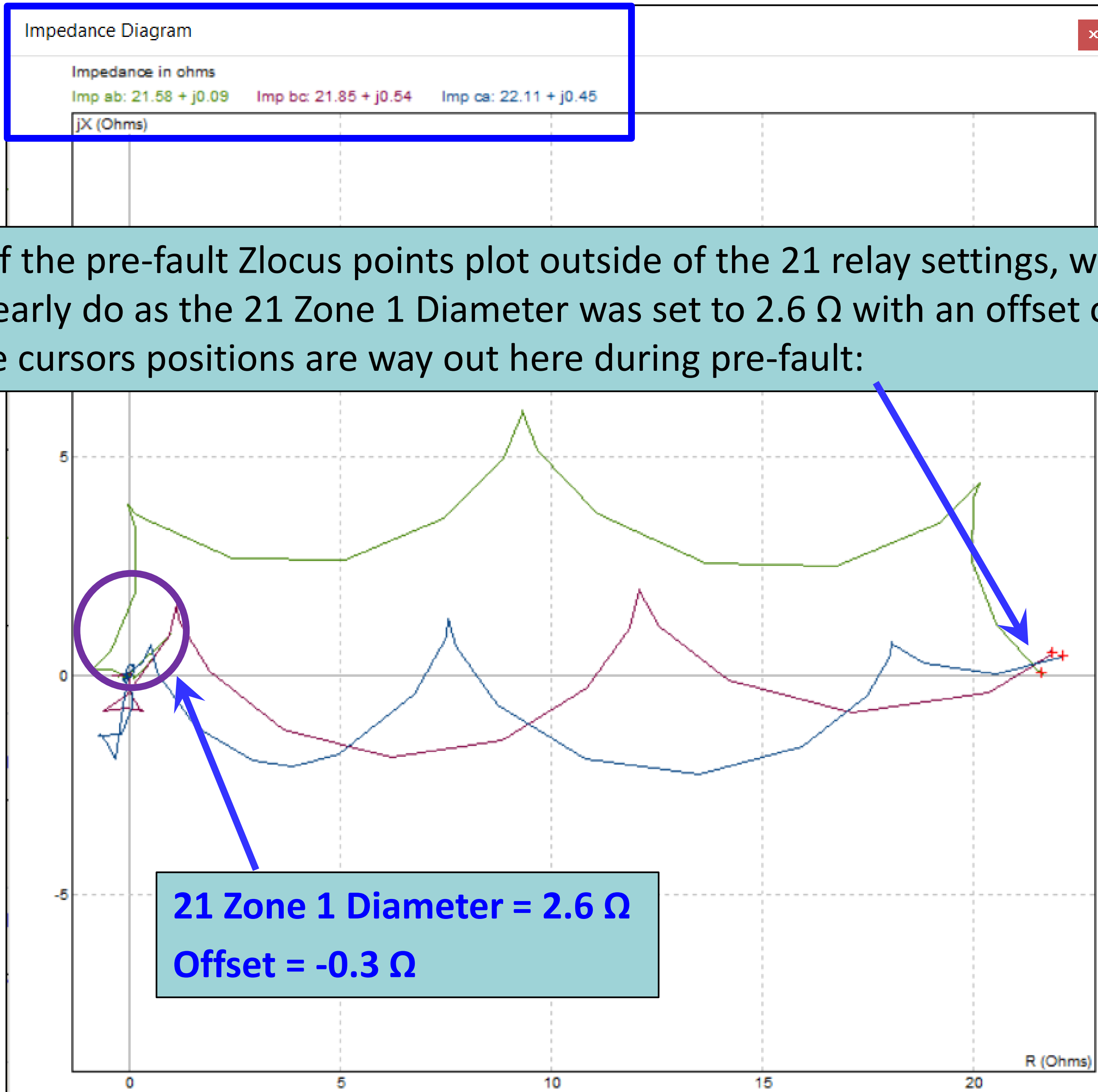


- Confirmed it does look like normal load current during the pre-fault or pre-event period.

- Zoom in to see a bit of pre-fault up until output assertion and breaker opening:



- Plot the RX Diagram to see where Zload plots at the cursor position:

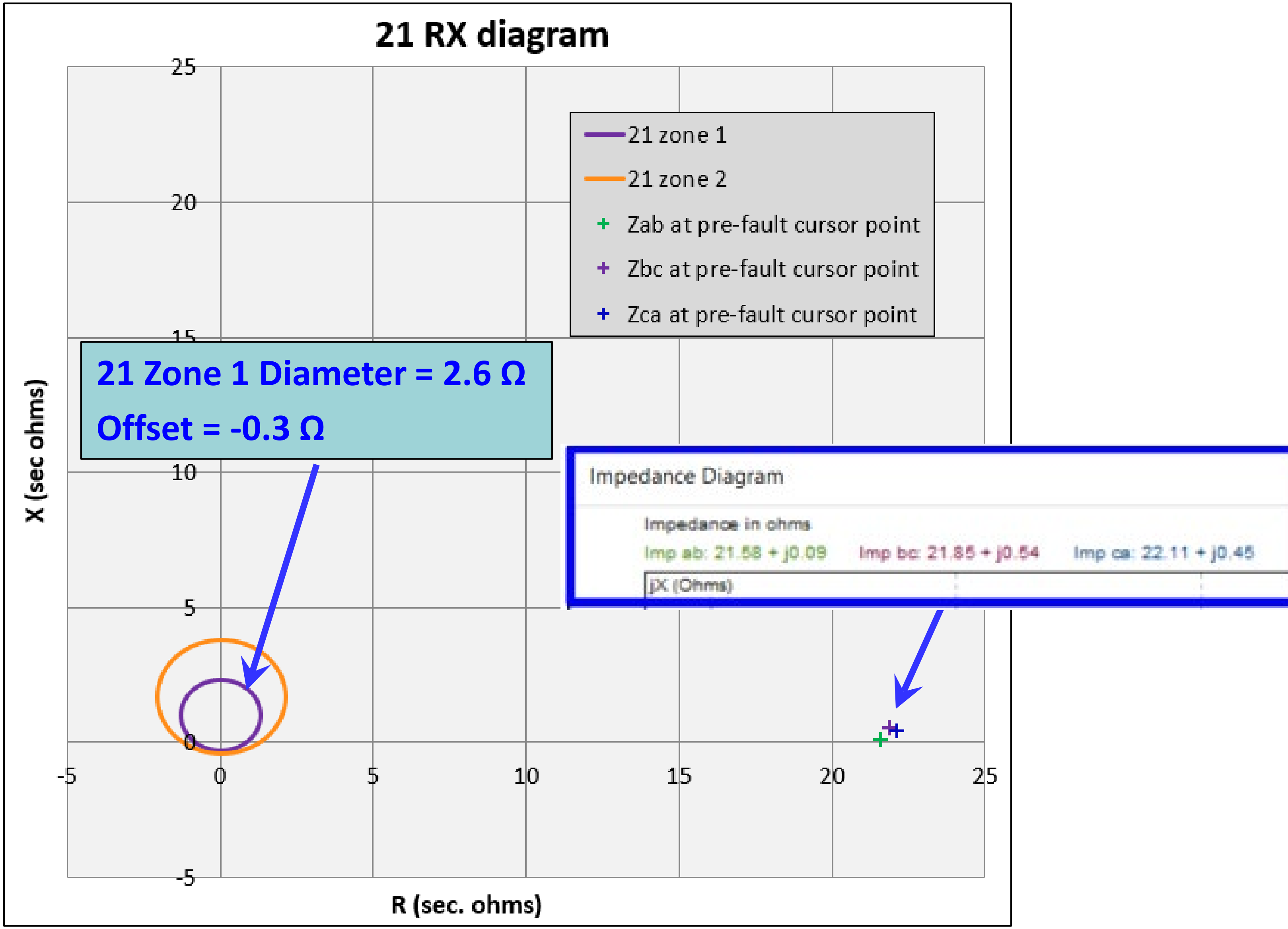


- Check if the pre-fault Zlocus points plot outside of the 21 relay settings, which they clearly do as the 21 Zone 1 Diameter was set to 2.6 Ω with an offset of -0.3 Ω and the cursors positions are way out here during pre-fault:

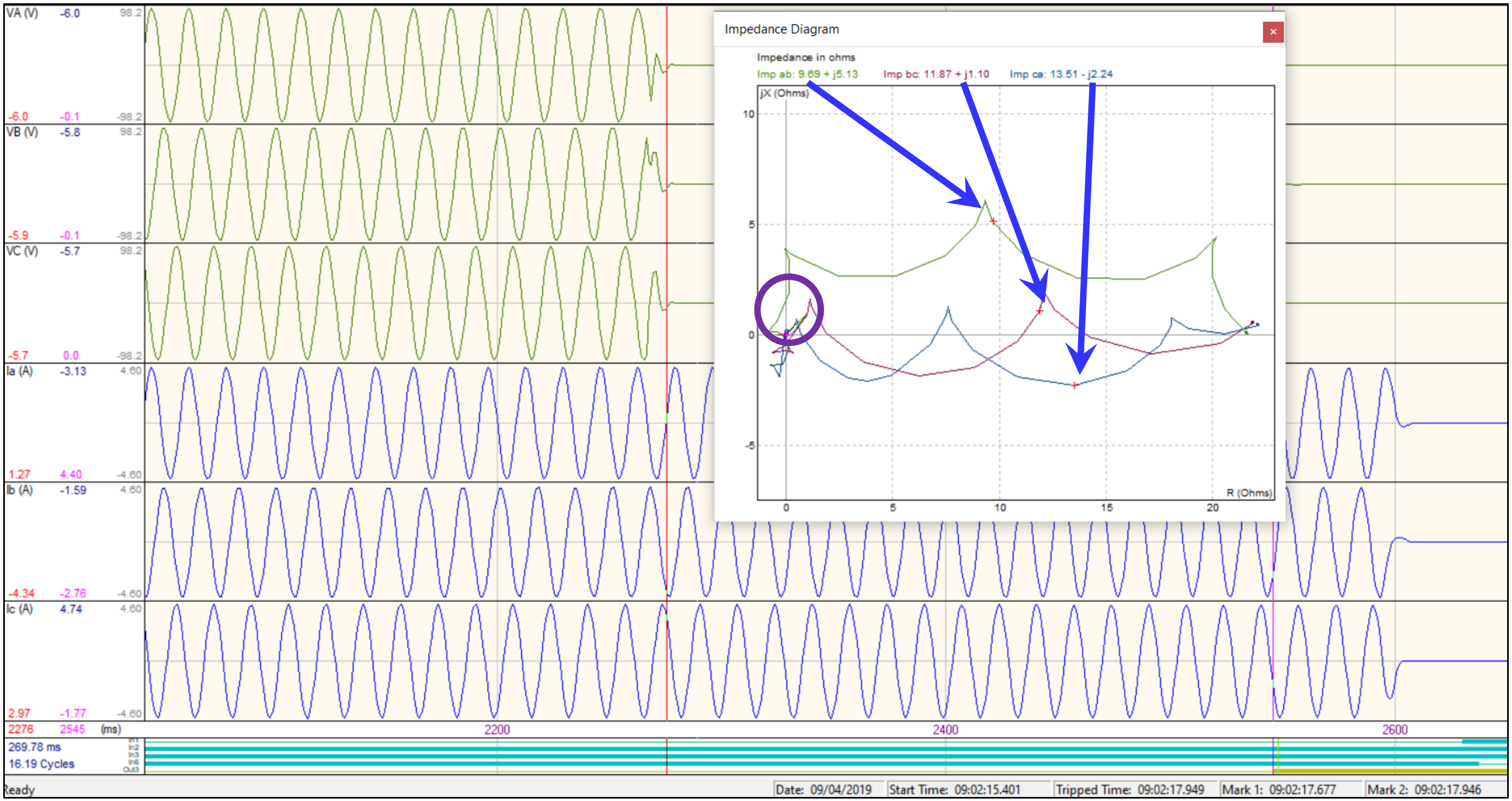
21 Zone 1 Diameter = 2.6 Ω

Offset = -0.3 Ω

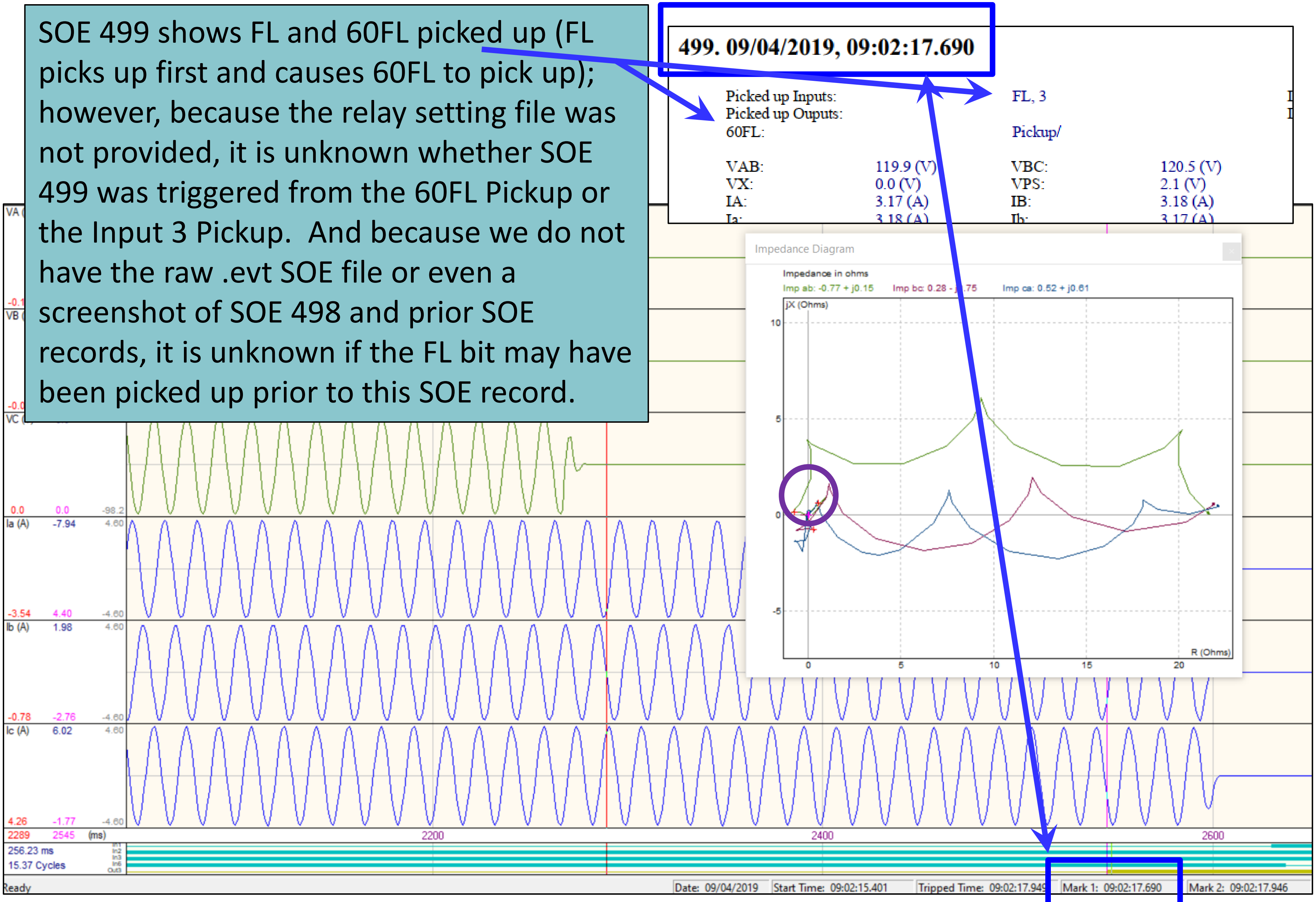
- Or could plot the Zload points from OSC or SOE vs relay settings:



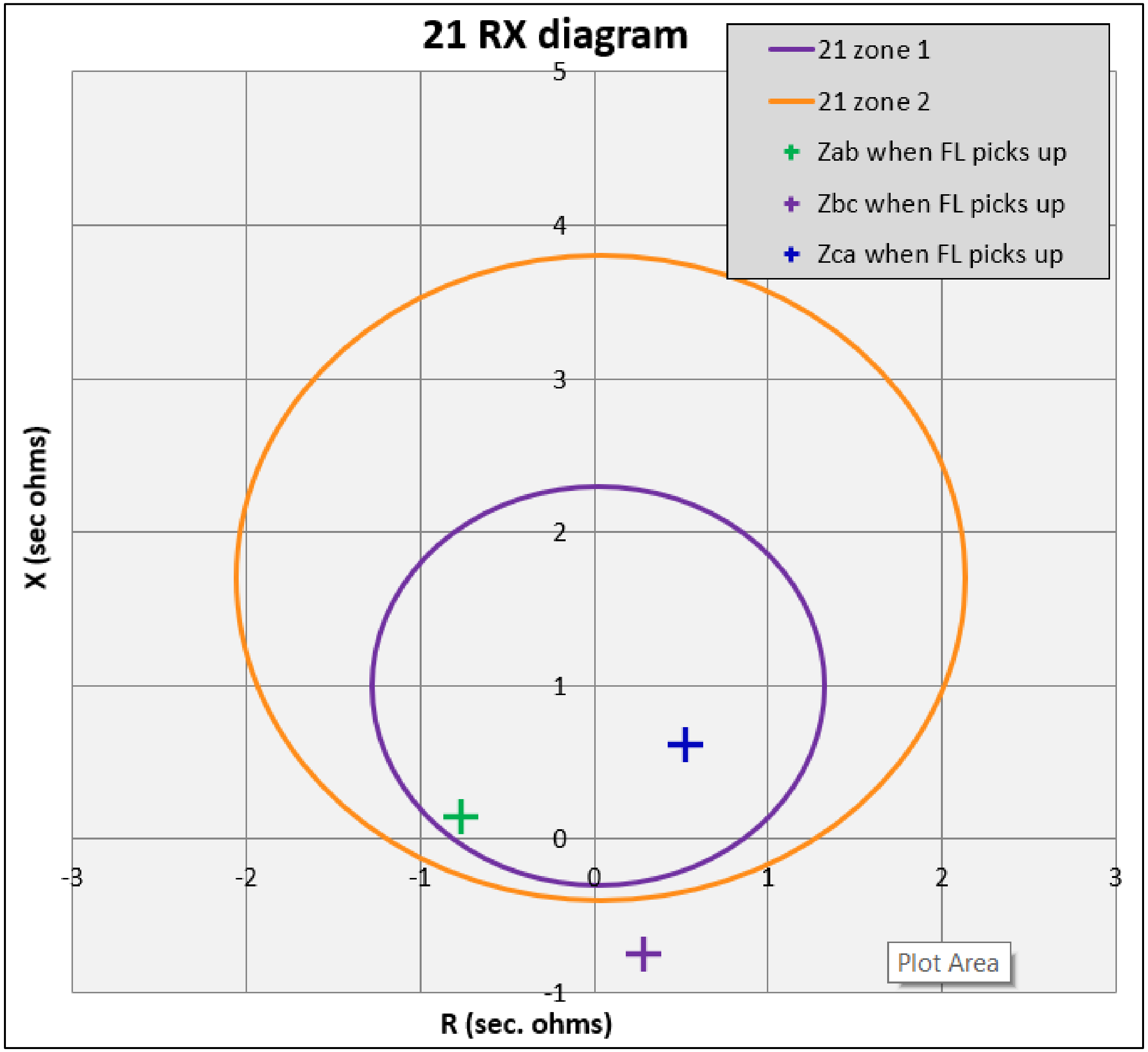
- Gen is on-line and running normally when all 3 voltages are lost which is consistent with the reported VT secondary thermal breaker operation.
- Here, the event loci (Zab, Zbc, Zca) are shown as they traverse from Zload or Zstart position towards the origin of the RX diagram which represents 0 V at the gen VT location:



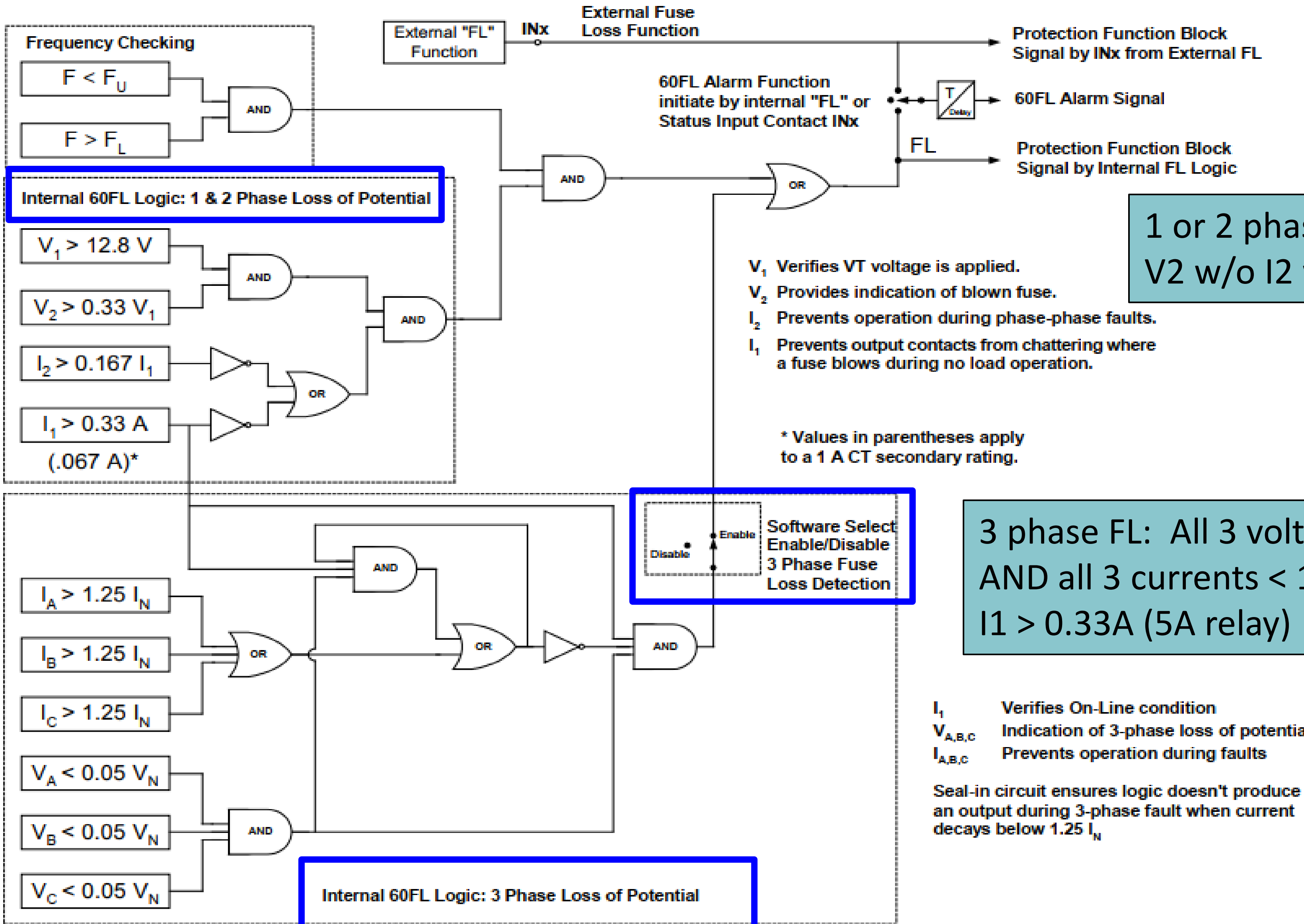
SOE 499 shows FL and 60FL picked up (FL picks up first and causes 60FL to pick up); however, because the relay setting file was not provided, it is unknown whether SOE 499 was triggered from the 60FL Pickup or the Input 3 Pickup. And because we do not have the raw .evt SOE file or even a screenshot of SOE 498 and prior SOE records, it is unknown if the FL bit may have been picked up prior to this SOE record.



- Cursors at timestamp of SOE 499 when FL picked up where Zab and Zca have entered the zone 1 mho circle, but Zbc is still outside the mho circle; however, because these are OR’d together in the 21 algorithm therefore if Zab or Zbc or Zca enters mho circle, 21 zone 1 would have picked up but it didn’t because FL was blocking it at this timestamp:



- Review FL Logic Diagram:



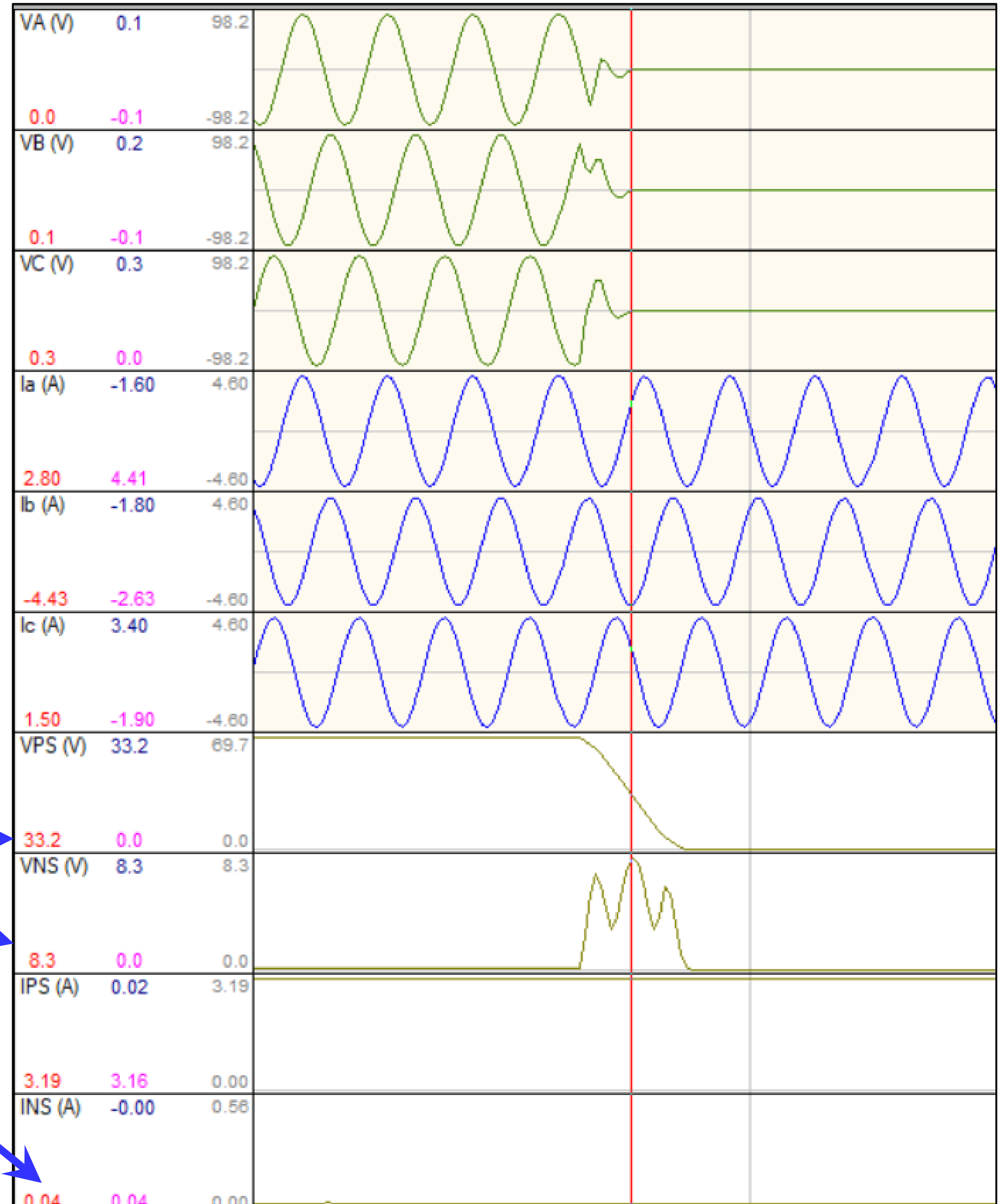
1 or 2 phase FL:
V2 w/o I2 with min V1

3 phase FL: All 3 voltages < 5% AND all 3 currents < 125% AND I1 > 0.33A (5A relay)

It can be seen at this cursor position that initially when the 3 phases of voltages are lost that:

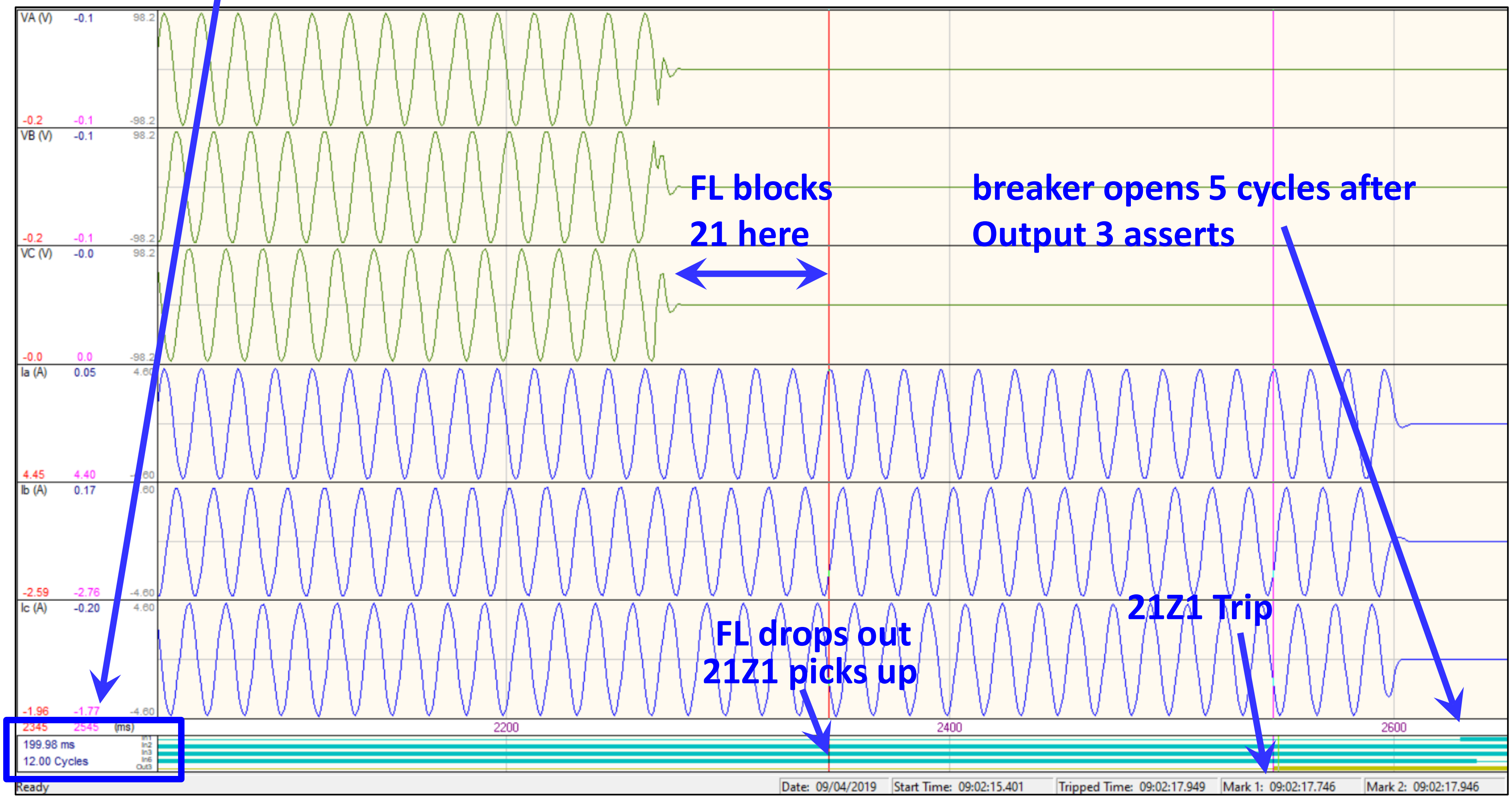
- V1 (VPS) > 12.8 V
- and there is some V2 (VNS)
- but there is no I2 (INS)

therefore, FL may have initially picked up on its 1 or 2 phase fuse loss logic portion of the algorithm.



Dropped Inputs:	FL
Dropped Ouputs:	
60FL:	Drop

- But then a few cycles later, SOE shows that FL drops out and then 21 zone 1 and 2 pick up and 12 cycles later (equaling the 21 zone 1 time delay setting), 21 zone 1 times out and trips, asserting Output 3 as programmed:



- But the question is, why did the FL relay word bit drop out?

- All the phase voltages were still gone and even if initially the FL bit was picked up from the 1 or 2 phase fuse loss portion of its algorithm due to unequal rate of the phase voltages getting to zero,

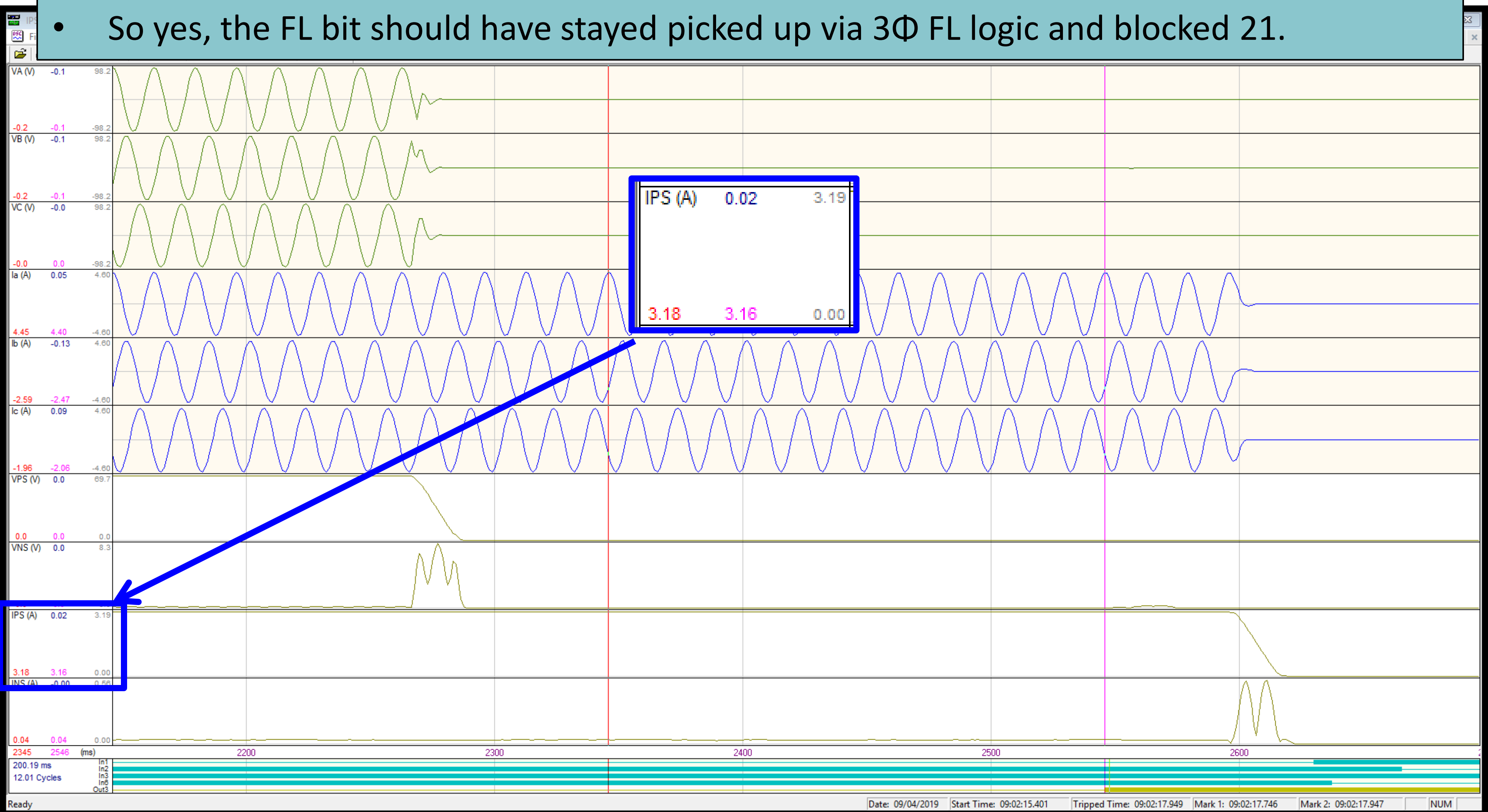
- the **screenshot** of the 60FL settings that was provided did show that the 3 phase FL detection logic was Enabled,

- so even though the 1 or 2 phase fuse loss logic portion of the algorithm would have de-asserted once all the voltages settled down to 0 V,

- FL should have stayed picked up via its 3 phase FL logic portion of its algorithm, but check 3 phase FL logic criteria just to be sure:

Checking the 3 phase FL logic:

- I1 > 0.33 A? Yes, it is 3.18 A
- All 3 phase voltages < 0.05*Vnom? We don't know what Vnom is, but likely yes
- All 3 currents < 1.25*Inom? We don't know what Inom is, but likely yes
- So yes, the FL bit should have stayed picked up via 3Φ FL logic and blocked 21.



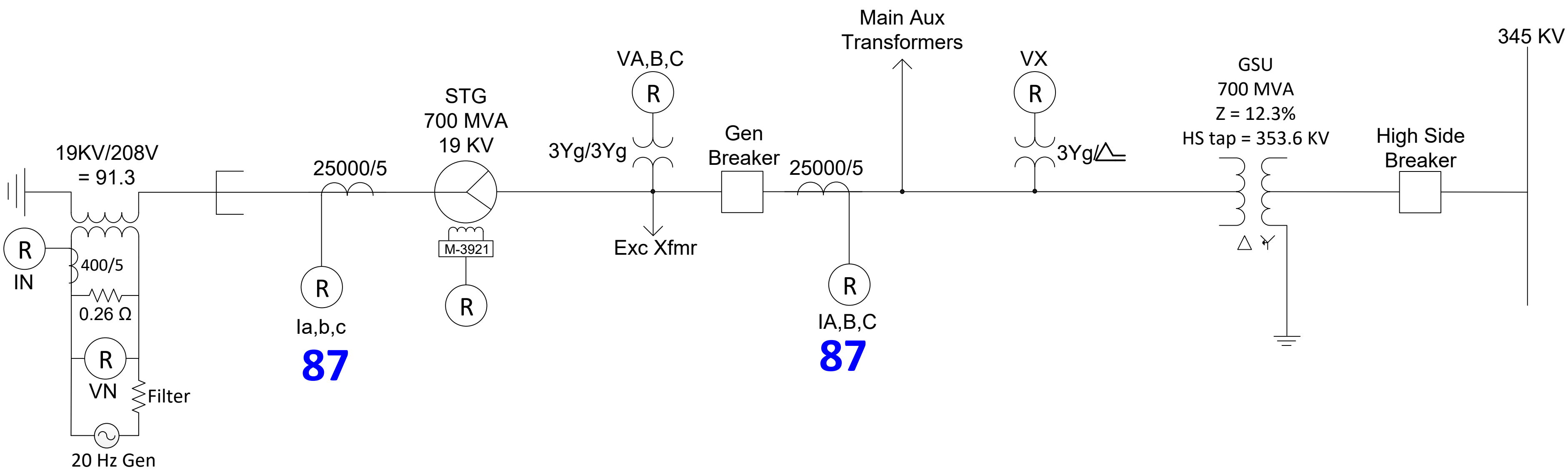
21 Event Analysis Conclusion

- It is suspected that the 60FL setting "Three Phase Fuse Loss Detection" is Disabled in the settings that are installed on the relay.
- The native, "as-left" relay setting file in the mfg specific software format (e.g. .ips extension file) was not provided.
- The relay setting file should always be downloaded from the relay after the event (not a copy of the native, supposed "as-left" file from some storage location) along with all the other files: OSC, SOE, Target List, etc.
- The other possibility is that the relay operated incorrectly; however, this would be an odd failure mode i.e. failure of the relay code that represents the 60FL algorithm to execute in the manner as displayed in the 60FL logic diagram

Recommendations:

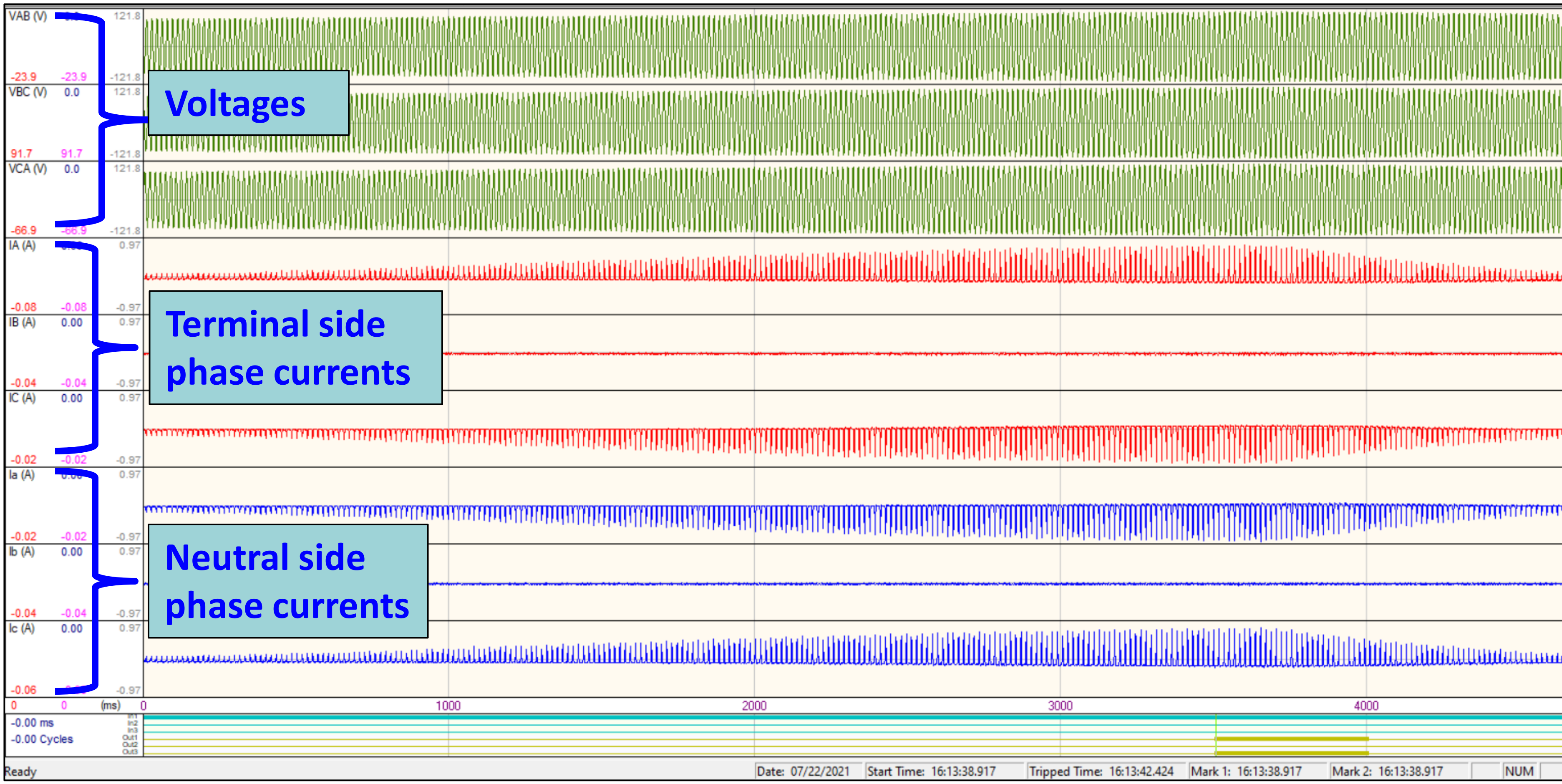
- Check the applied relay settings to ensure that the 60FL "Three Phase Fuse Loss Detection" is really Enabled.
- However, if it is Enabled, then recommend secondary injection test the relay.
- Did not hear back from customer on what was found, although I assume my guess may have been correct; otherwise, I am sure I would have heard something.

87 – Phase Differential

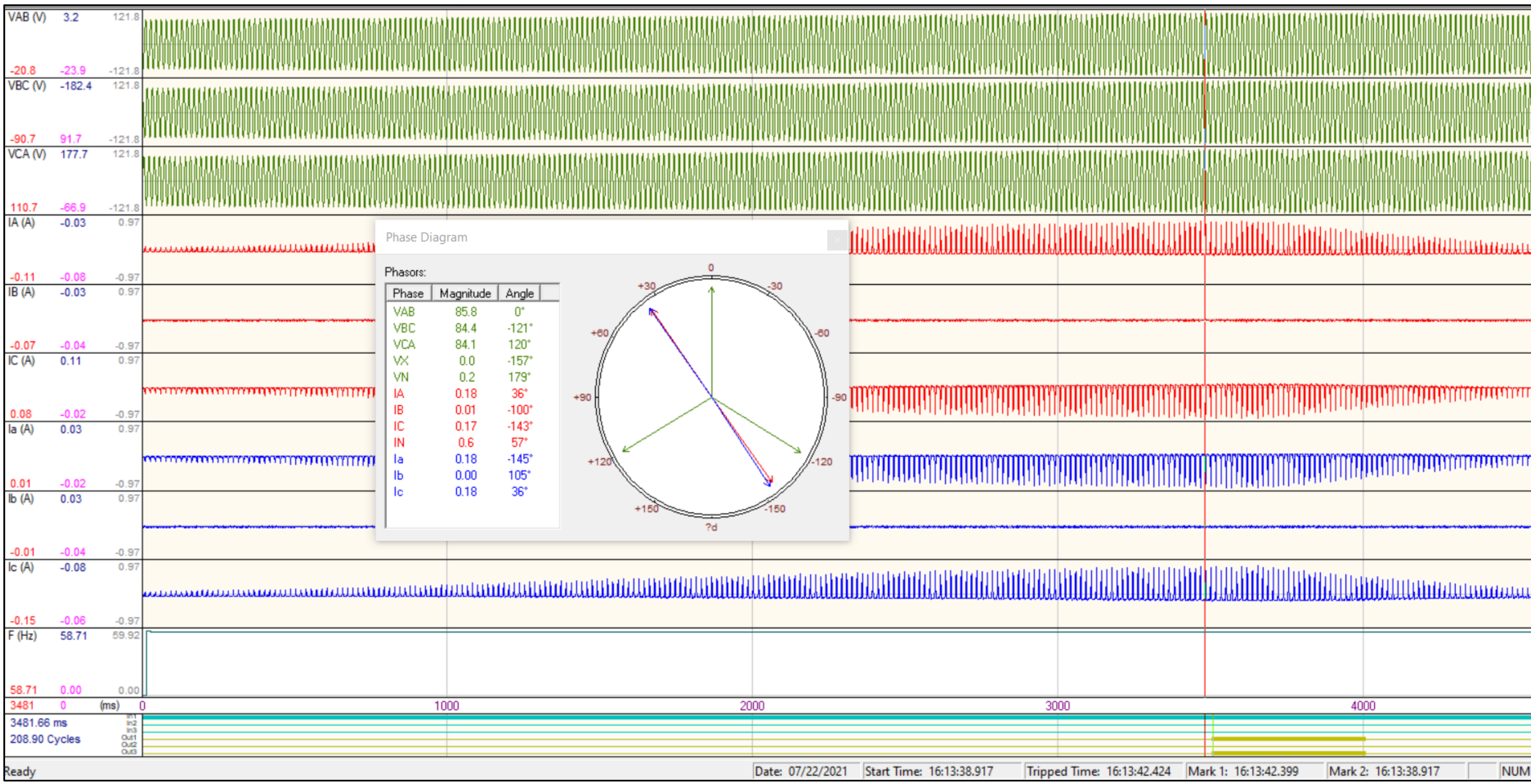


87 Event 1 Analysis

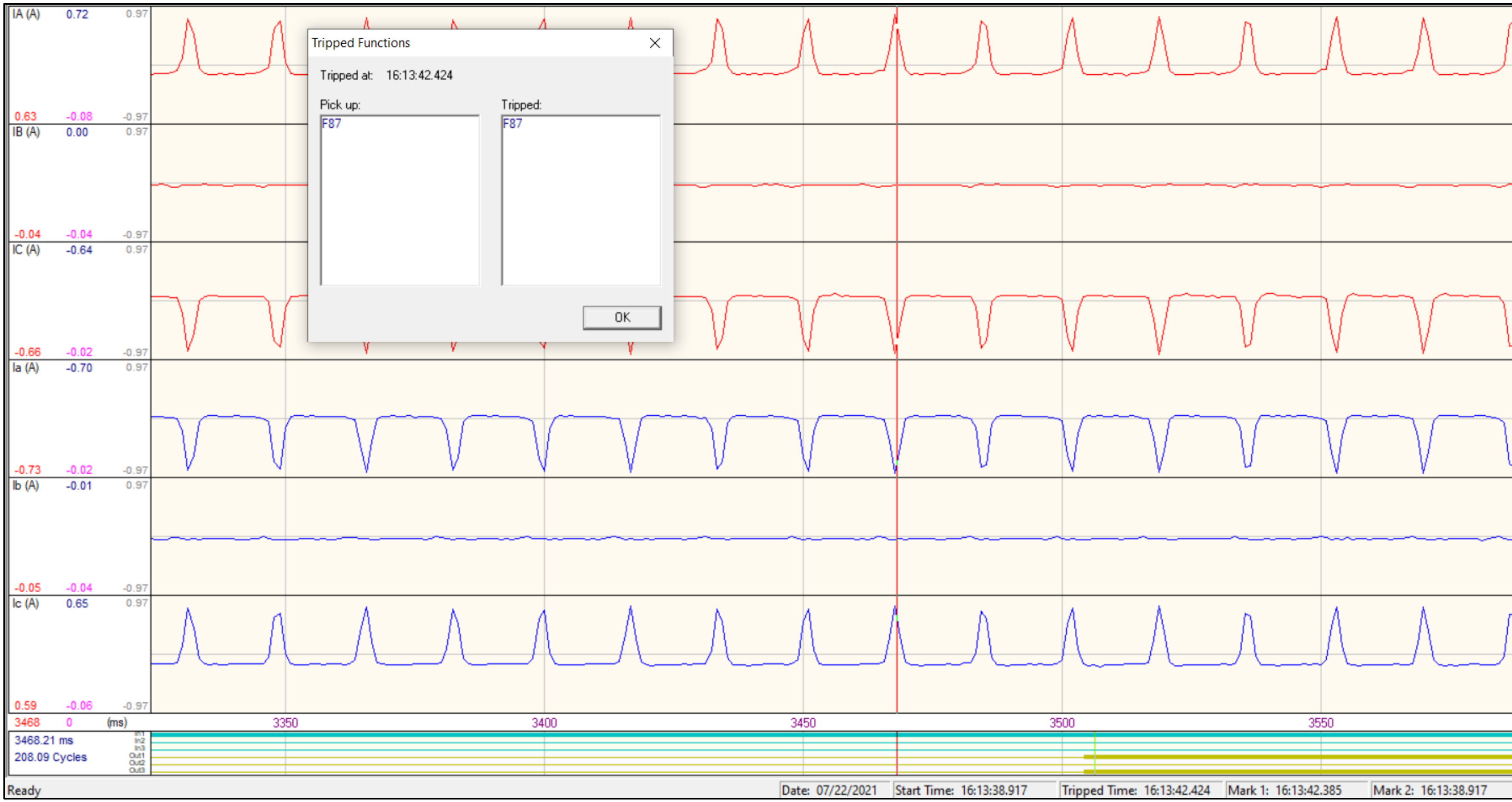
- Customer reported an 87 trip on startup during the very first energization of a new generator installation.
- No low side gen breaker, only a GSU high side unit breaker



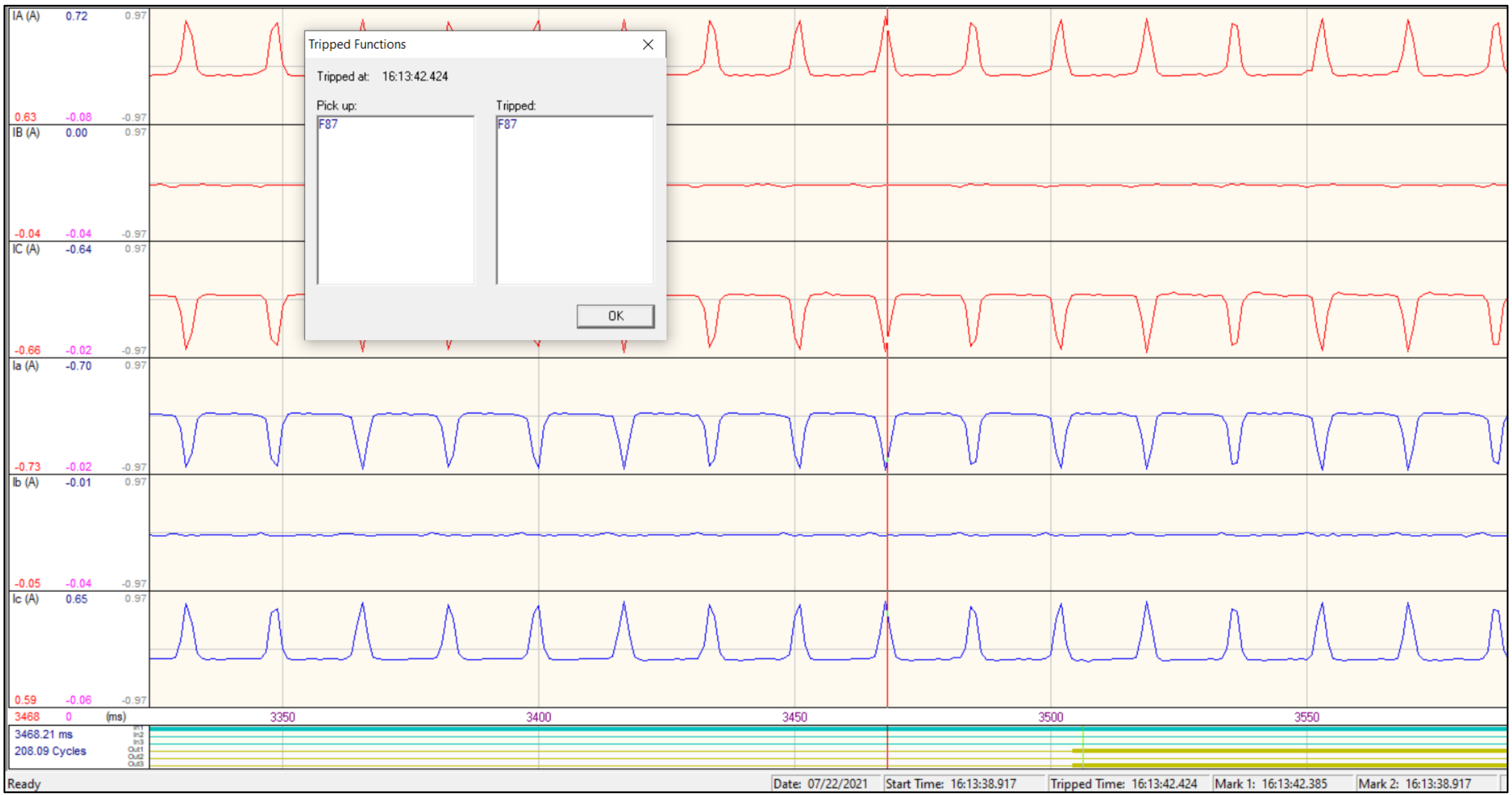
- Voltages were increasing during the event from approx. 67 VLL at start of event up to approx. 86 VLL (75% of Vnom) just prior to assertion of outputs.
- Frequency was at 58.7 Hz.
- Voltages look typical for the build up of the field during startup, so get rid of the voltage tracings and zoom in on the currents.



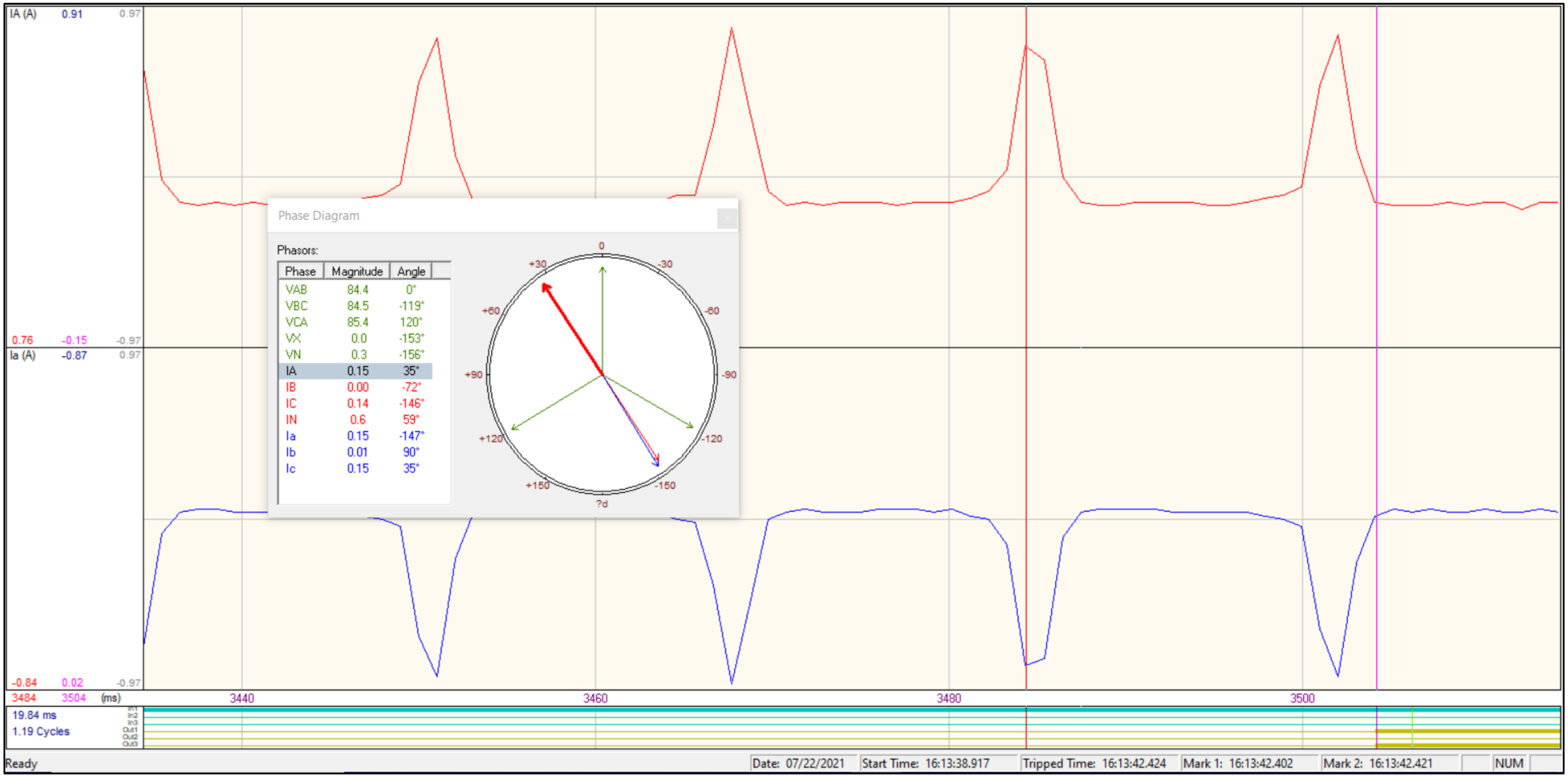
- Current waveforms with half the wave chopped off is indicative of inrush current.
- During startup as the field is building up, this type of GSU magnetizing inrush current is normal for applications with no GSU LS gen breaker and only a GSU HS unit breaker to synch across.



- Notice there are no “IB” or “Ib” currents, does this mean there are open circuits somewhere from the CTs to the relay current inputs?
- In this case probably not, because inrush can present as no inrush current being seen on one phase if the other 2 phases cancel out.
- “IA” and “IC” (also “Ia” and “Ic”) oppose and match each other. “IA” positive peak coincides with “IC” negative peak, therefore IA + IB + IC = +0.63 + 0 + -0.66 ≈ 0.

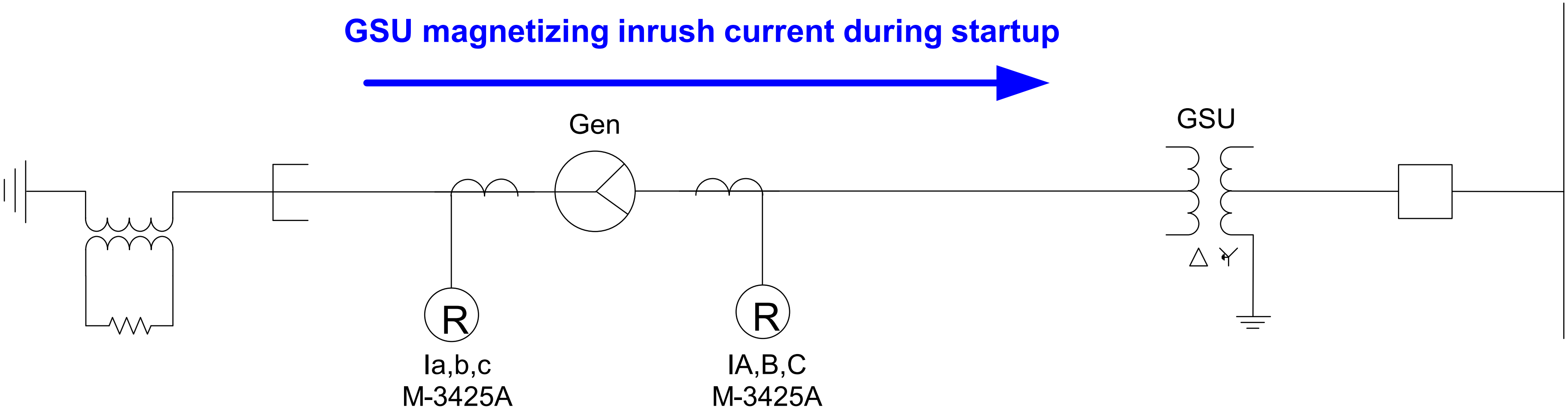


- Now zoom-in on like phases, “IA” and “Ia”, what is their phase relationship?



- Currents on each side of the generator are 180° out-of-phase, is that correct?

- The primary representation of the inrush currents on each side of the generator are 180° out-of-phase:



- But for the secondary currents going into the relay current inputs, it depends on the specific mfg's relay current input polarity requirements.
- For most other mfg's relays, thru currents being 180° out-of-phase would be correct.
- So why is it not the same for Beckwith M-3425A relays?

For the M-3425A relay 87 algorithm differential equation, “IA” and “Ia” are subtracted from each other:

$$87A_{operate} = \left|\overline{(IA} * CTC) - \overline{Ia}\right| \qquad 87A_{restraint} = \frac{|\overline{IA} * CTC + \overline{Ia}|}{2}$$

$$87B_{operate} = \left|\overline{(IB} * CTC) - \overline{Ib}\right| \qquad 87B_{restraint} = \frac{|\overline{IB} * CTC + \overline{Ib}|}{2}$$

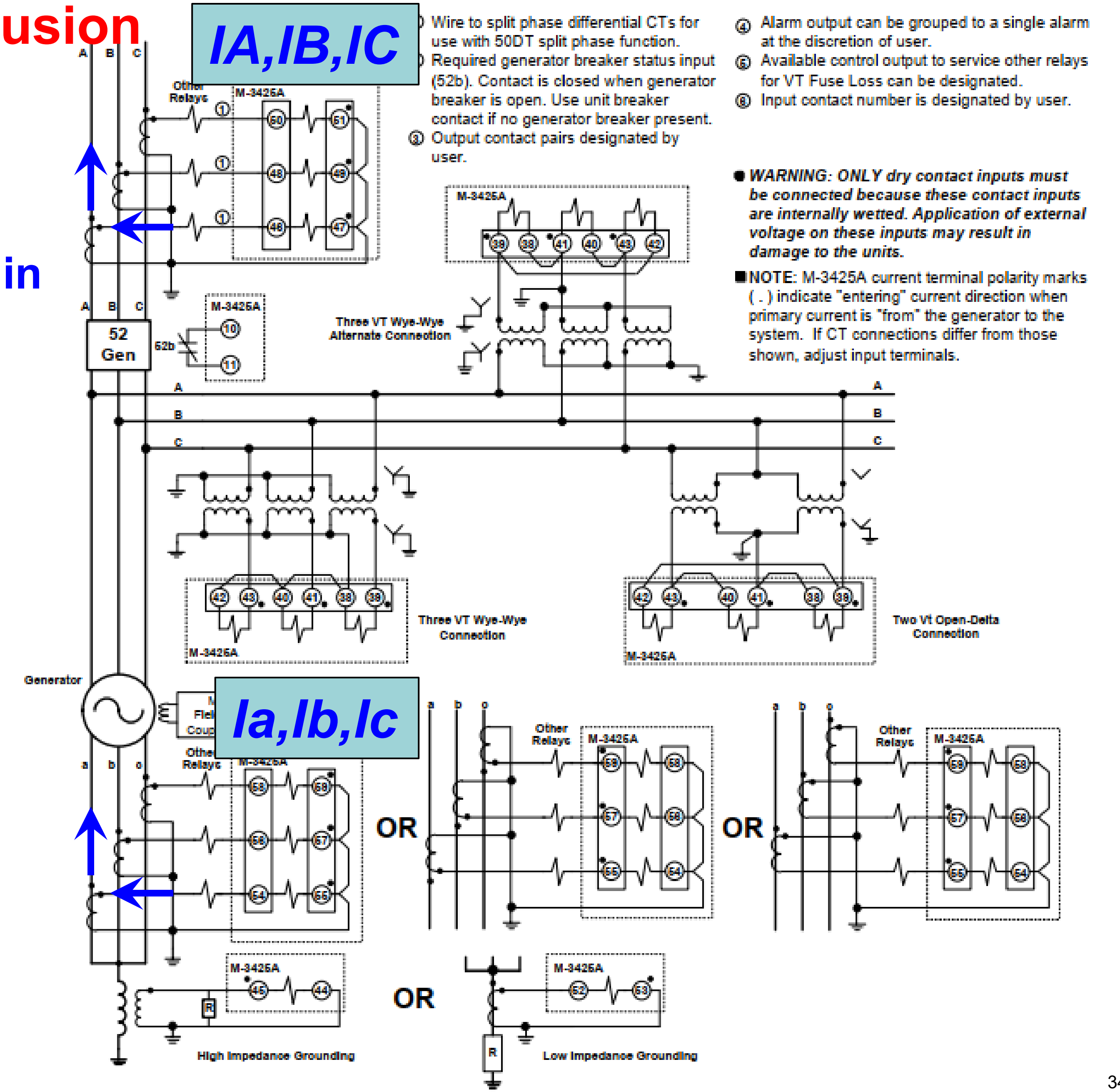
$$87C_{operate} = \left|\overline{(IC} * CTC) - \overline{Ic}\right| \qquad 87C_{restraint} = \frac{|\overline{IC} * CTC + \overline{Ic}|}{2}$$

other mfgs may add these

87 Event 1 Conclusion

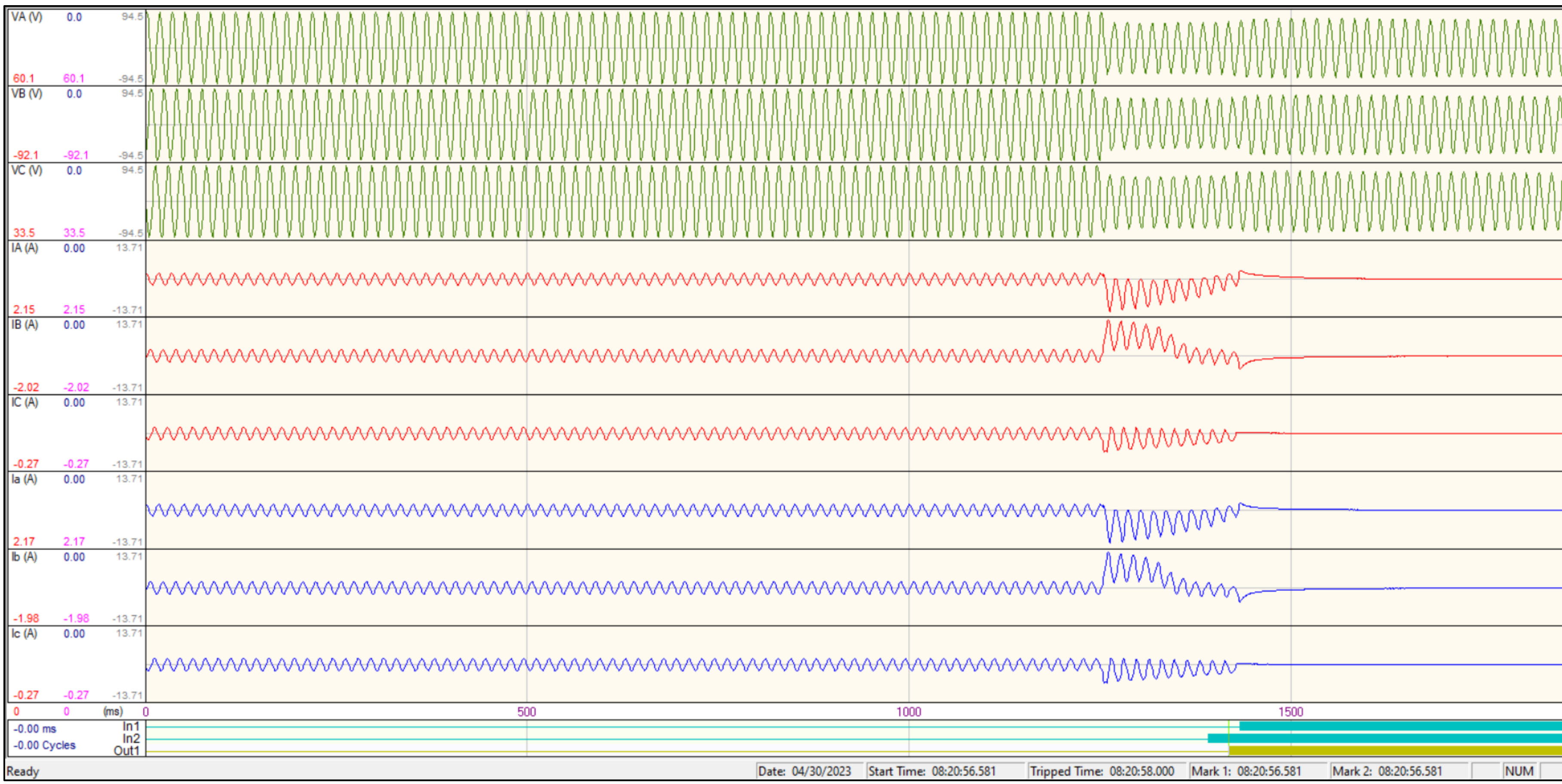
event caused by incorrect polarity wiring i.e. it is not wired per the 3-line in the M-3425A IB:

Because the operating current equation in the 87 algorithm <u>subtracts</u> the vector quantities of the current inputs from both sides of the stator winding, the CT and relay current input polarities need to be such that thru currents are in-phase with each other (enters relay polarity on both sides).

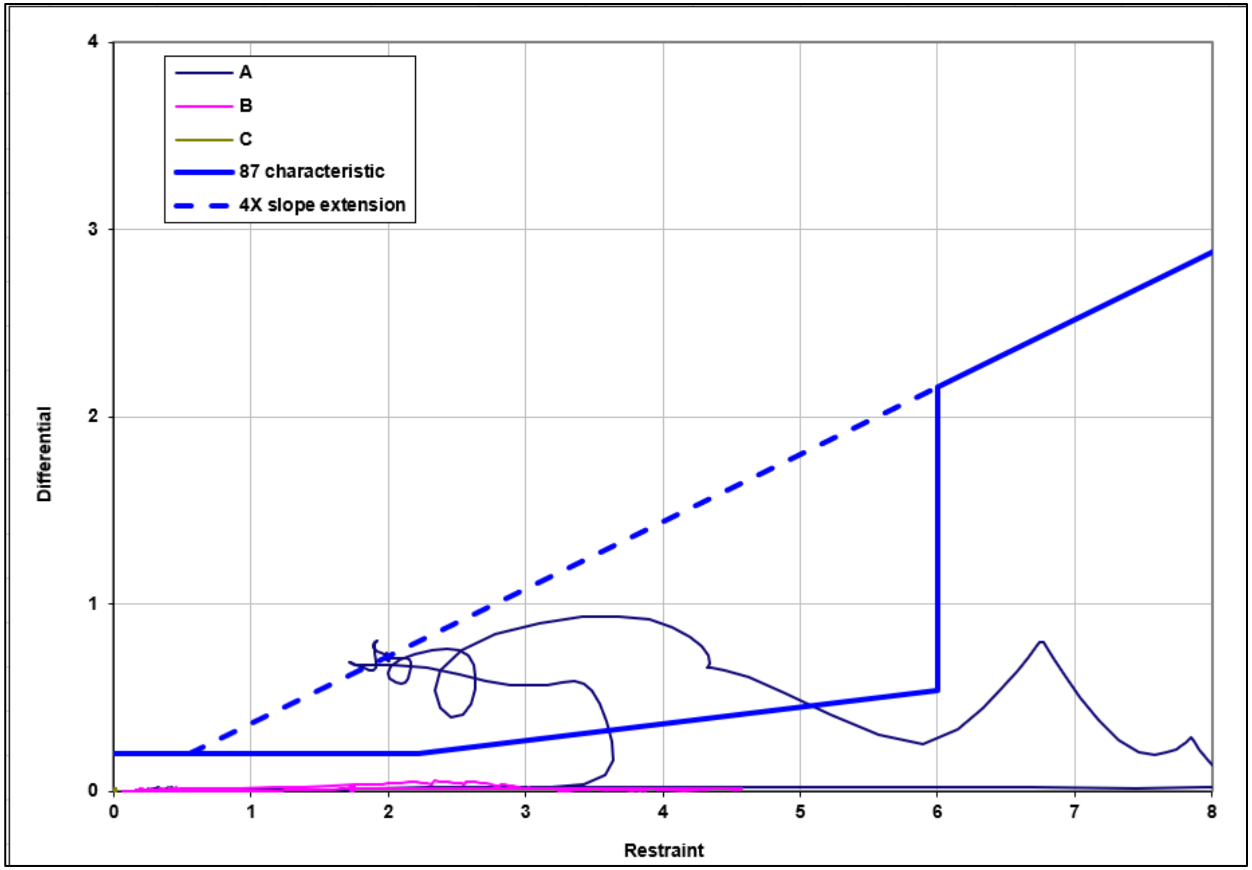


87 Event 2 Analysis

- Customer reported a generator 87 trip from an external event – when a reactor breaker out in the switchyard was closed in out-of-phase.
- Typically for out-of-phase closures, all 3 phases of voltages dip and all 6 phases of currents increase with a lot of DC offset.

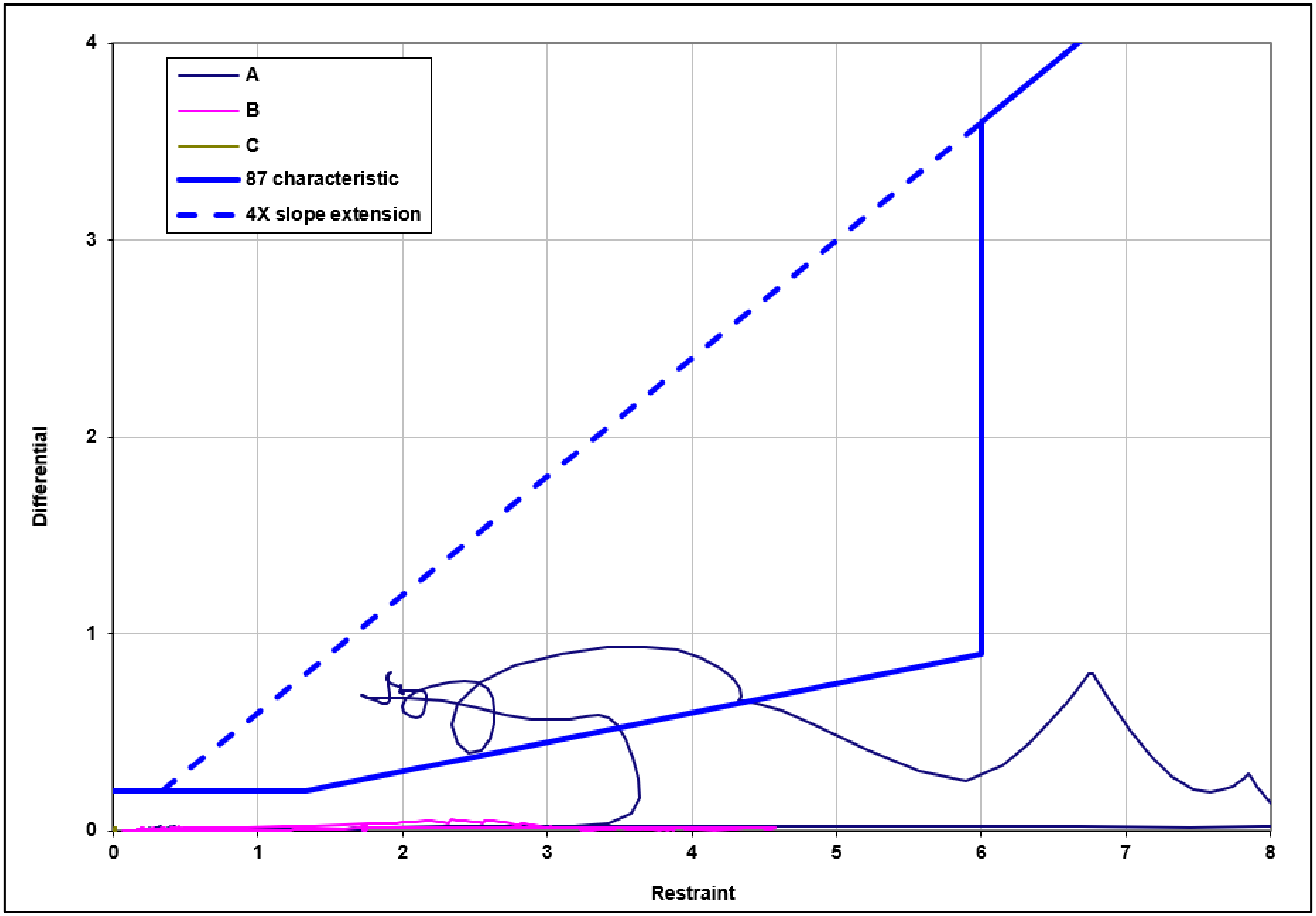


- When the event is played back, the event locus vs 87 curve plot as such (they had **87 slope set at 10%**):



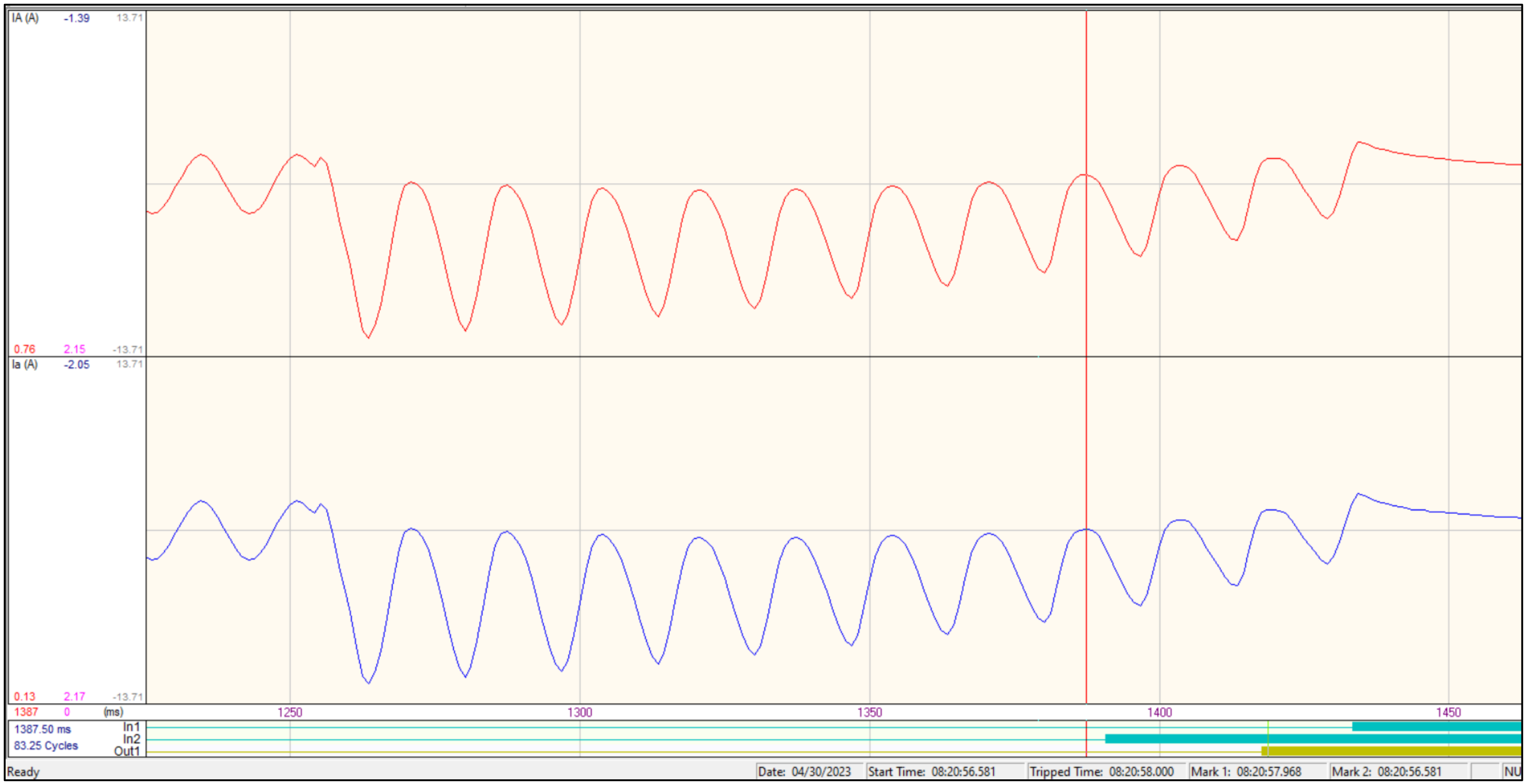
- The A-phase event locus plots slightly above the 4X slope extension portion of the 87 characteristic with the settings that it presently has installed.
- The 4X slope extension is invoked for high DC offset and/or harmonic content so it should have been invoked for this event.

- If the 87 Slope setting would have been set to **15%** (so 4X slope = 60%), then here is how that event when played back would appear i.e. it would have been secure with this slightly higher slope setting:



- The IA and Ia current waveforms both show DC offset current and they both enter saturation from the DC offset at about the same time; however, the rate at which each side comes out of saturation is slightly different:

- Zoomed-in, the rate at which the DC offset decayed on each side is slightly different thus causing the 87 trip.
- The CTs on each side did not saturate evenly with respect to time i.e. they did not come out of saturation at the same rate.



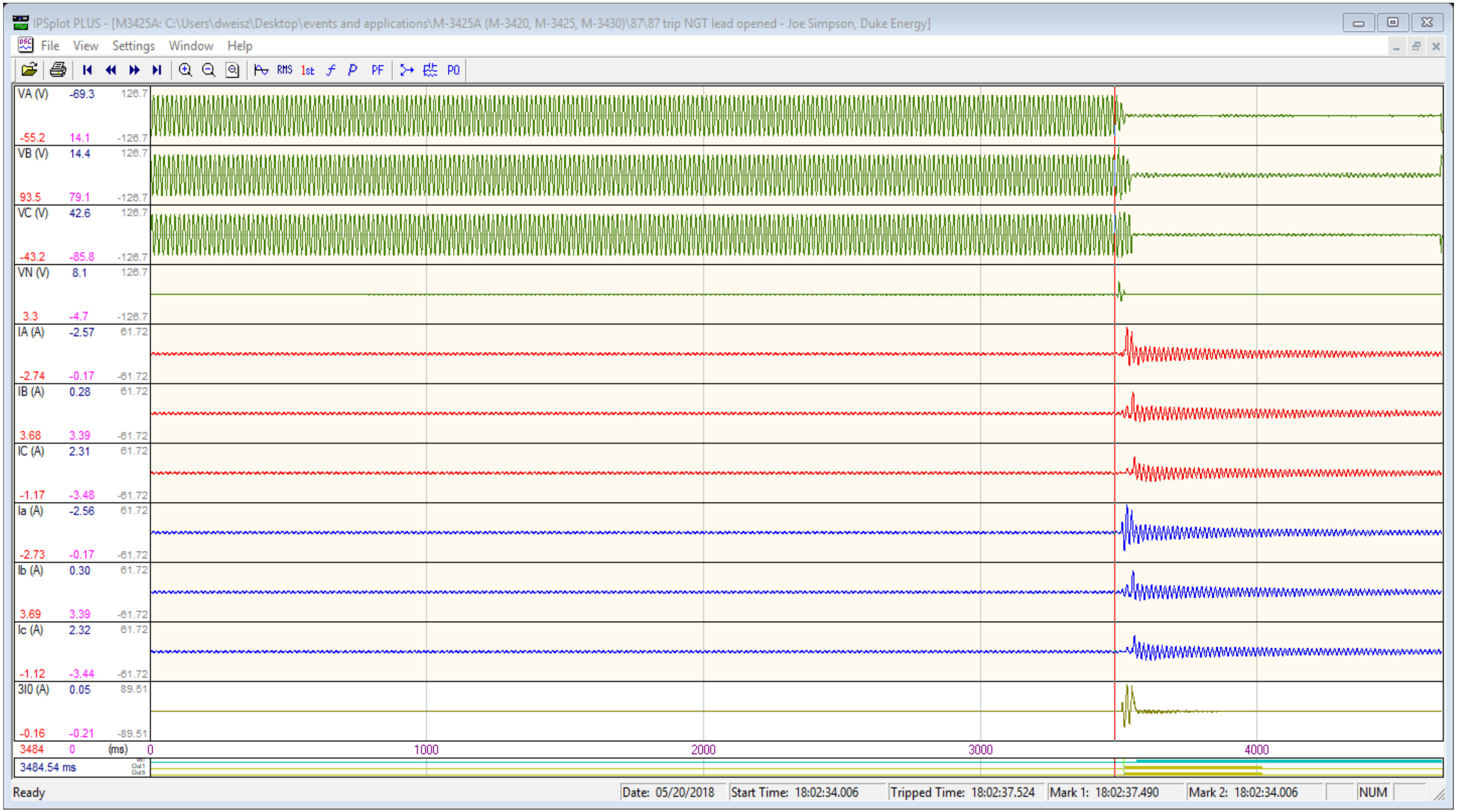
- If the CTs on each side enter saturation and come out of saturation at the same time, then the 87 algorithm would have correctly restrained for this external event.

87 Event 2 Conclusion

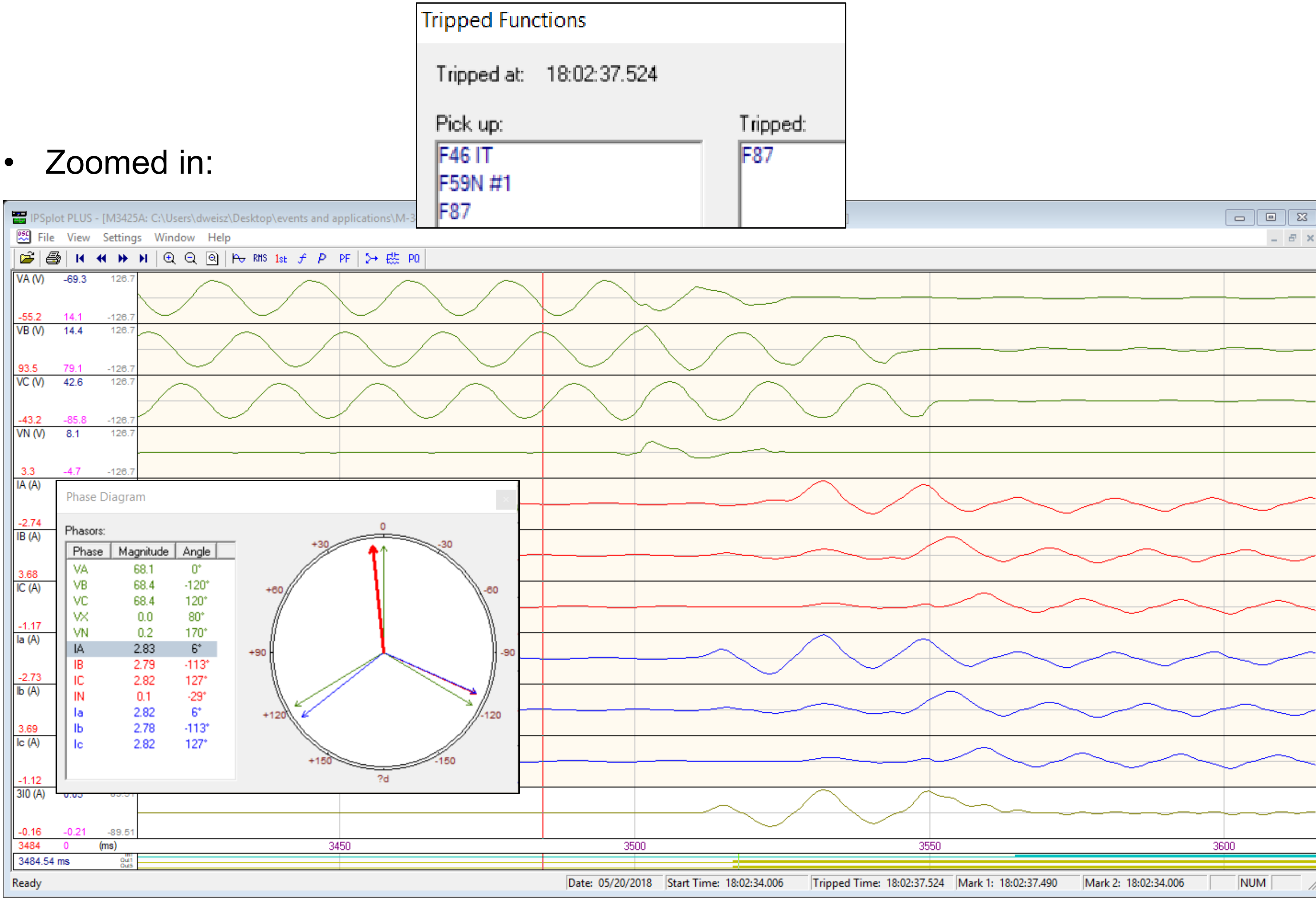
- Cause: CT saturation performance mismatch.
- Remedy 1: Address CT saturation performance mismatch – perform CT saturation calculations, look at burdens on each side, CT class on each side, CT knee point voltage on each side, CT secondary winding resistance on each side, CT cable length and wire gauge used on each side, etc.
- Remedy 2: Because correcting CT saturation performance mismatch is not trivial for existing installations, the situation is instead remedied via desensitizing 87 element settings: Pickup, Slope, and or time delay.
- Time delay could be increased to ride thru this mismatched CT saturation performance in addition to or instead of increasing the slope setting.
- However, for true internal faults, additional time delay is undesirable so the slope increase solution could be preferrable in this case.
- Prevent any future out of phase closures in the first place by addressing the cause whether it was wiring, settings, equipment failure, or human error.
- Isync Trip logic could be added for any future out of phase breaker closures.

87 Event 3 Analysis

- Customer reported 87 trip, and that they found the NGT lead had burned open and asked where to look inside the generator to locate the fault.



- Zoomed in:

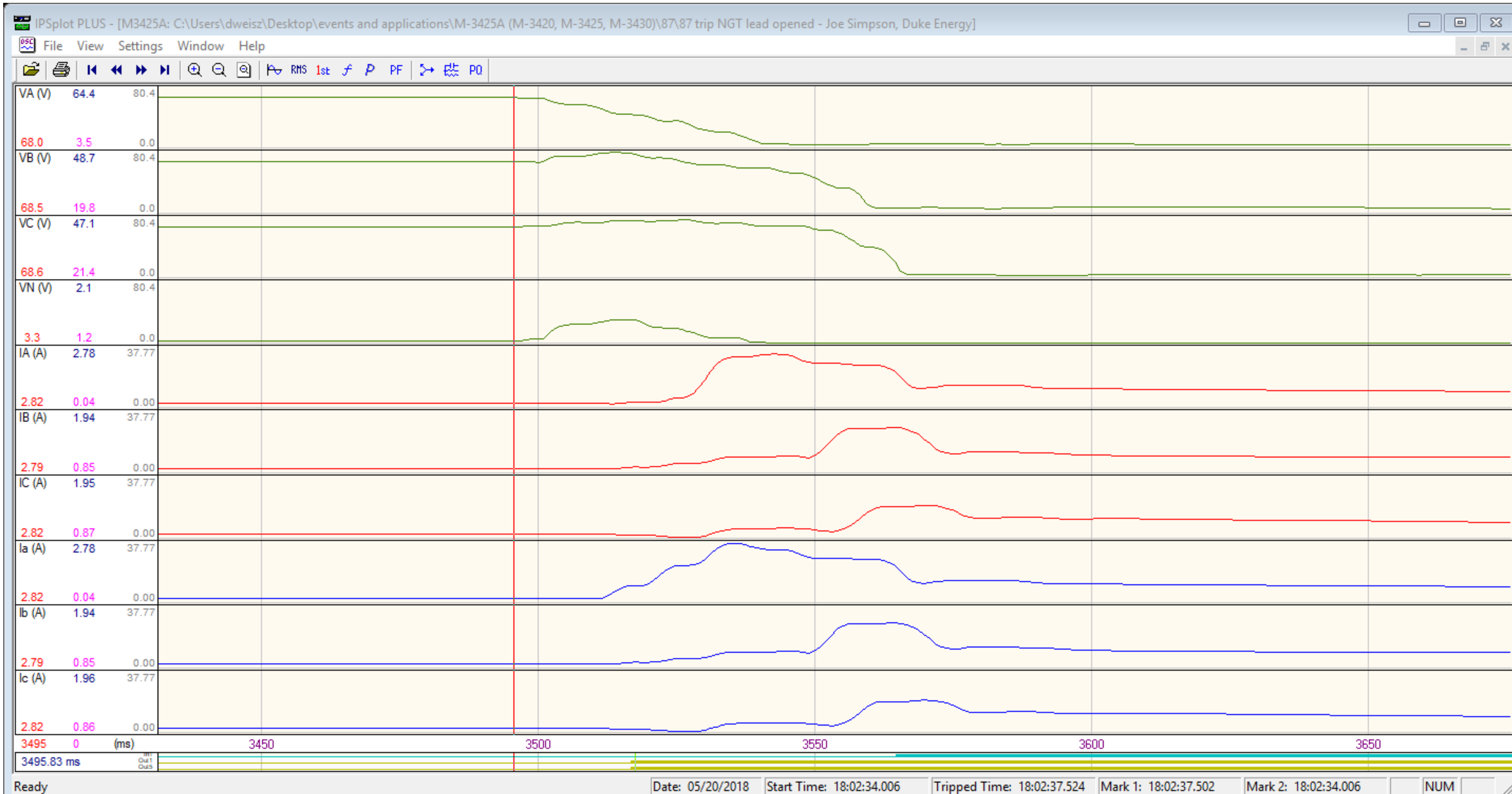


Tripped Functions
Tripped at: 18:02:37.524
Pick up:
F46 IT
F59N #1
F87
Tripped:
F87
File View Settings Window Help
VA (V)
VB (V)
VC (V)
VN (V)
IA (A)
IB (A)
IC (A)
Ia (A)
Ib (A)
Ic (A)
3I0 (A)
Phase Diagram
Phasors:
Phase Magnitude Angle
VA 68.1 0°
VB 68.4 -120°
VC 68.4 120°
VX 0.0 80°
VN 0.2 170°
IA 2.83 6°
IB 2.79 -113°
IC 2.82 127°
IN 0.1 -29°
Ia 2.82 6°
Ib 2.78 -113°
Ic 2.82 127°
3450
3500
3550
3600
3484.54 ms
Ready
Date: 05/20/2018
Start Time: 18:02:34.006
Tripped Time: 18:02:37.524
Mark 1: 18:02:37.490
Mark 2: 18:02:34.006
NUM

22 msec prior to the outputs asserting, the voltages start trending as follows:

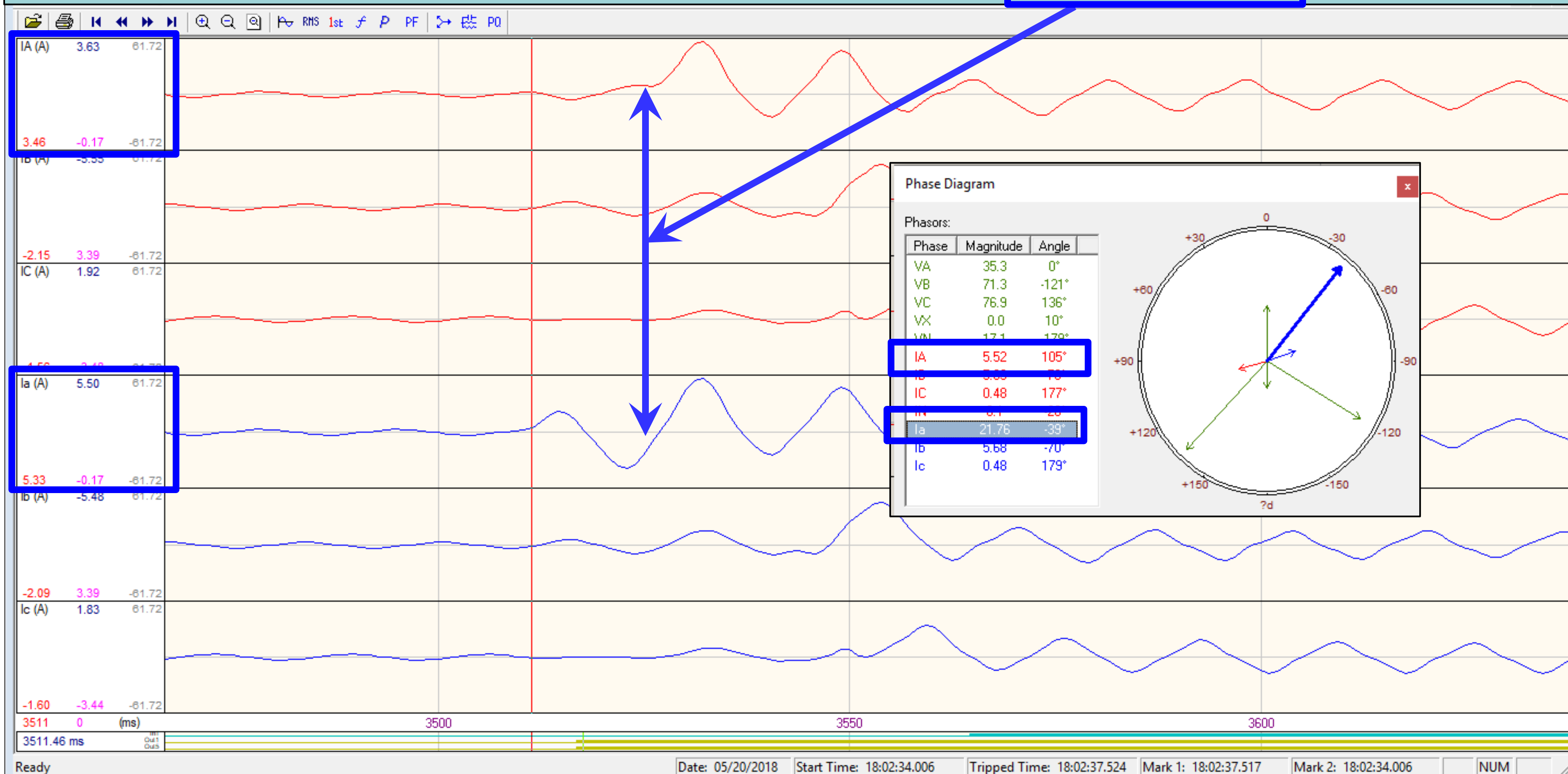
- VA started to decrease
- VB, VC, VN started to increase

This is consistent with the neutral shift that is seen on high impedance grounded systems where the faulted phase decreases and the other 2 phases increase as well as the ground voltage.

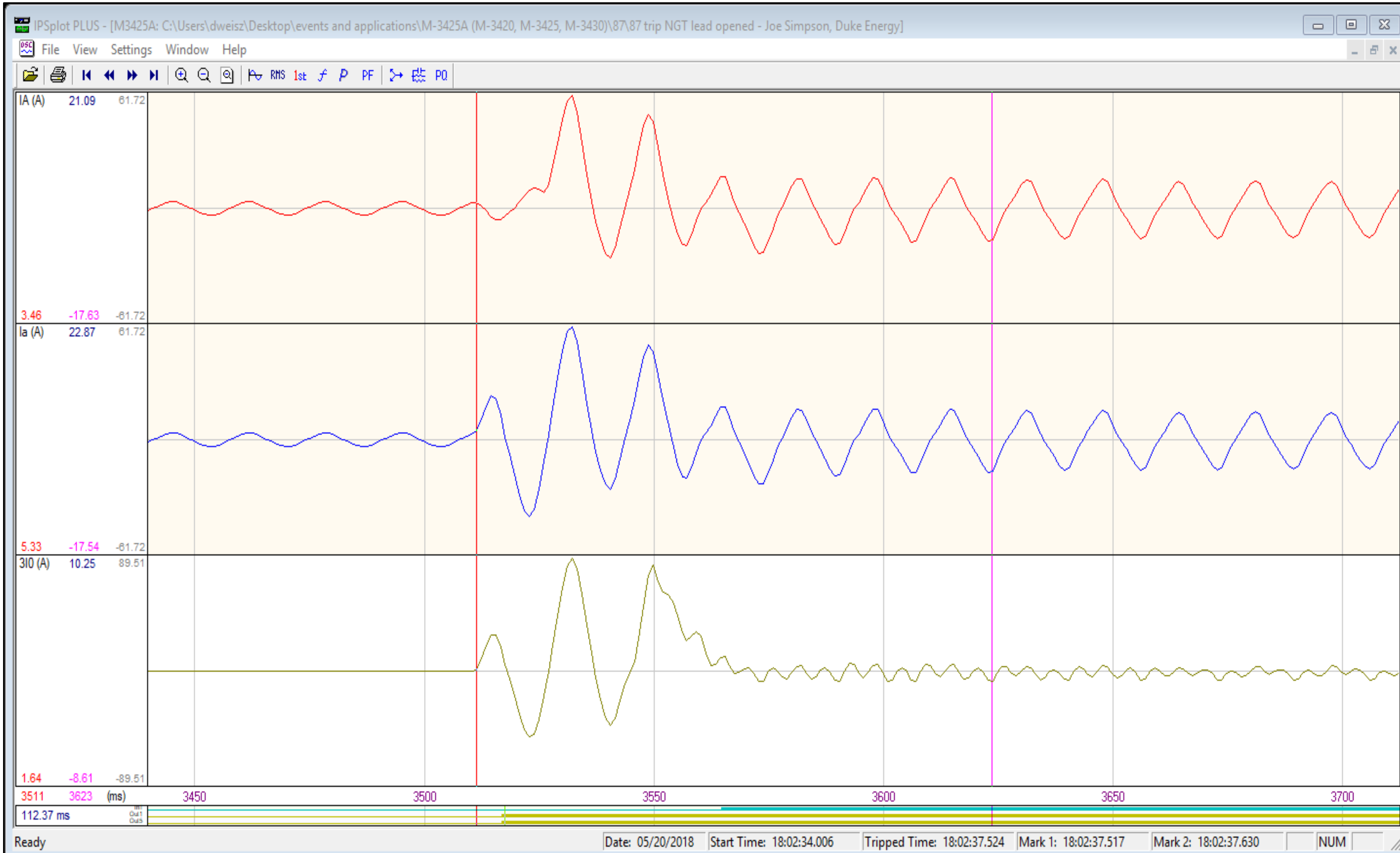


- 6 msec later, the measured VN value equaled 13.8 V, exceeding the 59N Pickup setting of 6.5 V.   This started to increment the 59N timer. But with the time delay set at 60 cycles, this 59N function never timed out as 87 would trip first.

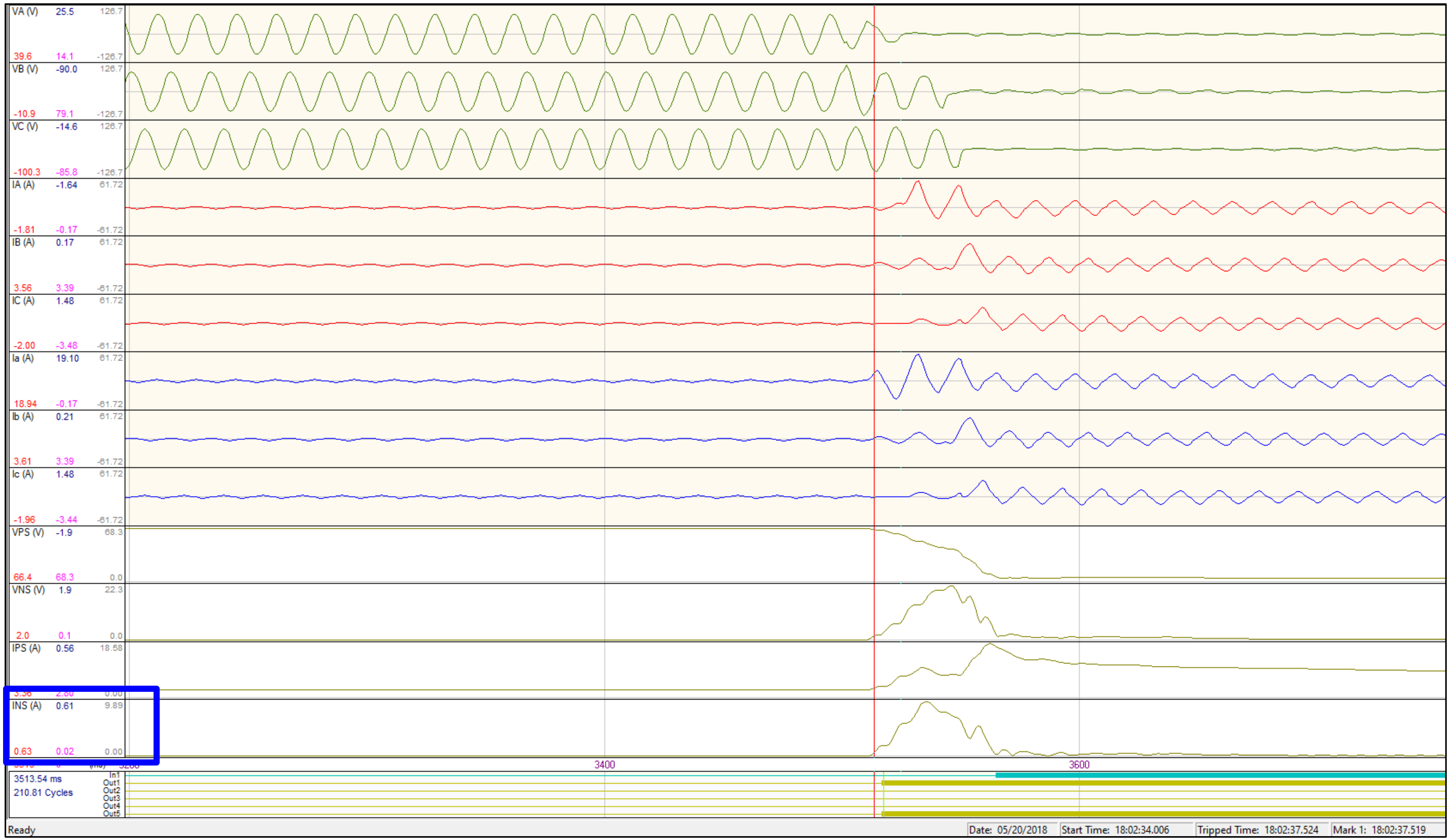
- 9 msec later or 15 msec after fault inception, the measured current begins to deviate from the pre-fault values and the calculated differential current on A-phase (Ia - IA = 5.33 - 3.46 = 1.87 A) first exceeds the 87 Pickup setting of 0.20 A. Specifically, Ia, the a-phase current measured on the neutral side of the generator is the first current to begin to deviate.
    - This is where the NGT failed and became a short circuit, solidly grounding the machine.
    - a-phase current goes from thru load current, to an internal fault i.e. Ia and IA go from being in-phase with each other to being approximately 180° out of phase



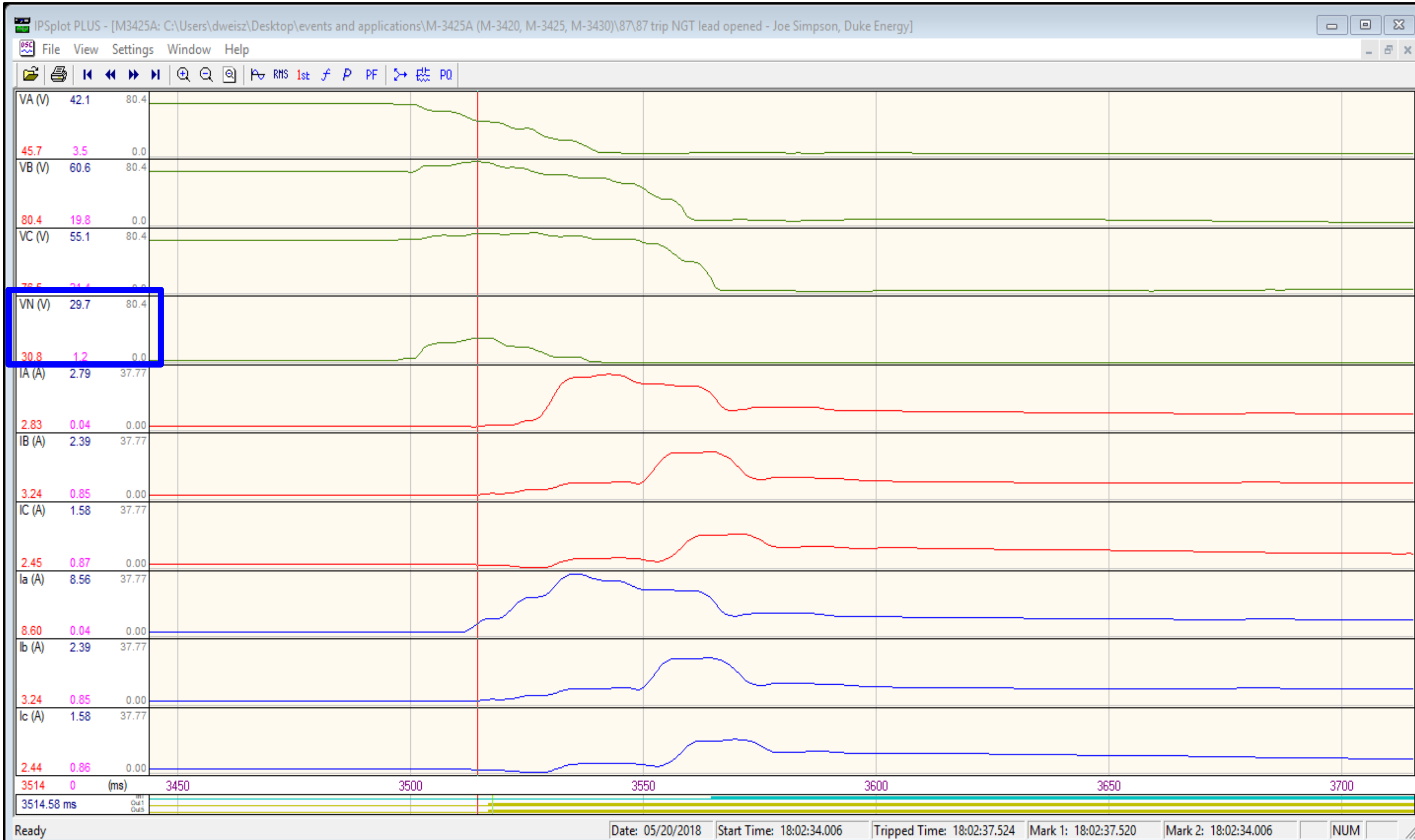
3Io is also seen at this sample point for the first time (the displayed 3Io tracing is calculated from Ia+Ib+Ic) and 3Io is in phase with Ia:



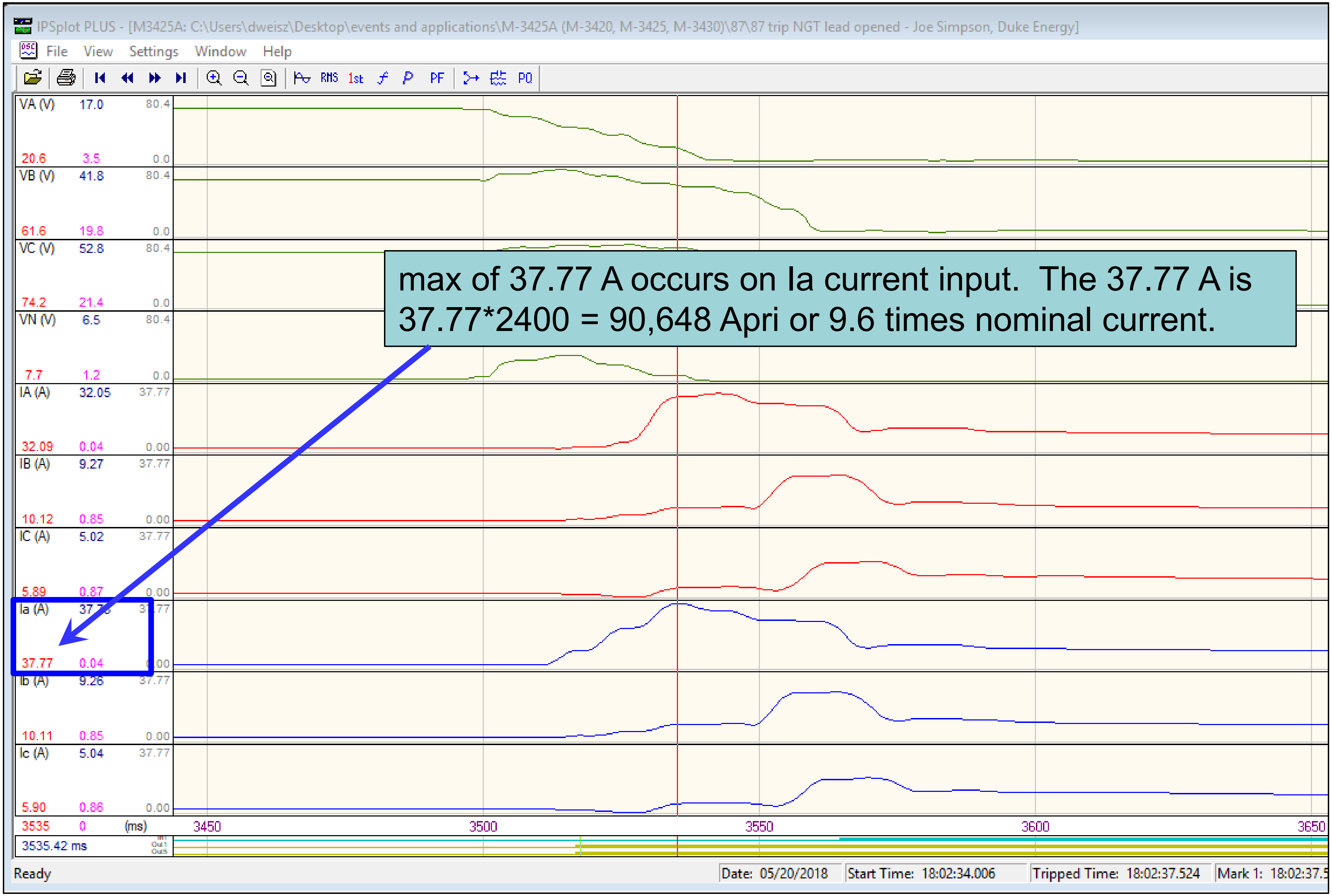
2 msec later or 17 msec after fault inception, the measured negative sequence current equaled 0.63 A, exceeding the 46IT Pickup setting of 0.314 A (8% of Inom). 46IT started to time, but it did not time out as the 87 function would trip first.



1 msec later or 18 msec after fault inception, the peak VN value is measured at 30.8 V, which is 24% of the 129.8 V. **This indicates a fault location of 24% of the stator winding from the neutral end.**



- 2 msec later or 20 msec after fault inception, Outputs 1 and 5 are activated by the 87 function.
- This is 5 msec after the current first exceeds the 87 Pickup setting.


IPSplot PLUS - [M3425A: C:\Users\dweisz\Desktop\events and applications\M-3425A (M-3420, M-3425, M-3430)\87\87 trip NGT lead opened - Joe Simpson, Duke Energy]
File View Settings Window Help
max of 37.77 A occurs on Ia current input. The 37.77 A is 37.77*2400 = 90,648 Apri or 9.6 times nominal current.
VA (V) 17.0 80.4 20.6 3.5 0.0
VB (V) 41.8 80.4 61.6 19.8 0.0
VC (V) 52.8 80.4 74.2 21.4 0.0
VN (V) 6.5 80.4 7.7 1.2 0.0
IA (A) 32.05 37.77 32.09 0.04 0.00
IB (A) 9.27 37.77 10.12 0.85 0.00
IC (A) 5.02 37.77 5.89 0.87 0.00
Ia (A) 37.77 0.04
Ib (A) 9.26 37.77 10.11 0.85 0.00
Ic (A) 5.04 37.77 5.90 0.86 0.00
3535 0 (ms) 3450 3500 3550 3600 3650
3535.42 ms
Ready
Date: 05/20/2018
Start Time: 18:02:34.006
Tripped Time: 18:02:37.524
Mark 1: 18:02:37.5

87 Event 3 Conclusion

- The fault started as an AG internal fault at about 24% of the stator winding from the neutral end **(fault was found at 25%).**

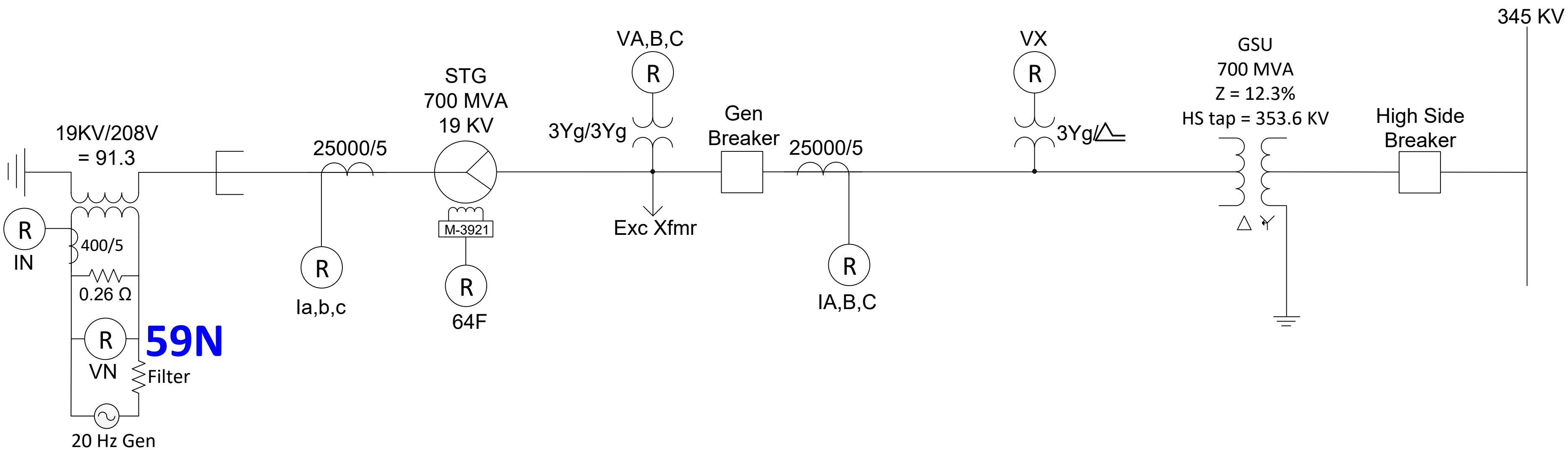
- The measured high current values (up to 90 KA) on this high-impedance grounded machine, indicates that the high impedance grounding network was compromised. This failure resulted in the NGT looking like a short circuit, thus making this high-impedance grounded machine appear as a solidly grounded machine with the accompanying very high fault current values.

- As an open lead was detected to the NGT in the post fault investigation, this likely indicates that the lead burned open only after having been shorted.

- The 87 function detected the fault and tripped very quickly, but with the machine’s field decay time constants and with all the stored inertia from the rotational energy, the fault current did not extinguish immediately.

- After the NGT was shorted, the fault briefly still looked like an internal AG fault before evolving into an external AG fault at the terminal end. It eventually involved B-phase and then C-phase making it into a three phase-to-ground fault.

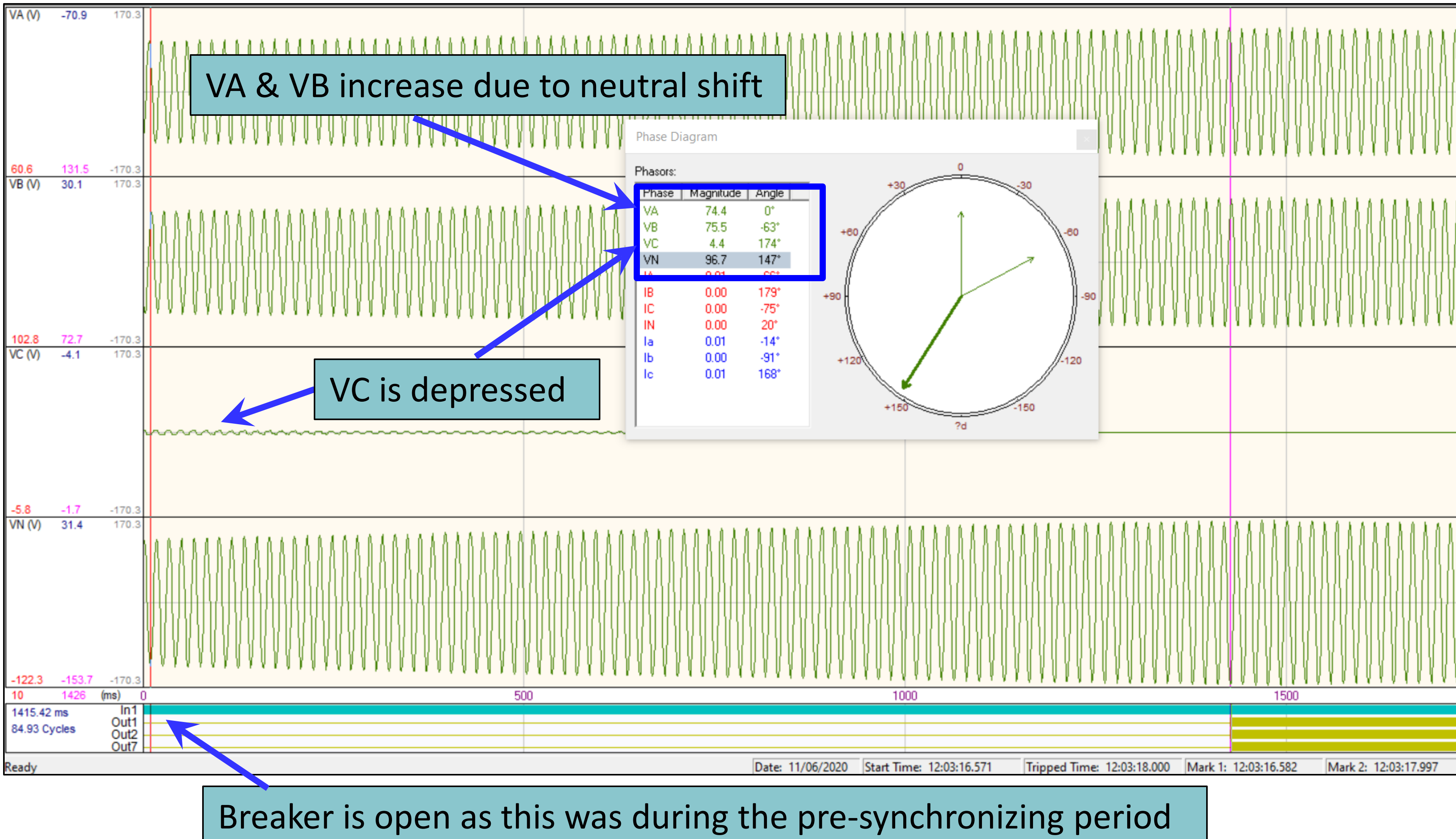
59N – Neutral Overvoltage (aka 64G, 59G)



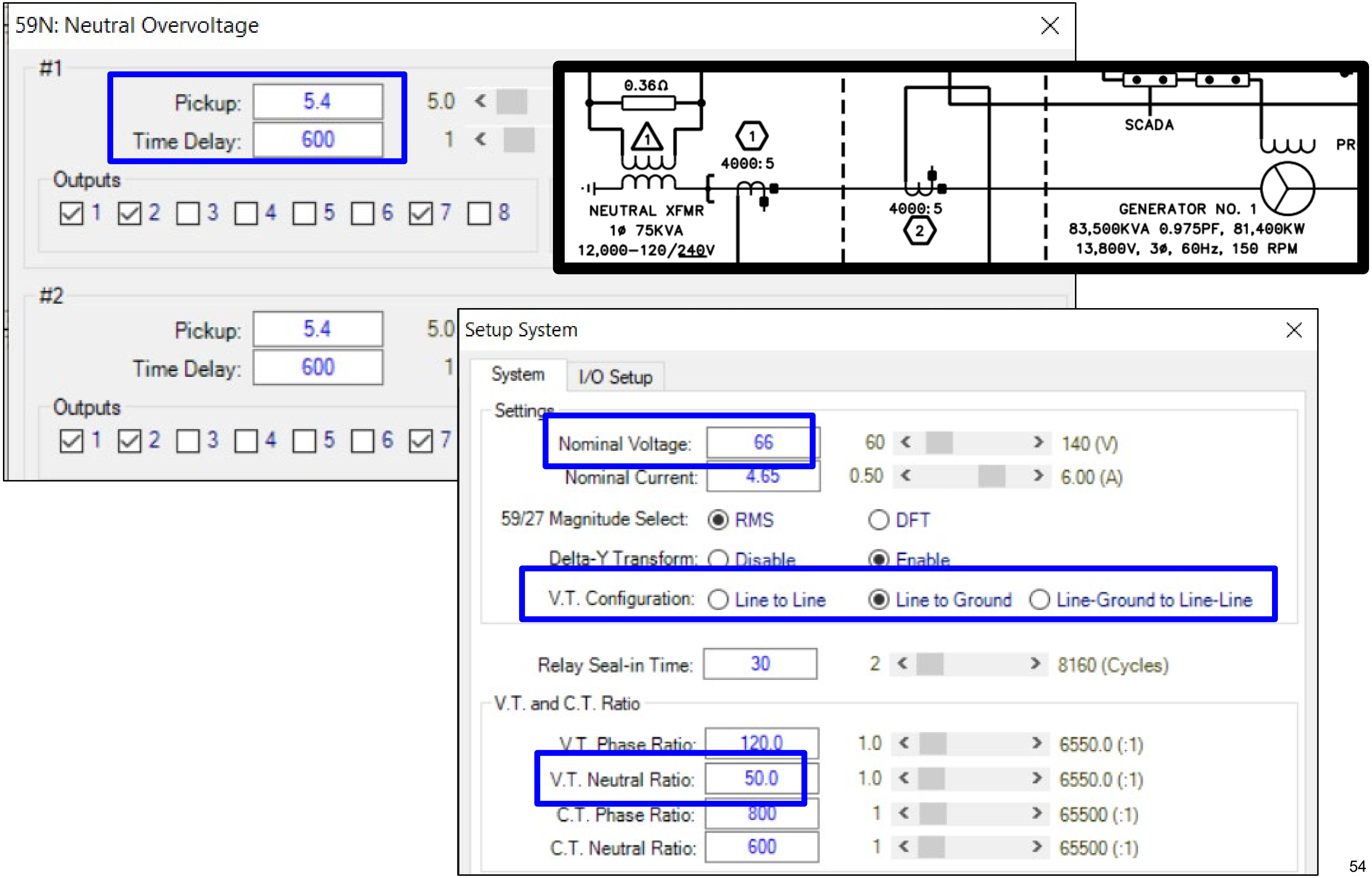
- **59N #1 – 95% stator ground fault protection**

59N Event Analysis – Event 1

- Customer reported 59N trip during startup:



- Let’s look at the applicable relay settings and a portion of the 1-line:



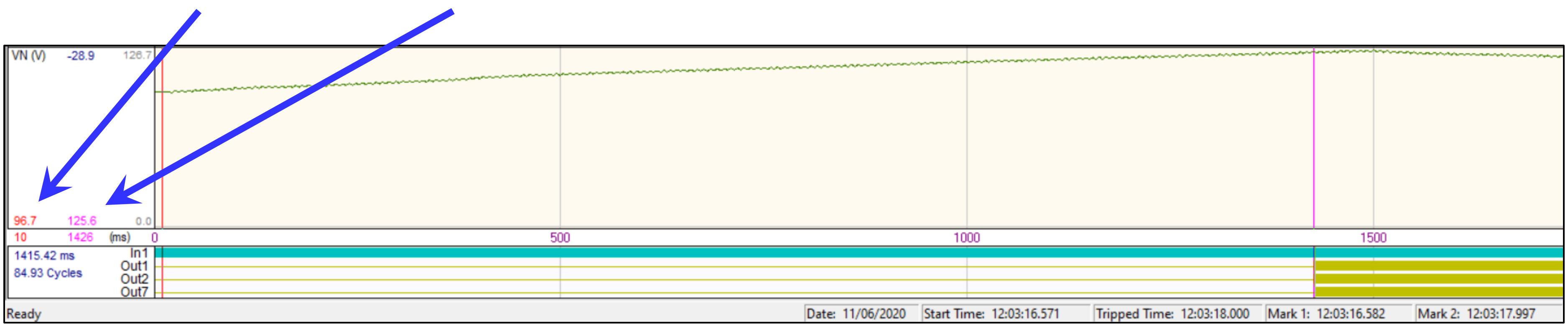
- We want to find out where in the stator winding the fault may be located so we know where to start looking.

- For a ΦG fault at 100% of the stator (at the terminal end of the stator winding), the voltage measured at the VN voltage input will be:

$$V_N = \frac{V_{LG}}{N} = \frac{13800}{\sqrt{3} * 50} = 159 \ \text{sec volts}$$

- What did the fundamental component of the VN waveform measure before the outputs asserted?

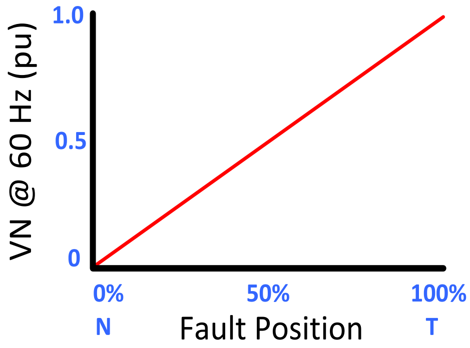
- From 96.7 V up to 125.6 V:



- What percentage of a fault at the terminal end of the stator winding are these VN voltages?

$$\frac{96.7}{159} * 100 = 61\%$$

$$\frac{125.6}{159} * 100 = 79\%$$



<u>Several factors may make this calculated fault location inaccurate:</u>

- Ignoring NGT impedance
- Fault resistance
- Startup/Shutdown – If the fault occurs during startup before the voltage has built up to 100%, then the measured VN voltage will be a percentage of whatever the voltage had been at the time of the trip – here we do not have enough pre-fault info to know exactly what the voltage had built up to.

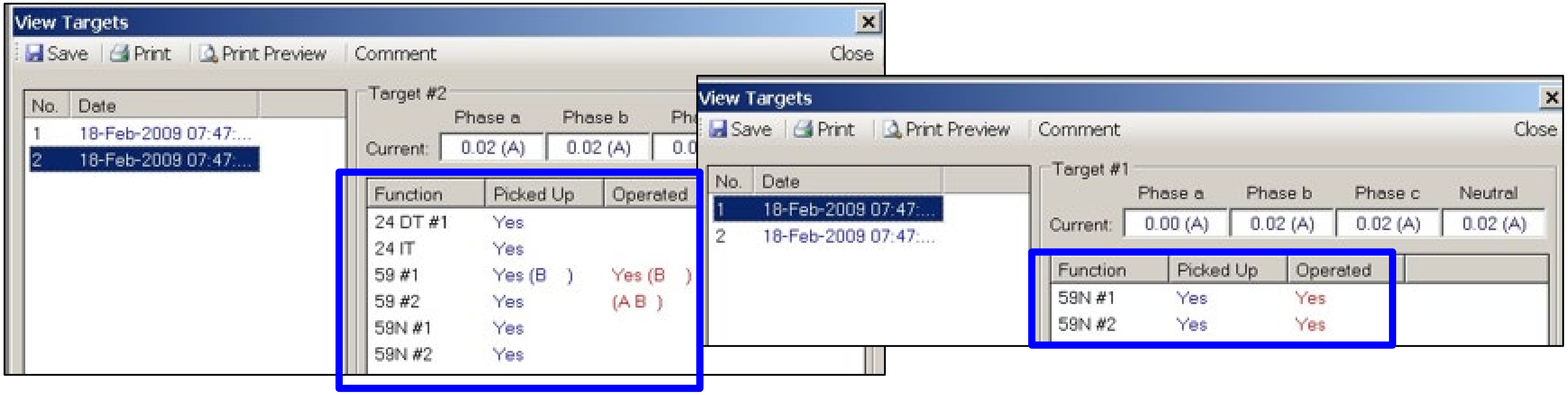
59N Event 1 Conclusion

- Customer reported finding a shorted coil to ground on C phase located at about 70% from the neutral end.

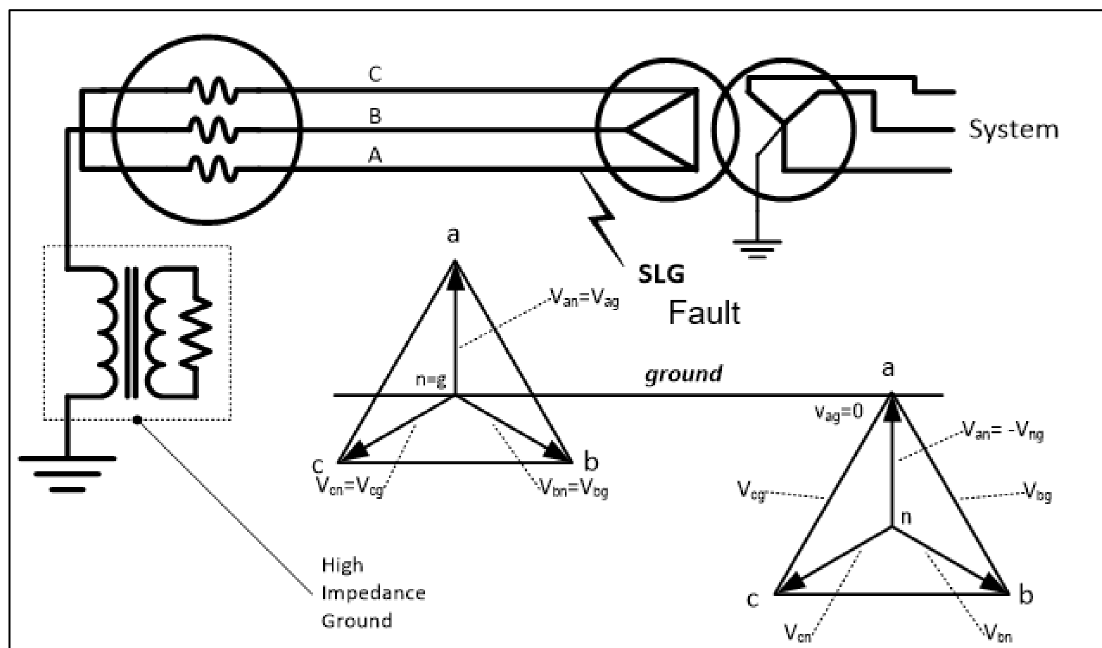
<u>Recommendations to customer:</u>

- Could put some discrimination between 59N #1 and #2 elements.
- A much shorter 59N time delay may be OK if the GSU high side relaying time to clear for ground faults on the high side of the GSU is known.
- If a newer relay is installed, then some of the 59N accelerated tripping schemes could be employed.
- Also, 64S could be added which would have detected this fault while still off-line i.e., even before the field was applied.

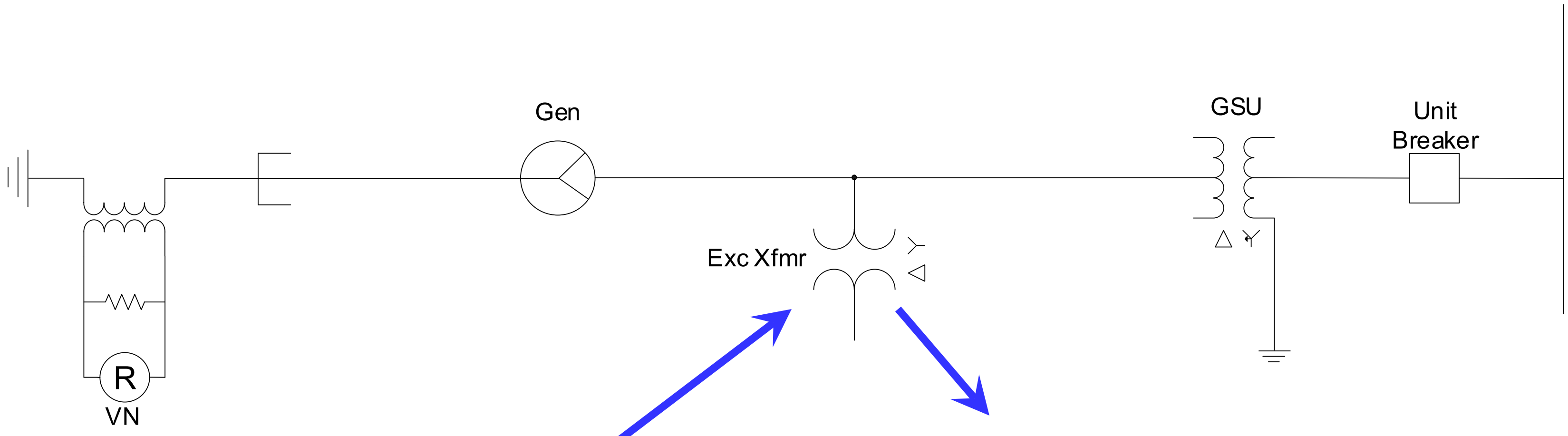
- Why were some 24 and 59 elements asserting just prior to the 59N trip?



- This is because of the neutral shift from ΦG fault on a high-impedance grounded gen.
- This can confuse and prolong the post-event investigation.
- It can be avoided by setting VT Config = LG-LL (and then all voltage-based settings must be set based on LL values).

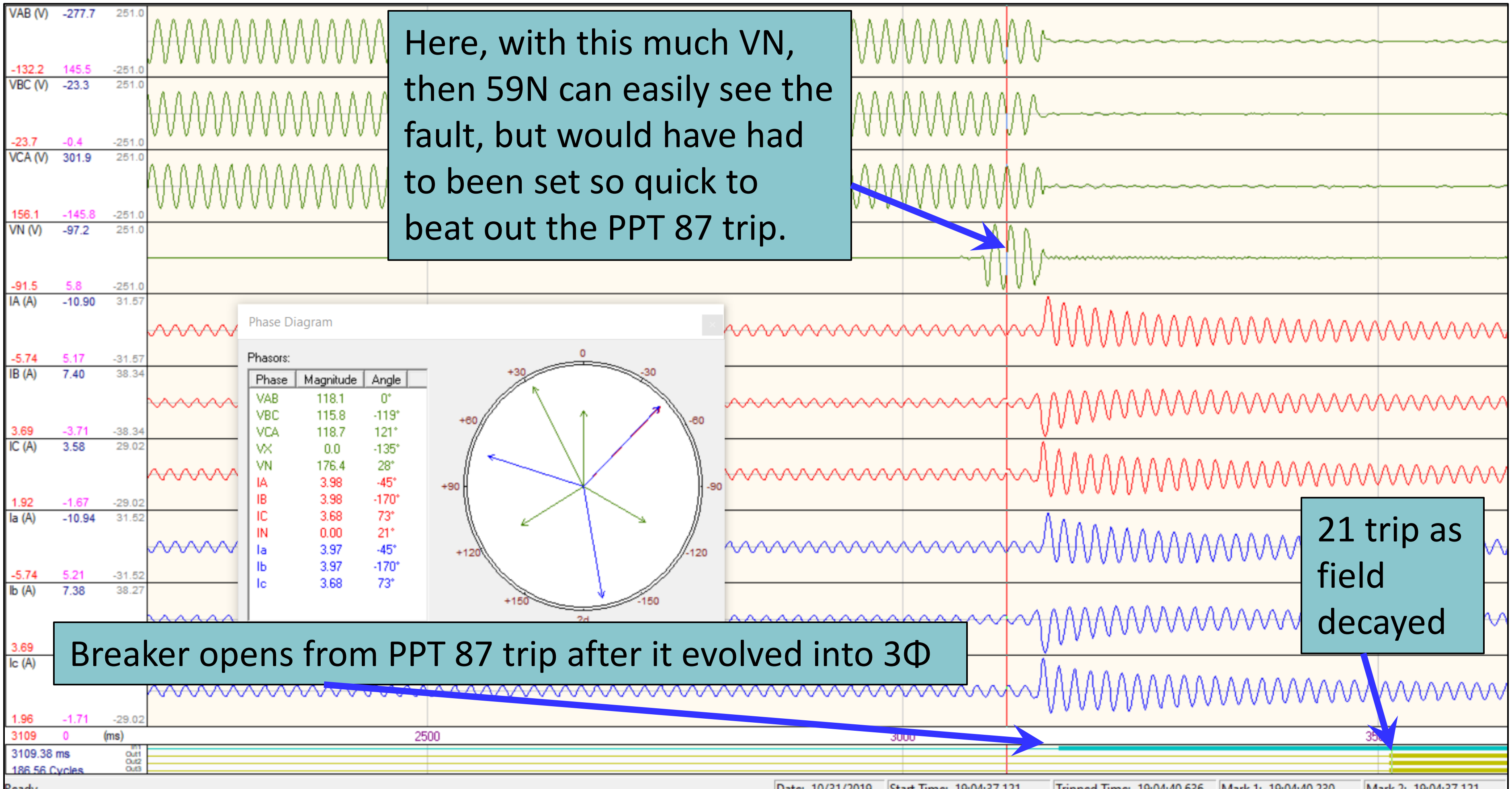


59N Event Analysis – Event 2



- Customer reported PPT failure:
- Asked why the 59N function sourced from the VN voltage input did not detect it.
- Also, asked what phase it started on?

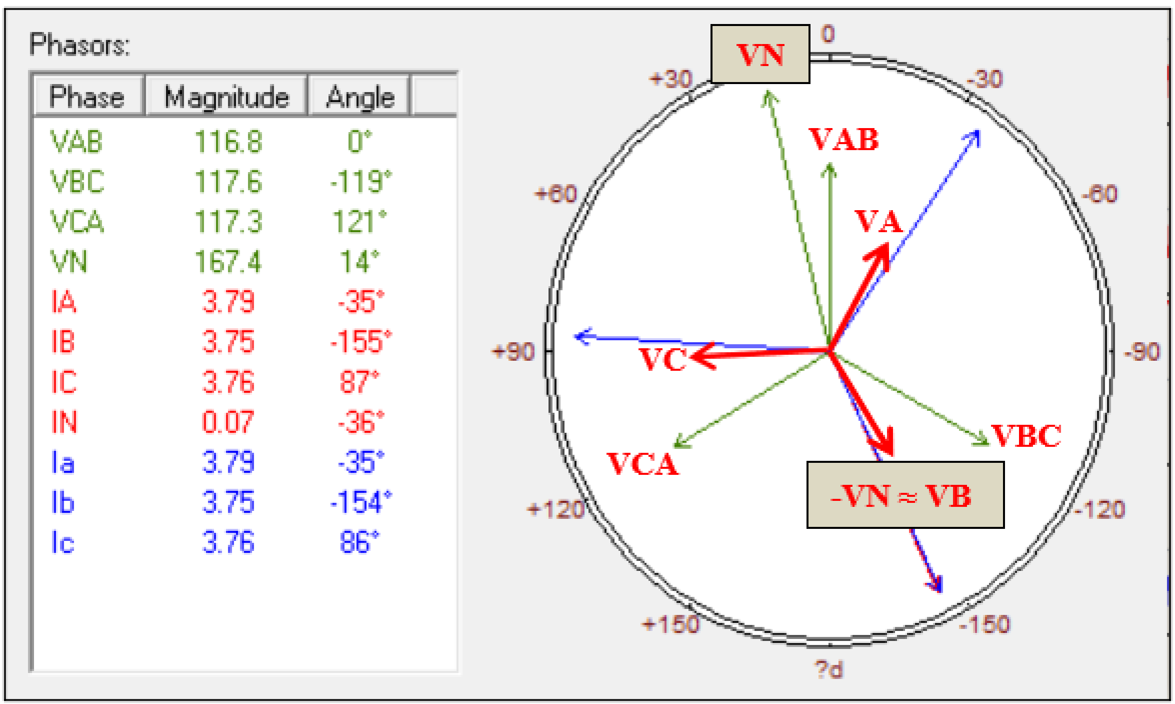
- 87 relay around the PPT issued the initial trip.
- But prior to that, there was a very low level VN measured of 4.1 V.
- The minimum setting range on most relay mfg's 59N/59G/64G elements is 5 V, so it could not see this low level, incipient ground fault initially.



- ***To address the question of what phase it started on:***

- ***When VT Configuration = LL the oscillography will show LL voltages, therefore identifying the faulted phase from a LG fault may not be readily apparent.***

- ***However, as VN will be 180 ° from the faulted phase of a LG fault, the VN vector can be rotated by 180 ° using the phasor diagram and that position should approximately match the phase angle of the faulted phase.***



- When VN did jump from that low level value of 4.1 V up to its max it saw of 176.7 V, what does that say about the fault location?

$$V_N = \frac{V_{LG}}{N} = \frac{20000}{\sqrt{3} * 60} = 192 \text{ sec volts}$$

$$\frac{176.7}{192} * 100 = 92\%$$

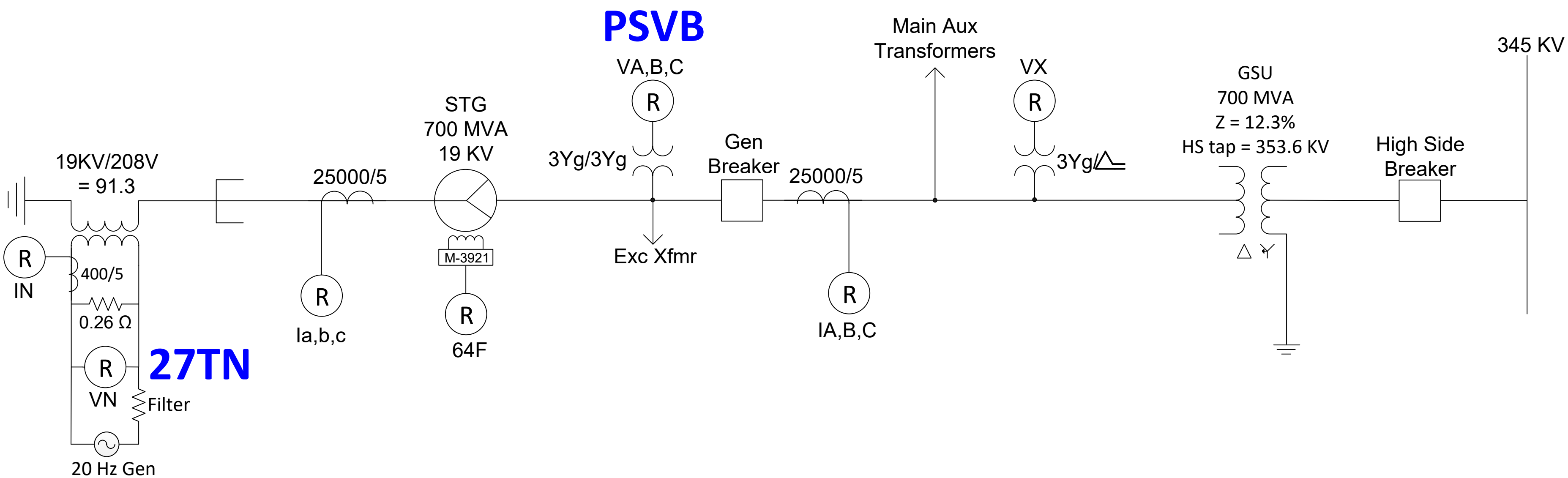
- In this case, of course we know the fault location was outside the stator.
- And with the resistance in the fault, it made a fault that was located outside the generator stator winding terminal side, look as though it were just barely inside the stator or just 8% from the terminal end.
- But anytime the fault location calculates to this high in the stator, it may be wise to first suspect or outside the stator as that area is easier to test.

59N Event 2 Conclusion

- Since 59N could not have been set sensitive enough to see the initial low-level ground, customer asked if 64S had been installed could it have seen it?
- That 4.1 V at VN calculated out to a ΦG fault with 40,346 Ω resistance in it.
- Because that high of a resistance is very close to what we consider to be a healthy insulation resistance of 50 KΩ to 100 KΩ, therefore it is hard to discriminate between normal conditions and this fault condition.
- For example, modelling 40 KΩ vs 50 KΩ works out to a difference of only 0.5 mA which is usually not enough margin to set a secure 64S setting, but if they wanted to accept a slightly insecure 64S setting then maybe they could have set such a sensitive setting that could have detected this incipient fault before it evolved and ended in catastrophic failure.
- If their PPT 87 relay would have tripped the unit breaker directly rather than first tripping an LOR which then tripped the breaker, they would have saved just a little bit of damage but still likely not repairable.

27TN – Third Harmonic Neutral Undervoltage

- IEEE identifies as 27TH
- may be referred to as 100% Stator Ground Protection
  - *Not technically true, but with 59N then yes 100%*

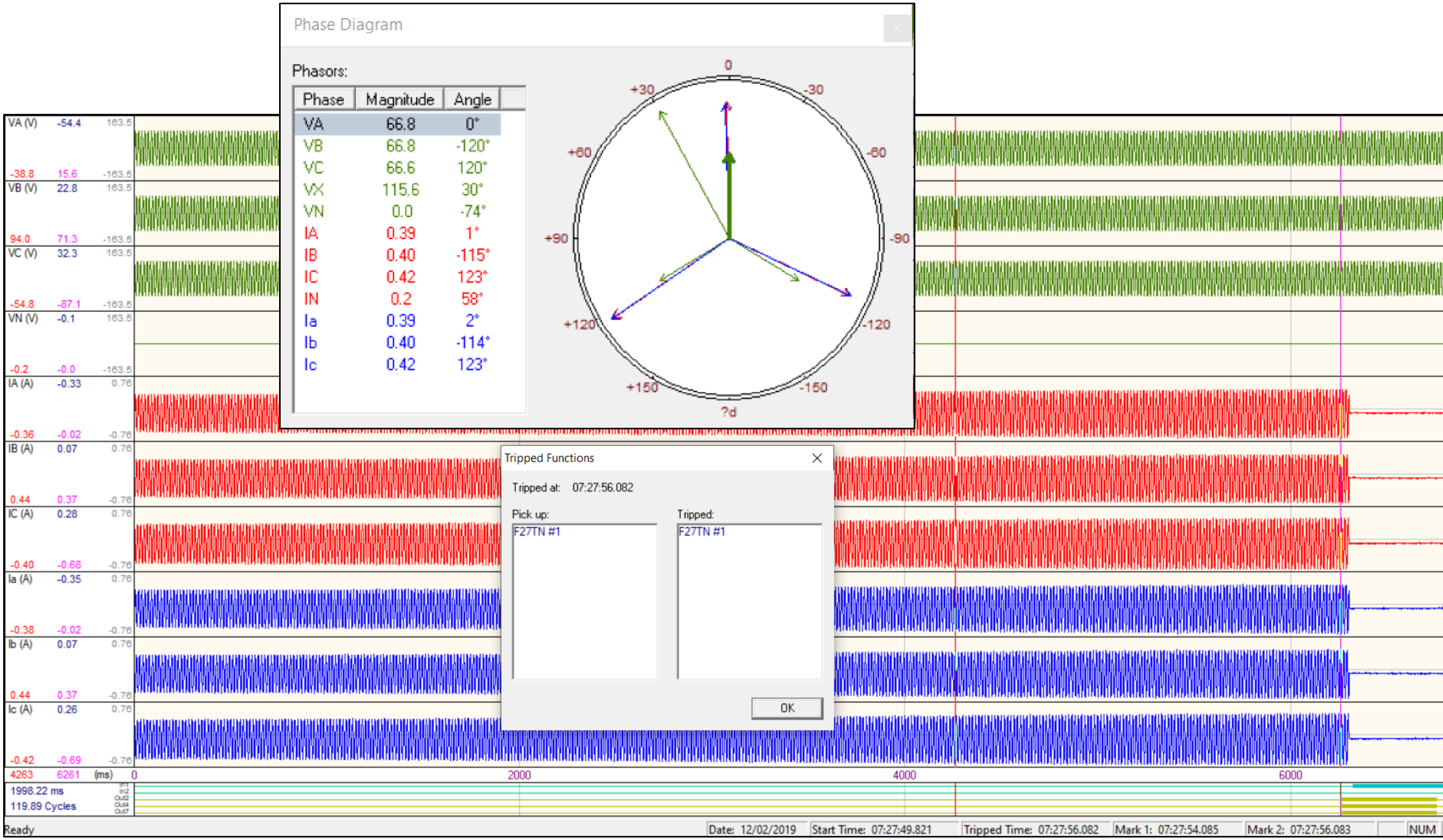


Blocking Inputs = FL, 1, 6

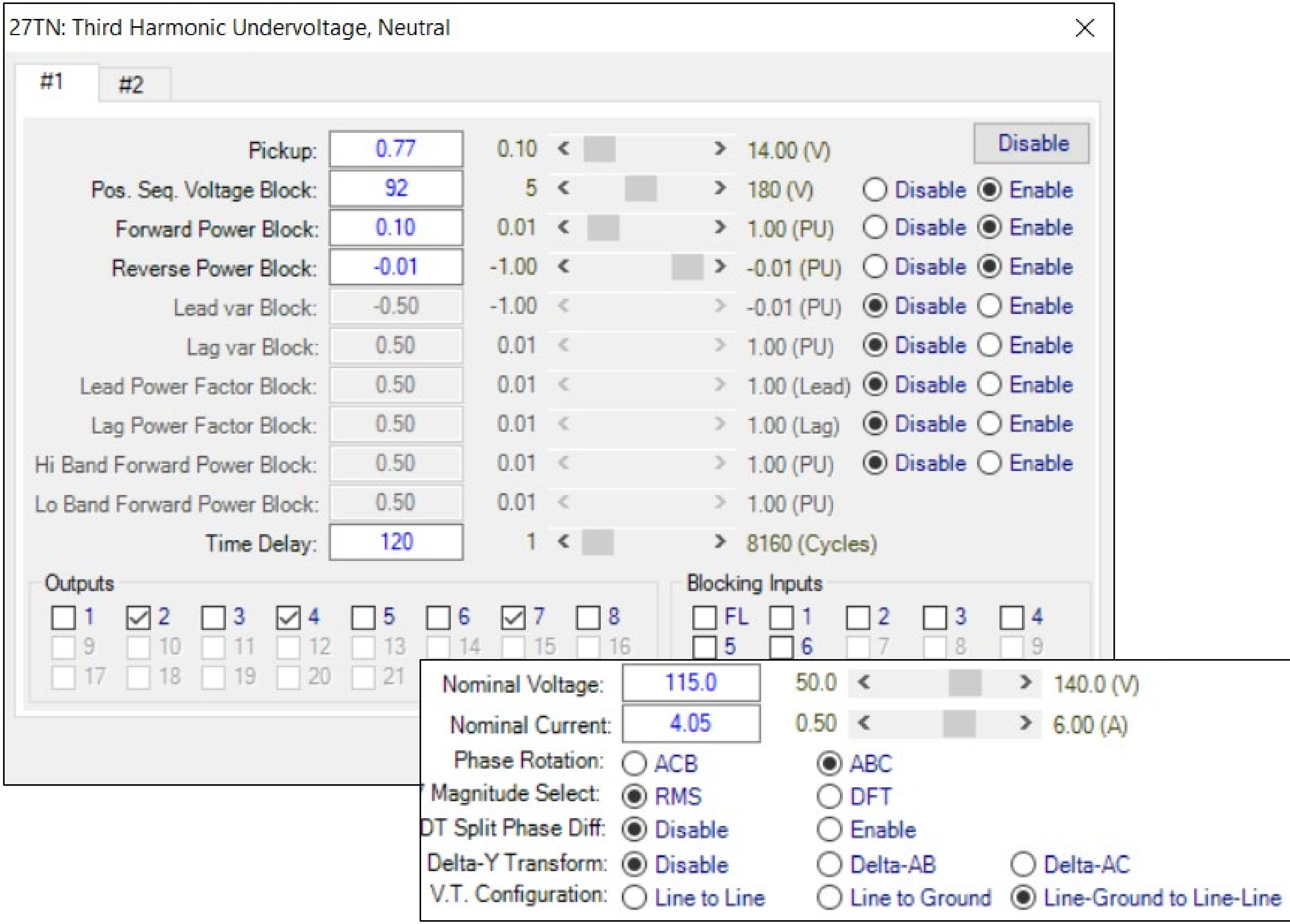
Input 6 is from 64S 20 Hz generator self-diagnostic alarm such that 27TN will be enabled when 64S is out of service.

27TN Event Analysis

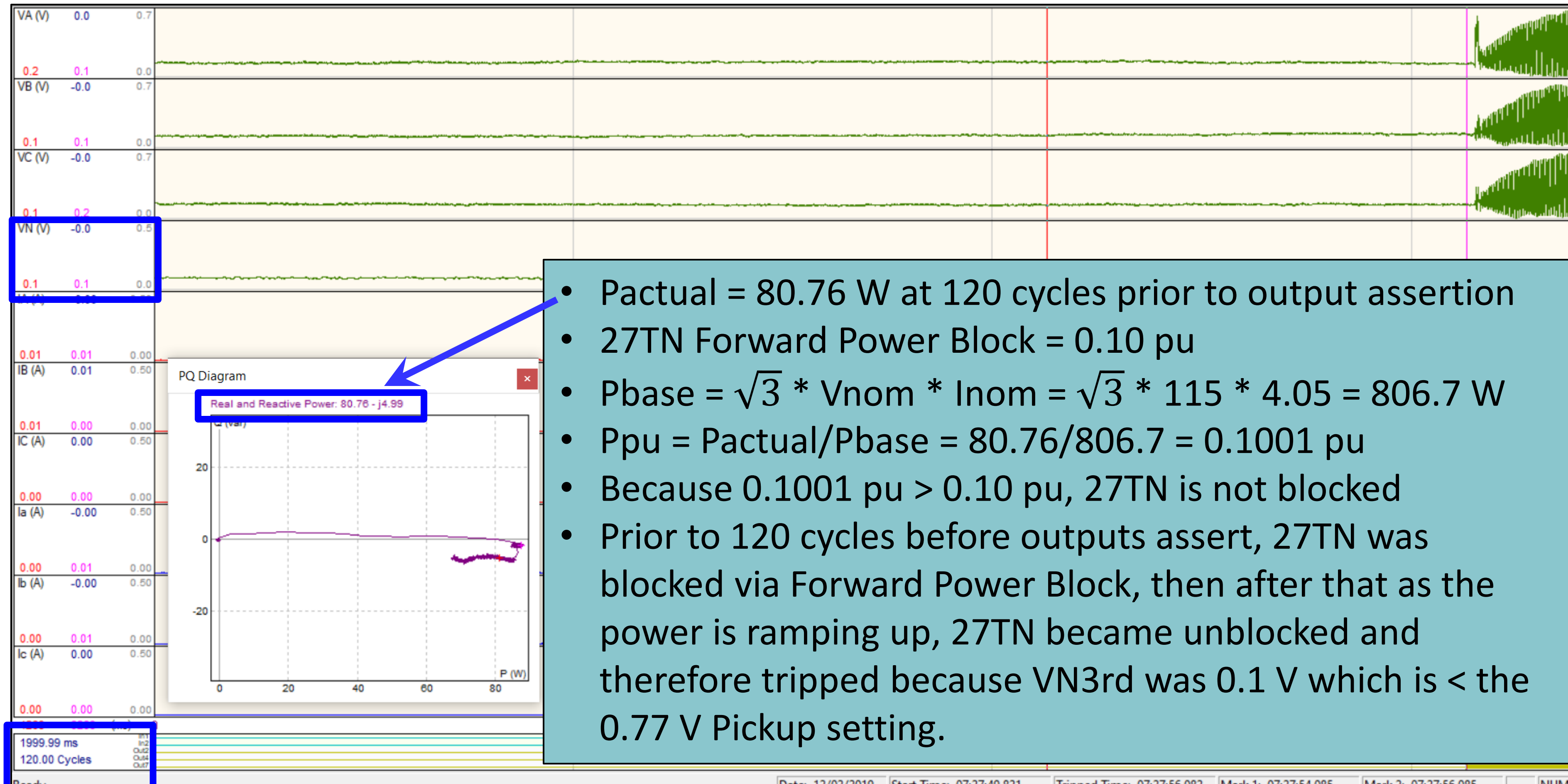
- Customer reported 27TN trip after unit synced on-line and as it was ramping up:



- Customer provided relay setting file in its native format:



- 27TN Time Delay = 120 cycles so placed one cursor at assertion of outputs mapped from the 27TN #1 element and another cursor 120 cycles prior to that.
- Display third harmonic content from tracings: VN3rd = 0.1 V for the entire event.
- Fundamental component of VN = 0 V, so likely not a true fault.

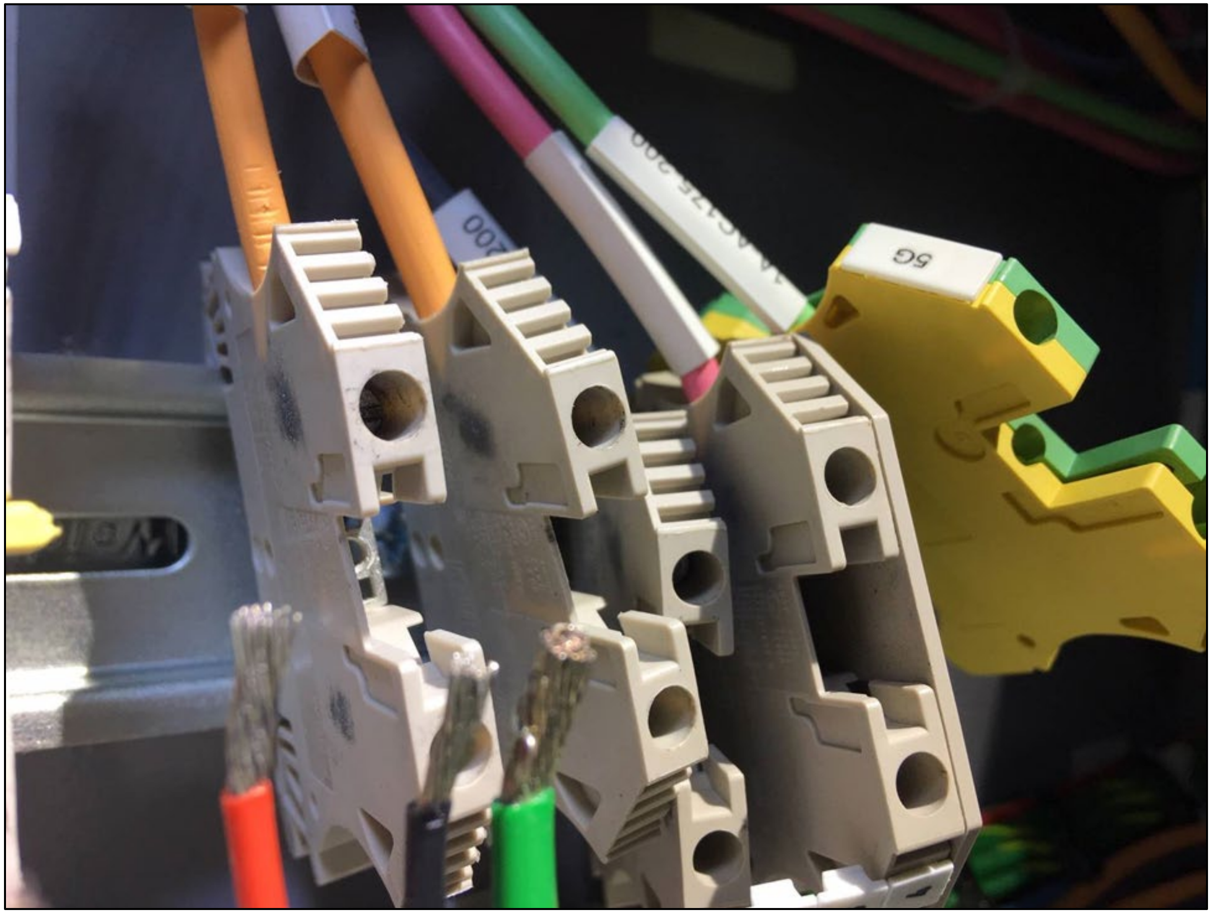


- Pactual = 80.76 W at 120 cycles prior to output assertion
- 27TN Forward Power Block = 0.10 pu
- Pbase = $\sqrt{3}$ * Vnom * Inom = $\sqrt{3}$ * 115 * 4.05 = 806.7 W
- Ppu = Pactual/Pbase = 80.76/806.7 = 0.1001 pu
- Because 0.1001 pu > 0.10 pu, 27TN is not blocked
- Prior to 120 cycles before outputs assert, 27TN was blocked via Forward Power Block, then after that as the power is ramping up, 27TN became unblocked and therefore tripped because VN3rd was 0.1 V which is < the 0.77 V Pickup setting.

27TN Event Analysis Conclusion

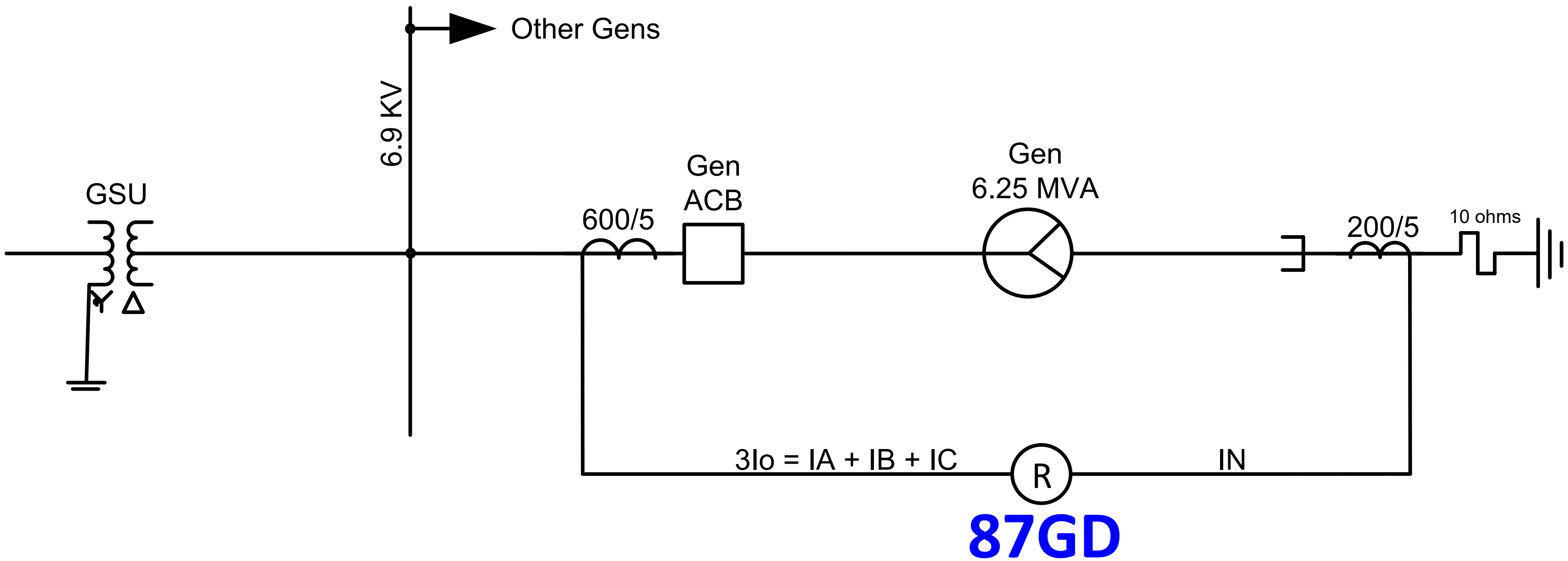
- Customer reported:

“the terminal block had built up enough metal shavings that after it rained, it tracked and shorted to ground the VN signal and therefore also the 3rd harmonic voltage signal at the VN terminal.”



87GD – Ground Directional Overcurrent

- The Zero Sequence Differential function provides ground fault protection for low impedance or solidly grounded machines.

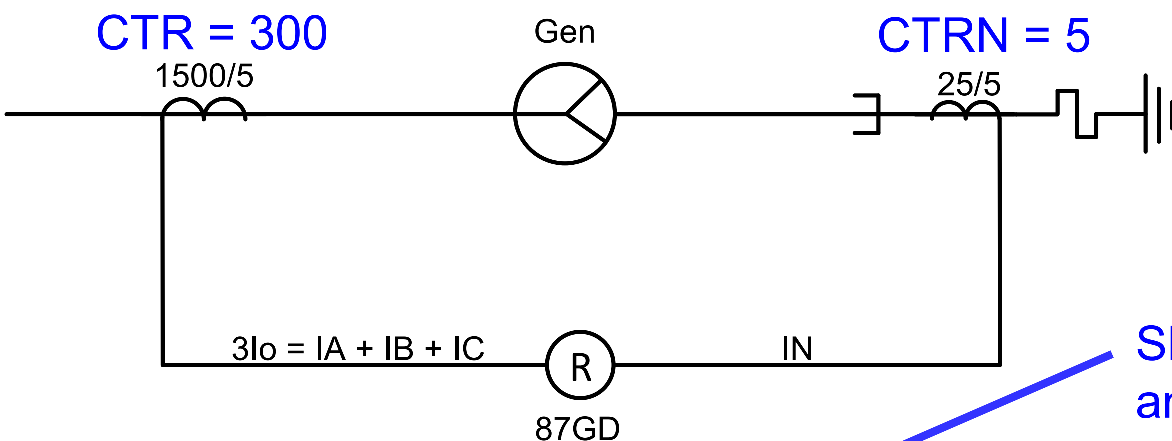


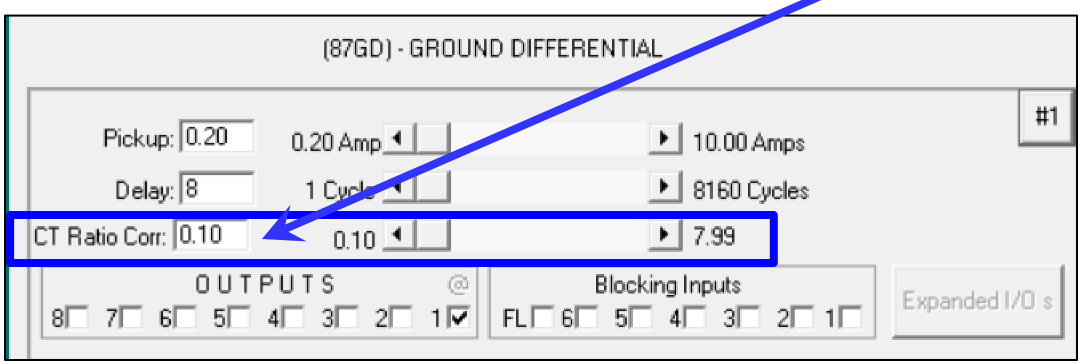
87GD – Event Analysis

<u>Mis-operation due to wrong CT Ratio Correction setting:</u>

87GD – Ground Directional Overcurrent

- First, calculate 3Io from terminal side CTs:
  - ✓ 3Io = IA + IB + IC = 0.077 A
- Because 0.077 A < 0.20 A, directional supervision is disabled.





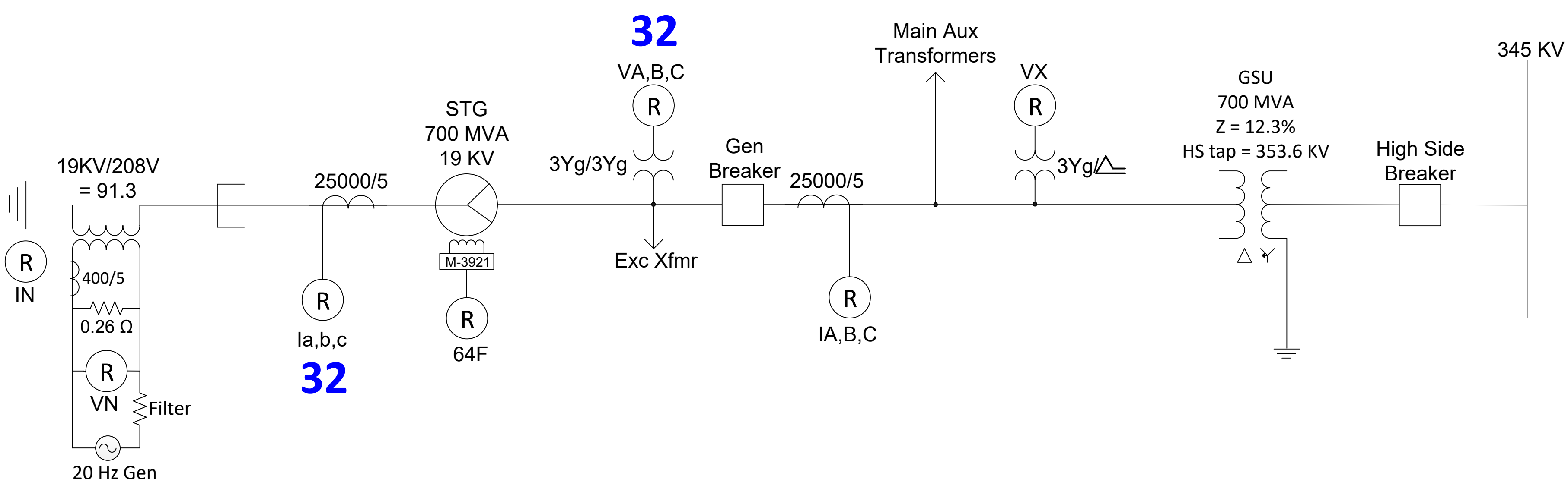
Should be set to 300/5 = 60, and instead it is set = 0.10 – max setting is 7.99 so at least that would have been better, but really it is a misapplication.

87GD – Ground Directional Overcurrent

- *IN = 0.43 A*
- *Rc = CT Ratio Correction was mistakenly set at 0.1*
- *Rc3Io = 0.1*0.077 = 0.0077 A*
- *|Rc3Io – IN| = |0.0077 – 0.43| = 0.42 A, since 0.42 > 0.20 (pickup), it correctly tripped.*

- *Ideally Rc = (1500/5)/(25/5) = 300/5 = 60, but max possible is 7.99, so for this particular fault if Rc = 7.99, then Rc3Io = 7.99*0.077 = 0.615 A*
- *|Rc3Io – IN| = |0.615 – 0.43| = 0.185 A, and since 0.185 < 0.2 (pickup), it would not have tripped for this fault had Rc been set to 7.99.*
- *This is a misapplication of 87GD function with the available CTRs, but the best it can be set is max Rc of 7.99 and probably increase Pickup and Time Delay.*

32 – Reverse Power



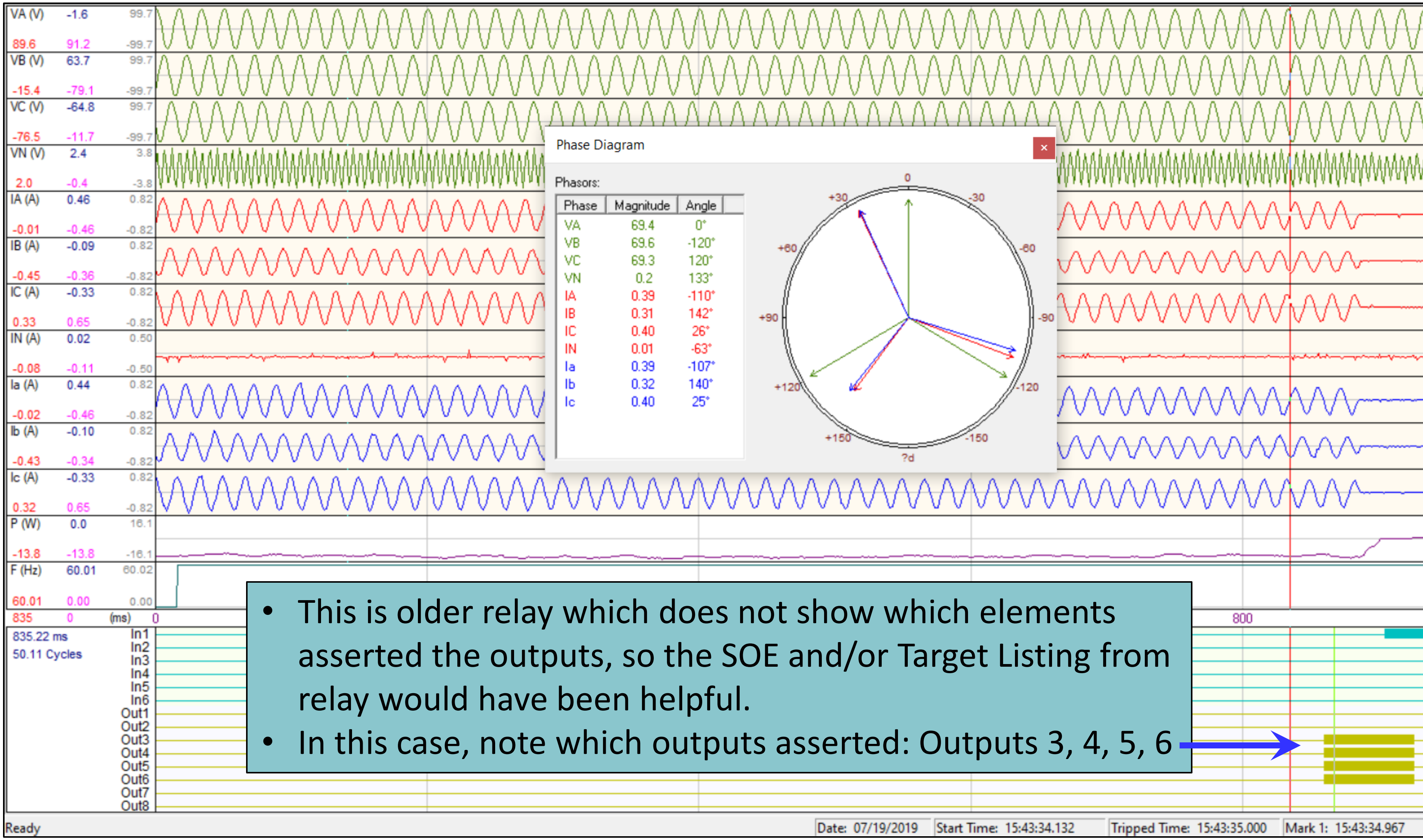
Blocking Inputs = FL, 1

$$P = VA * Ia * \cos(\theta_{VA} - \theta_{Ia}) + VB * Ib * \cos(\theta_{VB} - \theta_{Ib}) + VC * Ic * \cos(\theta_{VC} - \theta_{Ic})$$

32 Event Analysis – Event 1

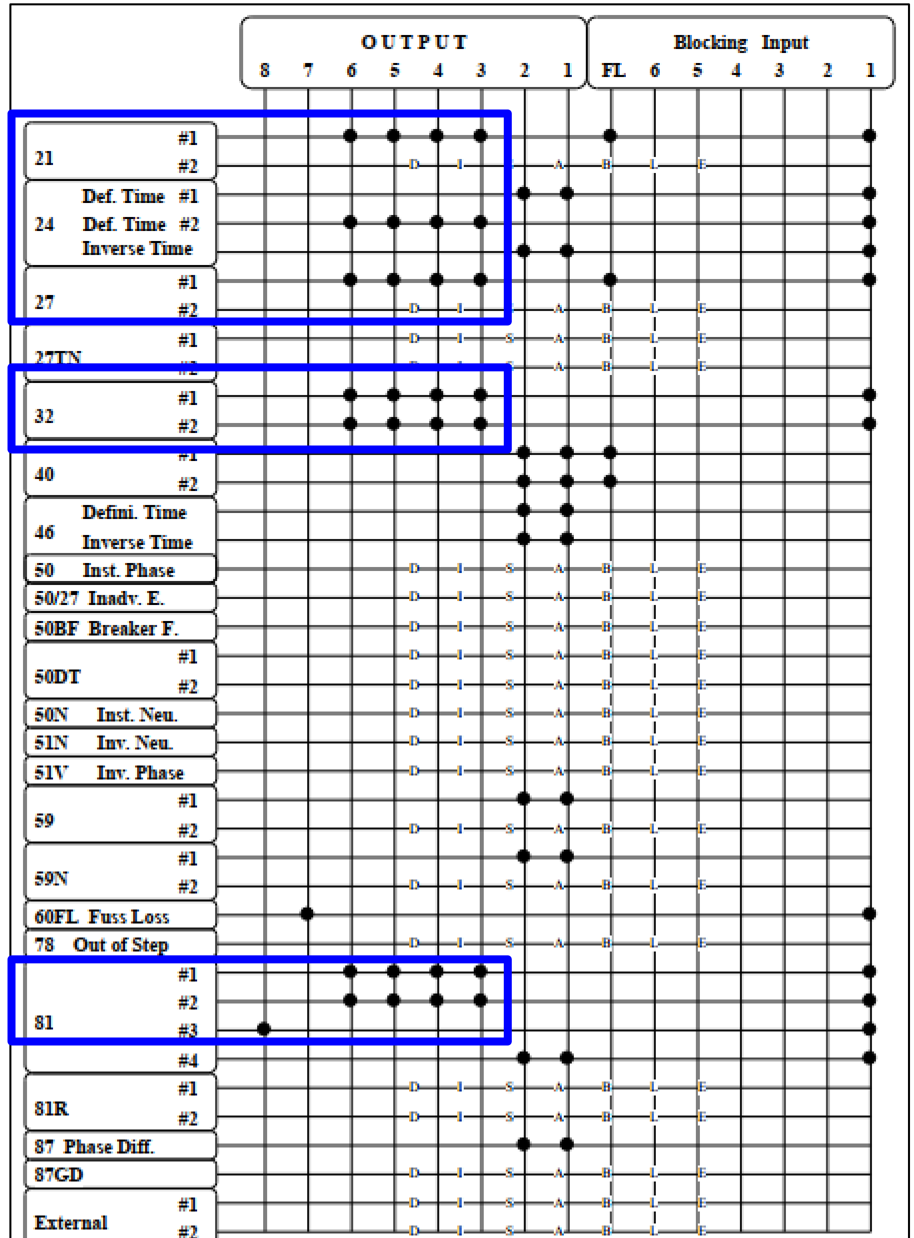
- Customer reported:
  - ✓ Relay trip
  - ✓ Asked why did the relay trip
  - ✓ No information was provided as to which Targets LEDs on the front of the relay were illuminated
  - ✓ No SOE was provided
  - ✓ No Target Listing from the relay software was provided
  - ✓ No description of operating conditions at time of event
  - ✓ relay setting file was provided in pdf format
  - ✓ Oscillograph record was provided

- First, take a big picture look at event displaying all Analog and Digital channels.
- Scroll cursor thru event with Phase Diagram which shows tracings were consistent for length of record.



- This is older relay which does not show which elements asserted the outputs, so the SOE and/or Target Listing from relay would have been helpful.
- In this case, note which outputs asserted: Outputs 3, 4, 5, 6

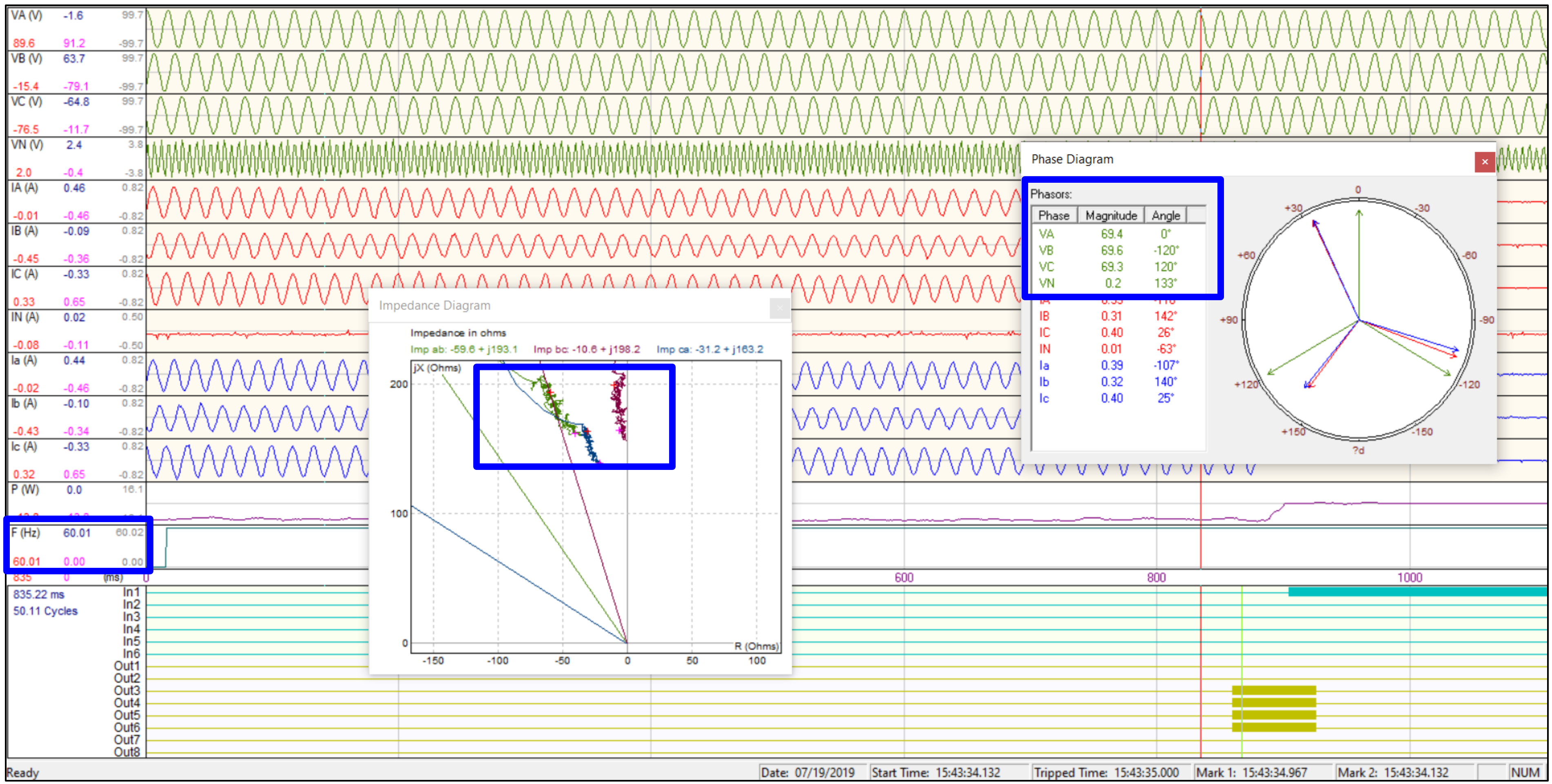
- Next, look at pdf of settings to see which elements are mapped to those outputs:



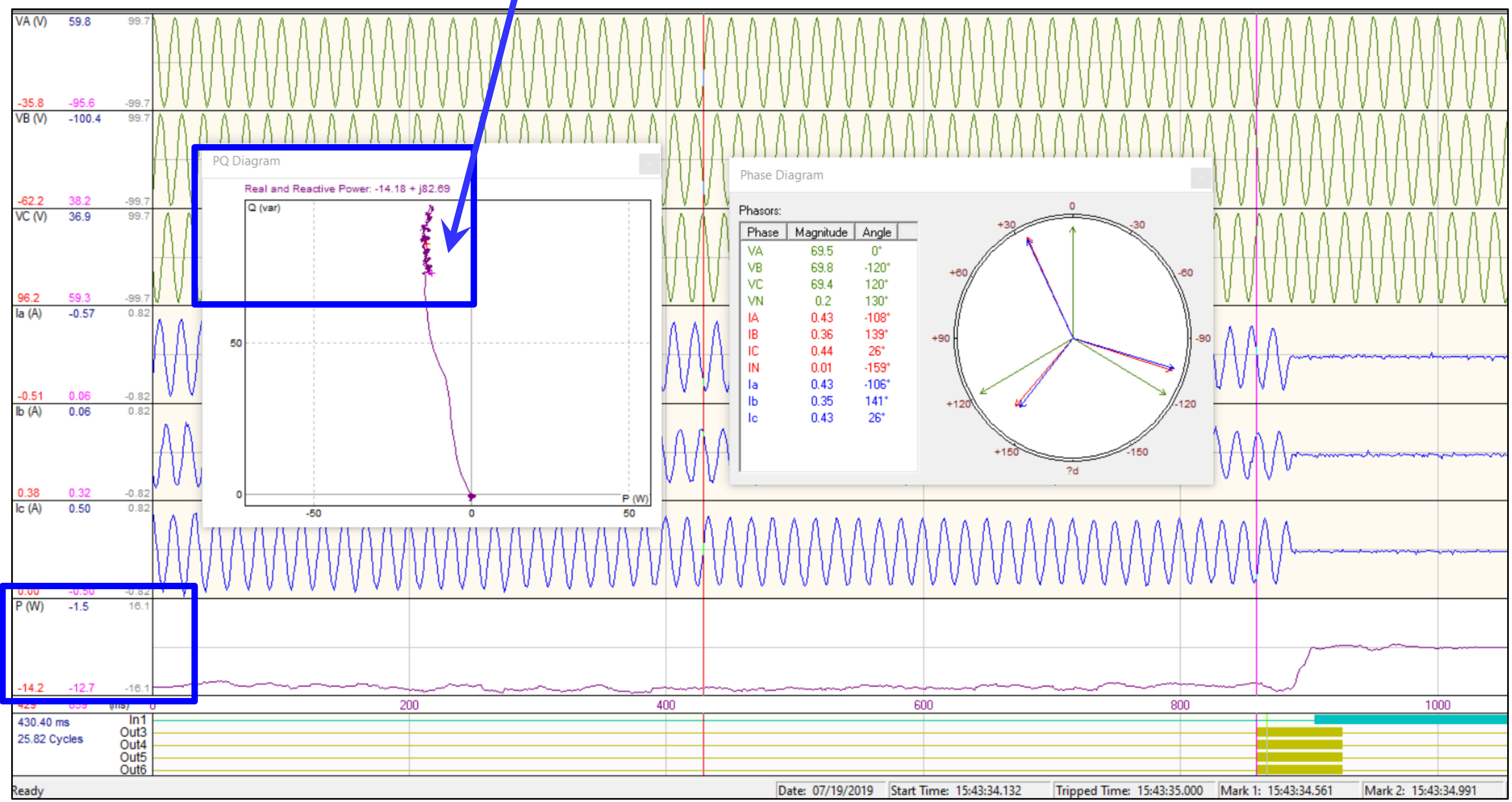
- Note that the following elements are mapped to outputs 3,4,5,6 that were asserted:
  - 21
  - 24
  - 27
  - 32
  - 81

Now review the oscillograph record with respect to each of these elements to find the guilty party.

- Voltage and Frequency were running at nominal throughout the event, so it is easy to eliminate the 24, 27, and 81 elements as having triggered this record.
- Next, looking at the RX Diagram, it can be seen loci are way outside of the 1.7 Ω setting of 21 zone #1 and 21 zone #2 is disabled.
- So that leaves us with the 32 element.



- Plotting the P (Watts) as one of the channels shows the Watts are negative.
- PQ Diagram shows the Watts are negative with operating points in the 2nd quadrant.
- Operating point in **2nd quadrant** indicates excitation still present, but turbine is lost or input to the prime mover is lost.



- Now, check the 32 relay settings and Nominal Current, Nominal Voltage, and VT Configuration settings as they will be needed to convert from per unit to actual secondary Watts to be able to compare operating point vs 32 setting:

[32] DIRECTIONAL POWER

PICKUP: -0.003 p.u.	**TIME DELAY:** 180 Cycles			**#1**
L.F.POWER Disabled				
OUTPUTS: 8 7 6 5 4 3 2 1 (X X X X under 7 6 5 4)	**BLOCKING INPUTS:** FL 6 5 4 3 2 1 (X under 2)			
PICKUP: -0.003 p.u.	**TIME DELAY:** 1800 Cycles			**#2**
L.F.POWER Disabled				
OUTPUTS: 8 7 6 5 4 3 2 1 (X X X X under 7 6 5 4)	**BLOCKING INPUTS:** FL 6 5 4 3 2 1 (X under 2)			

	6	5	4	3	2	1
Nominal Voltage: 120 V						
Nominal Current: 3.73 A						
Input Active State: open:					X	
close:	X	X	X	X		X
V.T.Configuration: Line-Gnd to Line-Line						
Delta-Y transform: Enable						

Convert Pickup into sec Watts:

$$Pact = Ppu * Sbase$$
$$= -0.003 * \sqrt{3} * 120 * 3.73$$
$$= \mathbf{-2.3\ Wsec}$$

Could multiply by VTR and CTR as well to get the Pickup in terms of primary Watts:

V.T. Phase Ratio:	150.0	:	1
C.T. Phase Ratio:	2000	:	1

$$-0.003 * \sqrt{3} * 120 * 3.73 * 150 * 2000 = \mathbf{-0.6977\ MW}$$

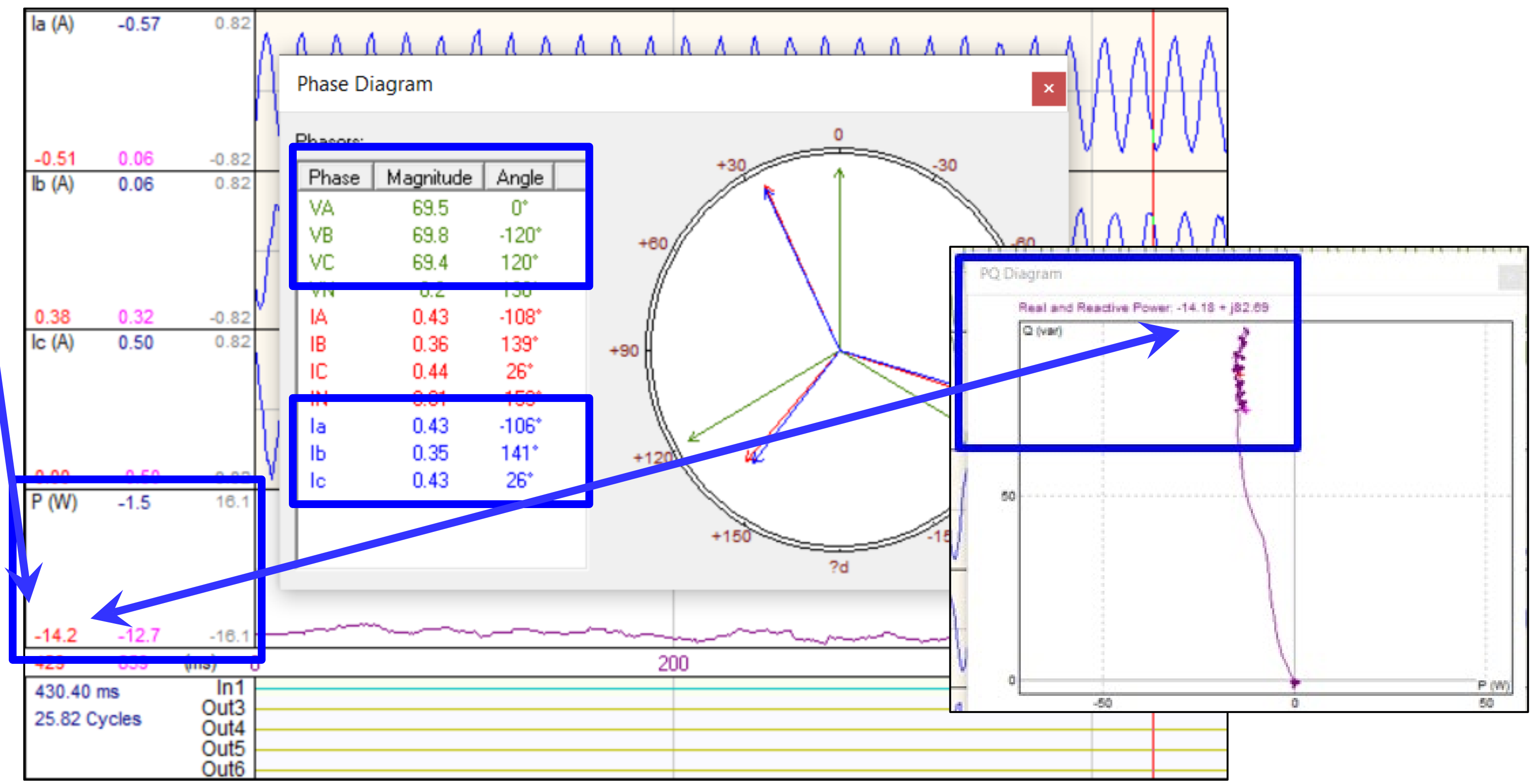
- Look at operating point from phase diagram in oscillograph record to calculate the P in sec watts or could just get the value right from the P (W) tracing or PQ diagram:

$$Pactual\_measured = VA * IA * \cos(\theta_{VA} - \theta_{IA}) + VB * IB * \cos(\theta_{VB} - \theta_{IB}) + VC * IC * \cos(\theta_{VC} - \theta_{IC})$$

$$= 69.5 * 0.43 * \cos(0° - -106°) + 69.8 * 0.35 * \cos(-120° - 141°) + 69.4 * 0.43 * \cos(120° - 26°)$$

$$= \mathbf{-14.14\ sec\,watts} \qquad (\text{or } -14.14 * 2000 * 150 = \mathbf{-4.24\ MW})$$

$$Ppu\_measured = \frac{Pactual\_measured}{Sbase} = \frac{-14.14}{\sqrt{3} * 120 * 3.73} = \mathbf{-0.018\,pu}$$



Compare operating point vs 32 Pickup setting in terms of:

- per unit

$$-0.018 \text{ pu} < -0.003 \text{ pu}$$

- sec Watts

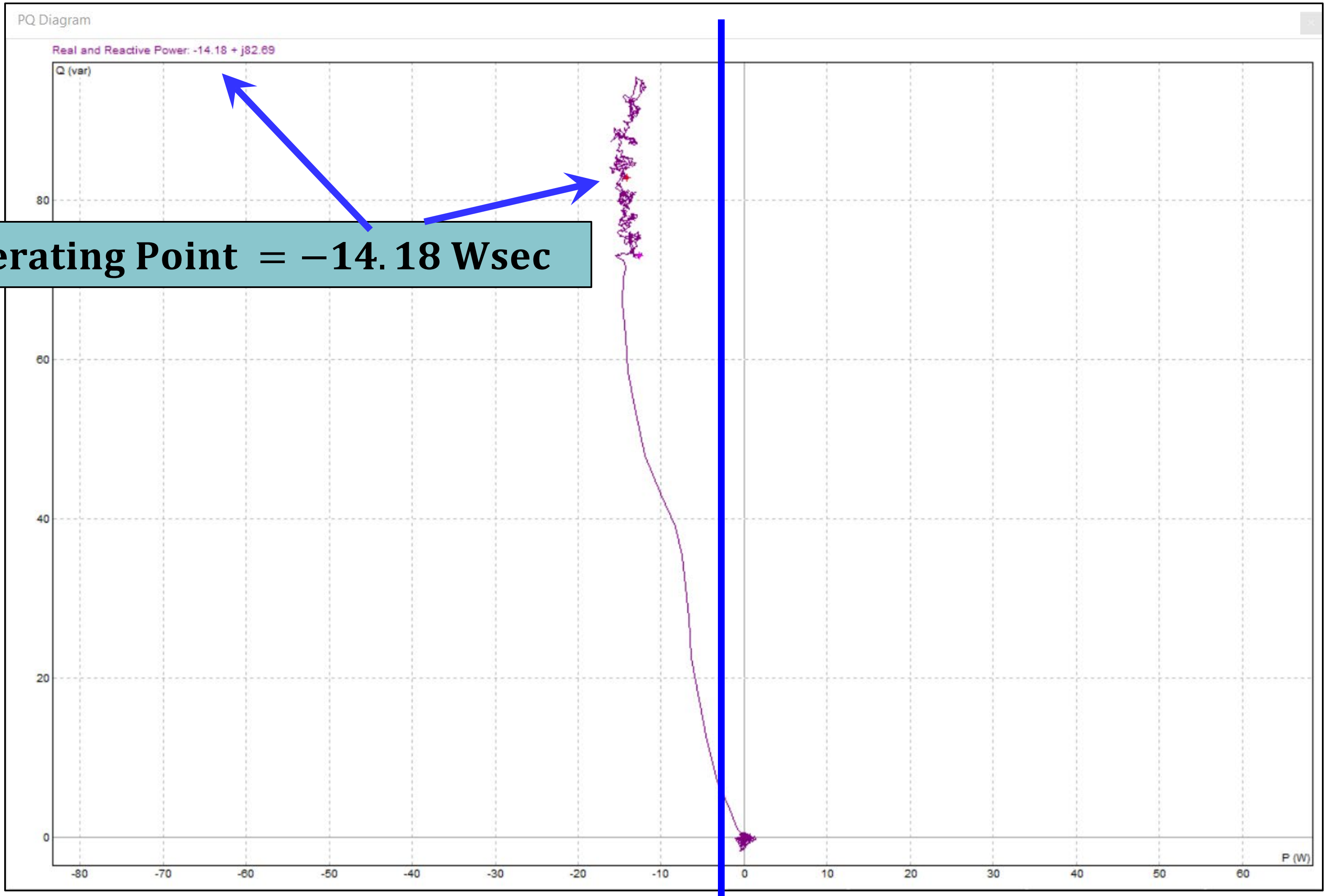
$$-14.14 \text{ Wsec} < -2.3 \text{ Wsec}$$

- pri Watts

$$-4.24 \text{ MW} < -0.6977 \text{ MW}$$

or $>$ in the negative direction

- View trip on PQ Diagram in Primary or Secondary values – here shown secondary:



Operating Point $= -14.18$ Wsec

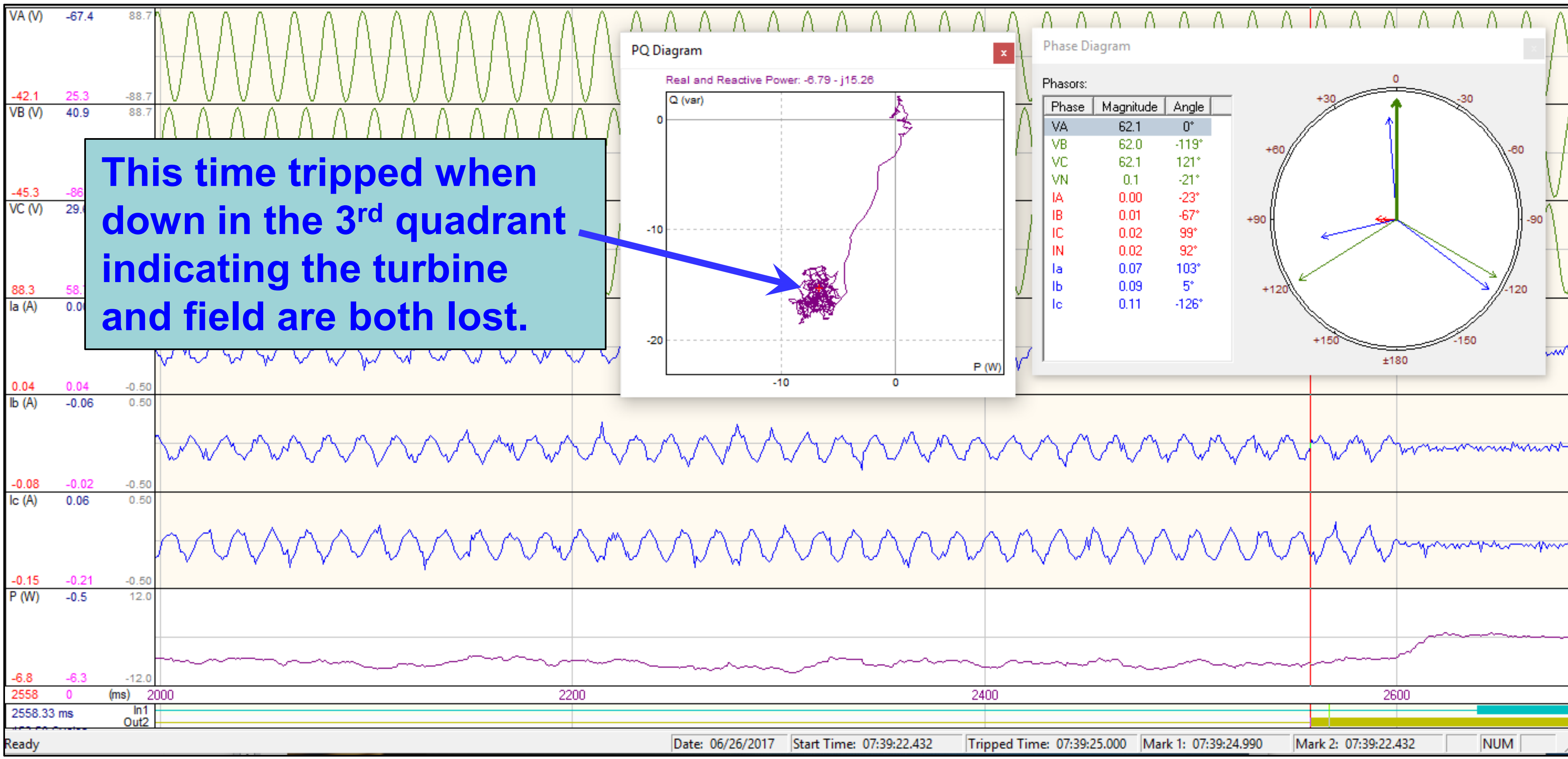
Pickup $= -2.3$ Wsec

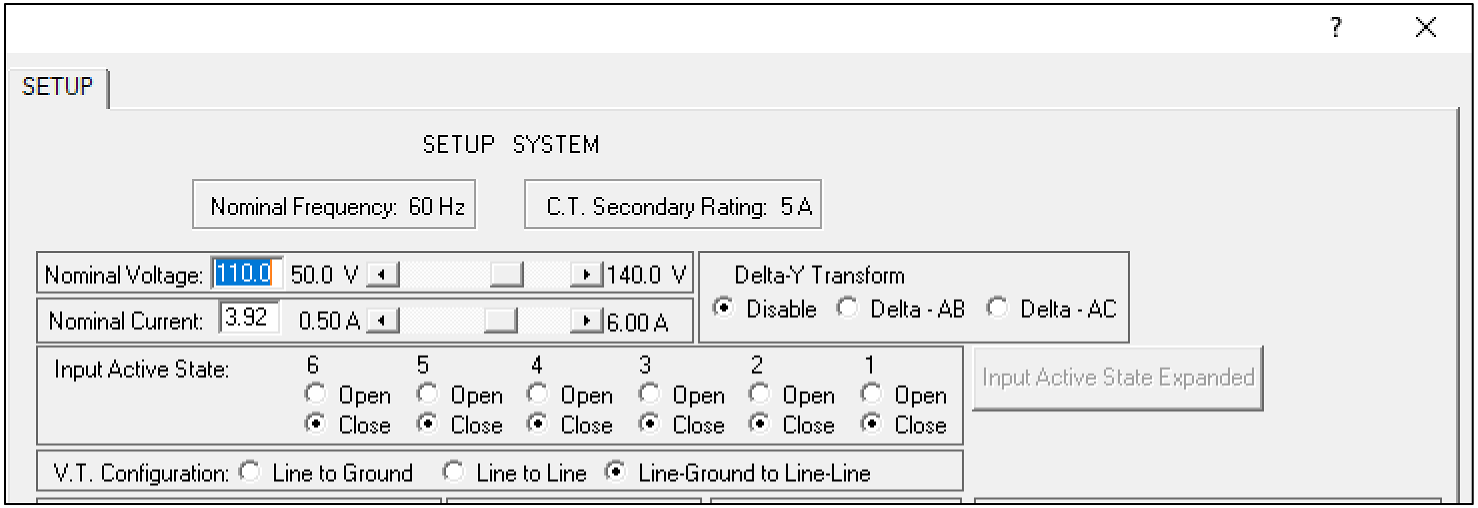
32 Event Analysis Conclusion – Event 1

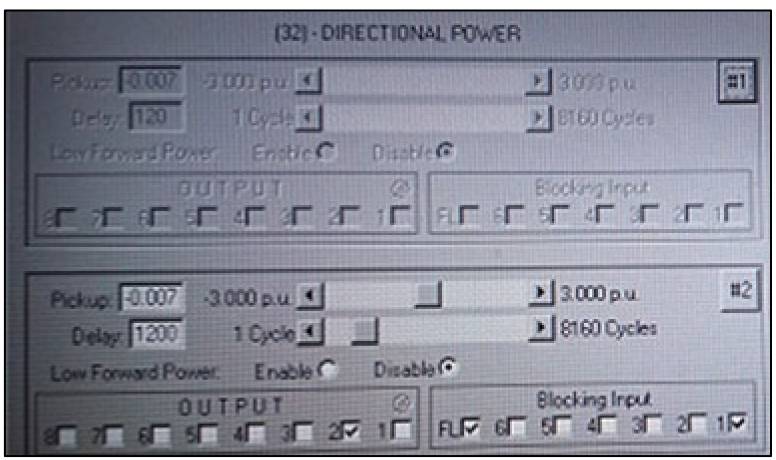
- Reported to customer that the relay tripped correctly based on settings.
- May have been a normal shutdown, sequential trip.
- Or there could have been an issue with the turbine, turbine control, etc.
- Recommended, if this was a normal shutdown sequential trip, that they may want some discrimination between 32 #1 and 32 #2 as both have the same outputs mapped and the same blocking input for open breaker – they could consider blocking for FL if 60FL is brought to DCS.
- 32 #1 appears to be a sequential trip as it is set for 3 seconds, while 32 #2 is set for 30 seconds so that is set as a reverse power protection element may typically be set.
- If 32 #1 is sequential trip, typically it may be mapped to a different output with that output being supervised by hardwired steam valve position contacts.
- Or if the steam valve position contacts are wired into a relay input, then that could be used as a Blocking Input for the normal shutdown, sequential 32 tripping element.
- No further information from customer on event.

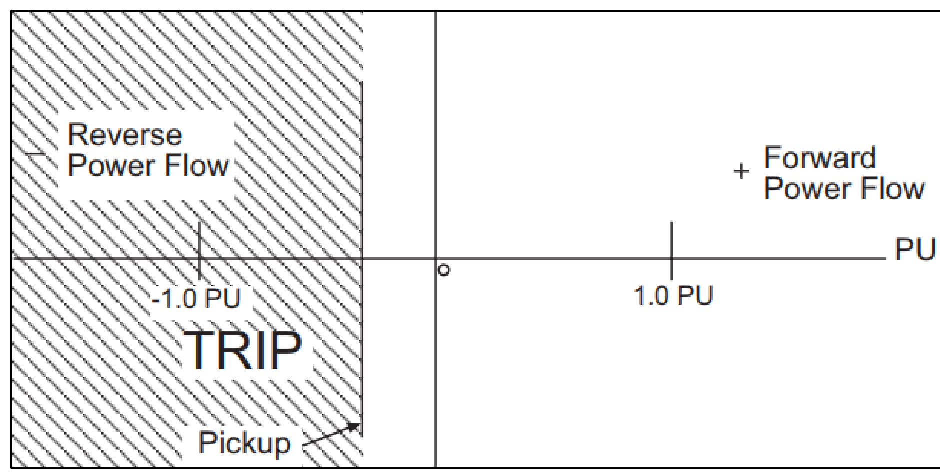
32 Event Analysis – Event 2

- Customer reported 32 trip and asked if it operated correctly:




?
SETUP
SETUP SYSTEM
Nominal Frequency: 60 Hz
C.T. Secondary Rating: 5 A
Nominal Voltage: 110.0 50.0 V 140.0 V
Nominal Current: 3.92 0.50 A 6.00 A
Delta-Y Transform
Disable Delta - AB Delta - AC
Input Active State: 6 5 4 3 2 1
Open Open Open Open Open Open
Close Close Close Close Close Close
Input Active State Expanded
V.T. Configuration: Line to Ground Line to Line Line-Ground to Line-Line


(32) - DIRECTIONAL POWER
#1
#2
Pickup: -0.007 -3.000 p.u. 3.000 p.u.
Delay: 1200 1 Cycle 8160 Cycles
Low Forward Power: Enable Disable
OUTPUT
Blocking Input


–
Reverse
Power Flow
+
Forward
Power Flow
PU
-1.0 PU
1.0 PU
TRIP
Pickup

Because VT Configuration = LG-LL, use equation:

$$Sbase = Snom = \sqrt{3} * Nominal\ Voltage * Nominal\ Current$$
$$= \sqrt{3} * 110 * 3.92$$
$$= 746.86\ VAsec$$

$$Pactual = VA * Ia * \cos(\theta v - \theta i) + VB * Ib * \cos(\theta v - \theta i) + VC * Ic * \cos(\theta v - \theta i)$$
$$= 62.1 * 0.07 * \cos(-103°) + 62.0 * 0.09 * \cos(-124°) + 62.1 * 0.11 * \cos(247°)$$
$$= -6.726\ \sec watts$$

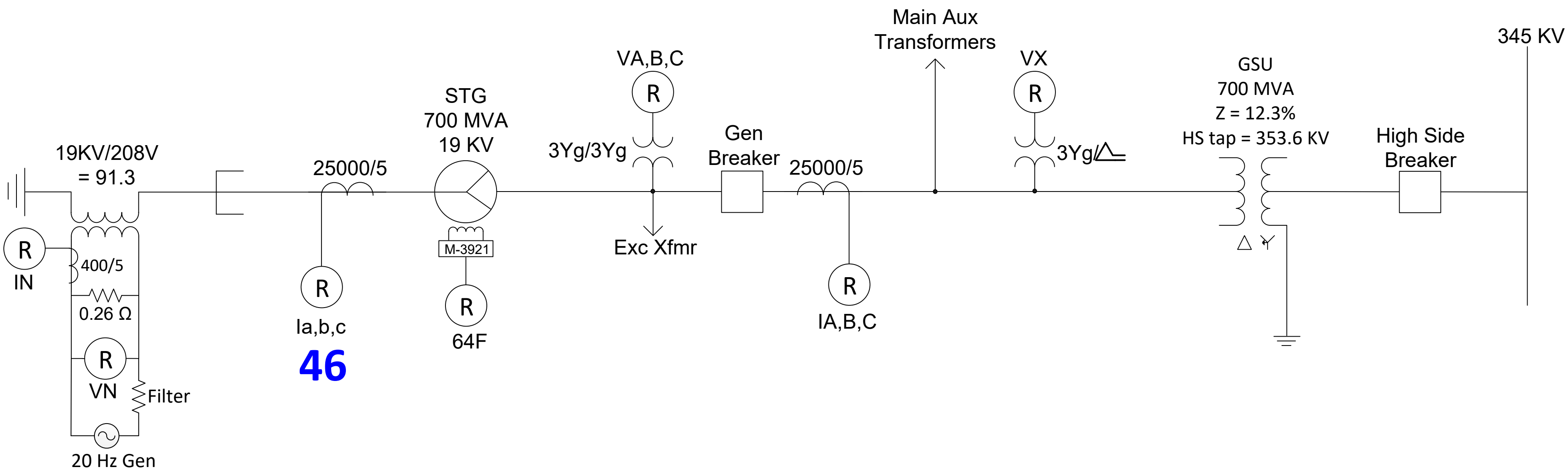
$$Ppu = \frac{Pactual}{Sbase} = \frac{-6.726}{746.86} = -0.009\ pu$$

And because -0.009 pu < -0.007 pu, therefore Yes, the relay operated correctly.

32 Event Analysis Conclusion – Event 2

- Reported that the relay operated per the settings and showed how it did so.
- I mentioned that if they would provide me with the setting file or tell me what their 40 settings are, then we will be able to see why the 40 elements did not trip prior to this 32 trip (as may typically be desired for operating points down in the 3rd quadrant) and based on that analysis and what they are trying to accomplish possibly suggest some setting adjustments to the 40 and/or 32 elements or maybe prove that it did operate as they wanted it too.
- No further information was provided from the customer.

46 – Negative Sequence Overcurrent

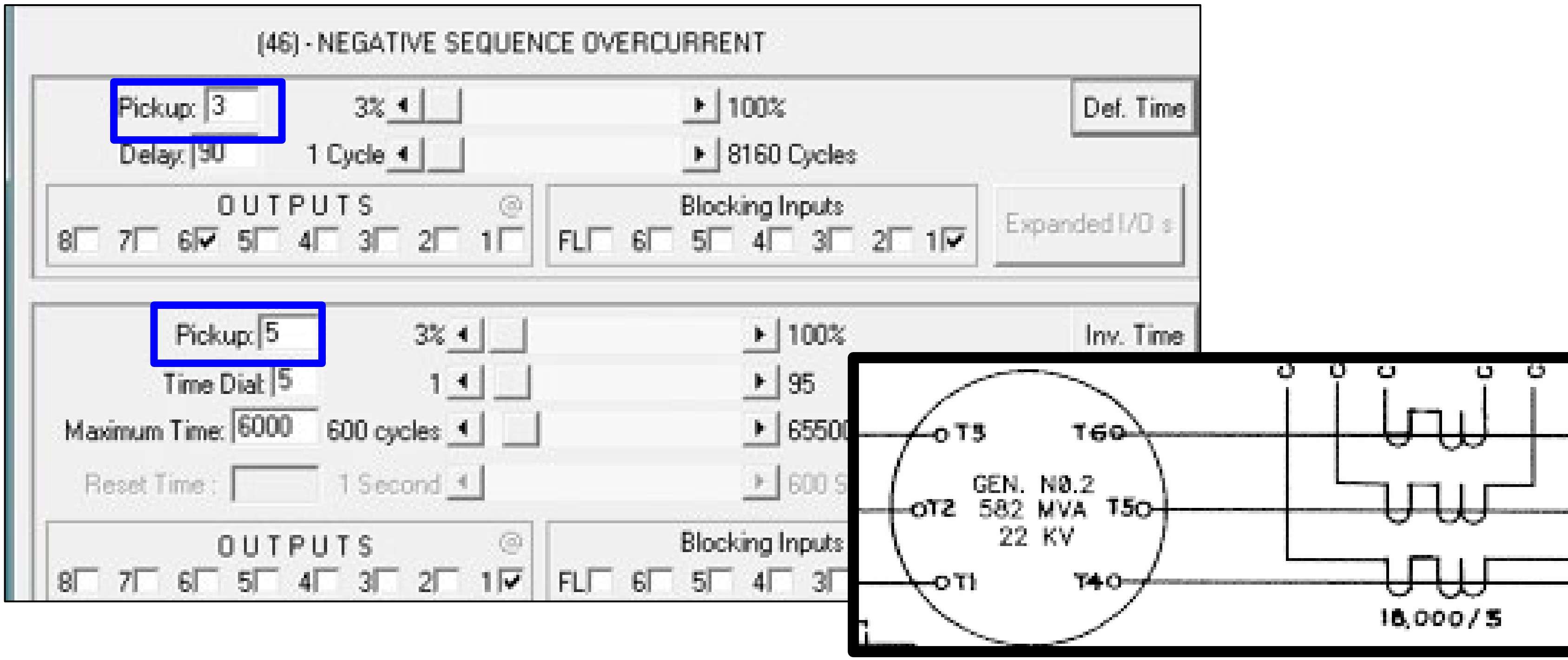


Blocking Inputs =

$$I_2 = \frac{1}{3}(Ia + a^2Ib + aIc)$$

46 Event Analysis

- Customer reported 46 Alarms at generating station typically when switching of transmission lines on GSU HS.
- First look at 46 settings for their application:



- No other settings were given, but 3-line provided so calculate:
- $$\text{Nominal Current} = \frac{\text{Sgen}}{\sqrt{3} * V_{\text{LL gen pri}}} * \frac{1}{\text{CTR}} = \frac{582\text{ M}}{\sqrt{3} * 22\text{ K}} * \frac{5}{18000} = 4.24\text{ A}$$

- Assume Directly Cooled round rotor, so per IEEE C50.13 the continuous I_2 ratings:

Continuous Unbalance Current Capability	
Generator Type	*Permissible I_2 Stator Rating Percent*
Salient Pole	
Connected Amortisseur Windings	10
Nonconnected Amortisseur Windings	5
Cylindrical Rotor	
Indirectly Cooled	10
Directly Cooled	
To 350 MVA	8
351–1250 MVA	8 – [(MVA-350)/300)]
1251–1600 MVA	5

$$\textbf{continuous gen } \mathbf{I_2} \textbf{ rating} = 8 - \frac{582 - 350}{300} = 7.23\ \%$$

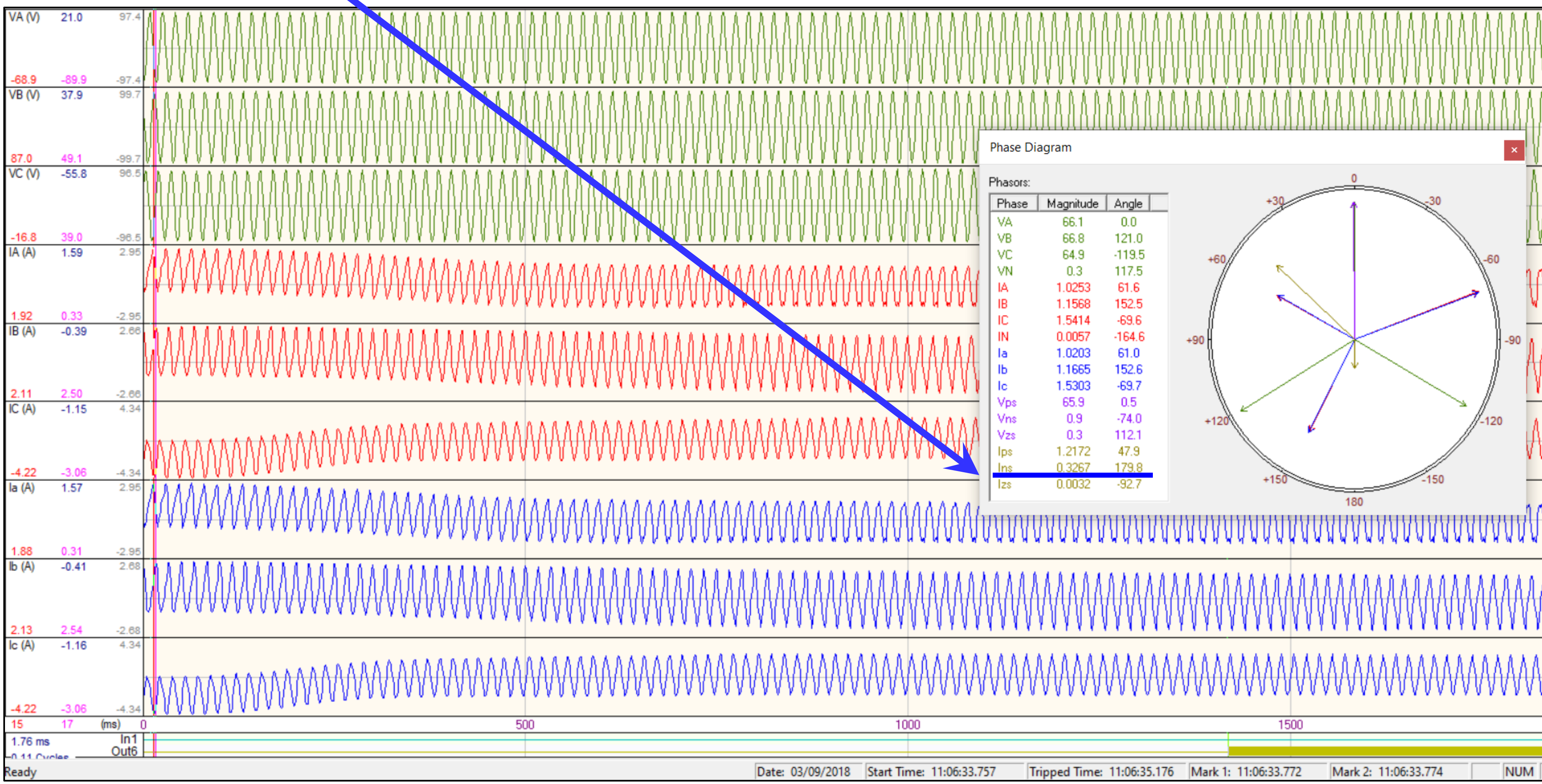
$$\mathbf{I_2} \textbf{ at full output} \le \textbf{46 IT Pickup} \le \textbf{cont. gen } \mathbf{I_2} \textbf{ rating; min } \mathbf{I_2} \textbf{ from unbalanced condition}$$

$$\le \textbf{46 IT Pickup} \le \quad \textbf{7.23\%} \quad ;$$

- Therefore, the **5% 46IT Trip Pickup** and the **3% 46DT Alarm Pickup** may be set just slightly more sensitive than required for this application.

- From beginning of event to the time the output asserts, the negative sequence current varies from 0.3267 A to 0.2510 A, which is

- $\left(\frac{0.3267}{4.24}\right) * 100 = 7.7\% \quad to \quad \left(\frac{0.2510}{4.24}\right) * 100 = 5.9\%$



46 Event Analysis Conclusion

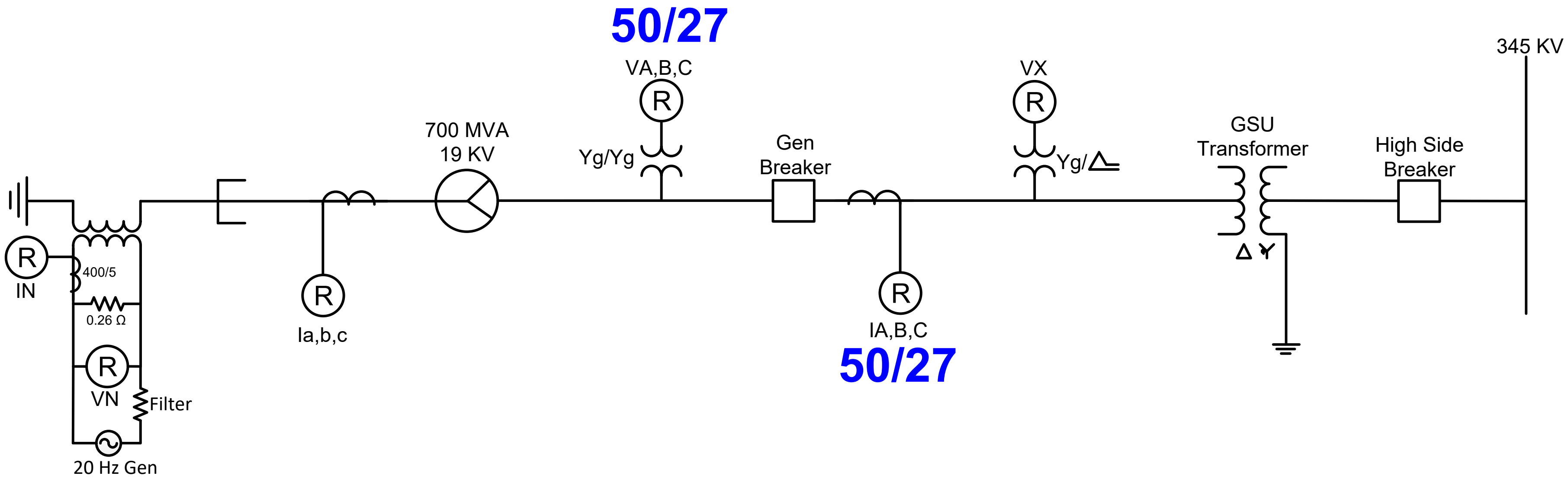
- Recommended to review the phasing transposition diagrams for the transmission lines on high side of GSU to ensure the phases are being transposed optimally.

- Recommended they could consider adjusting 46 settings:

  ✓ The 46IT Trip Pickup could be changed from 5% to 7%.

  ✓ The 46DT Alarm Pickup could be bumped up a bit too or it could be left at 3% so the operators have a chance to react before it trips, but it depends on what the normal, quiescent I_2 is for this application.

50/27 – Inadvertent Energizing



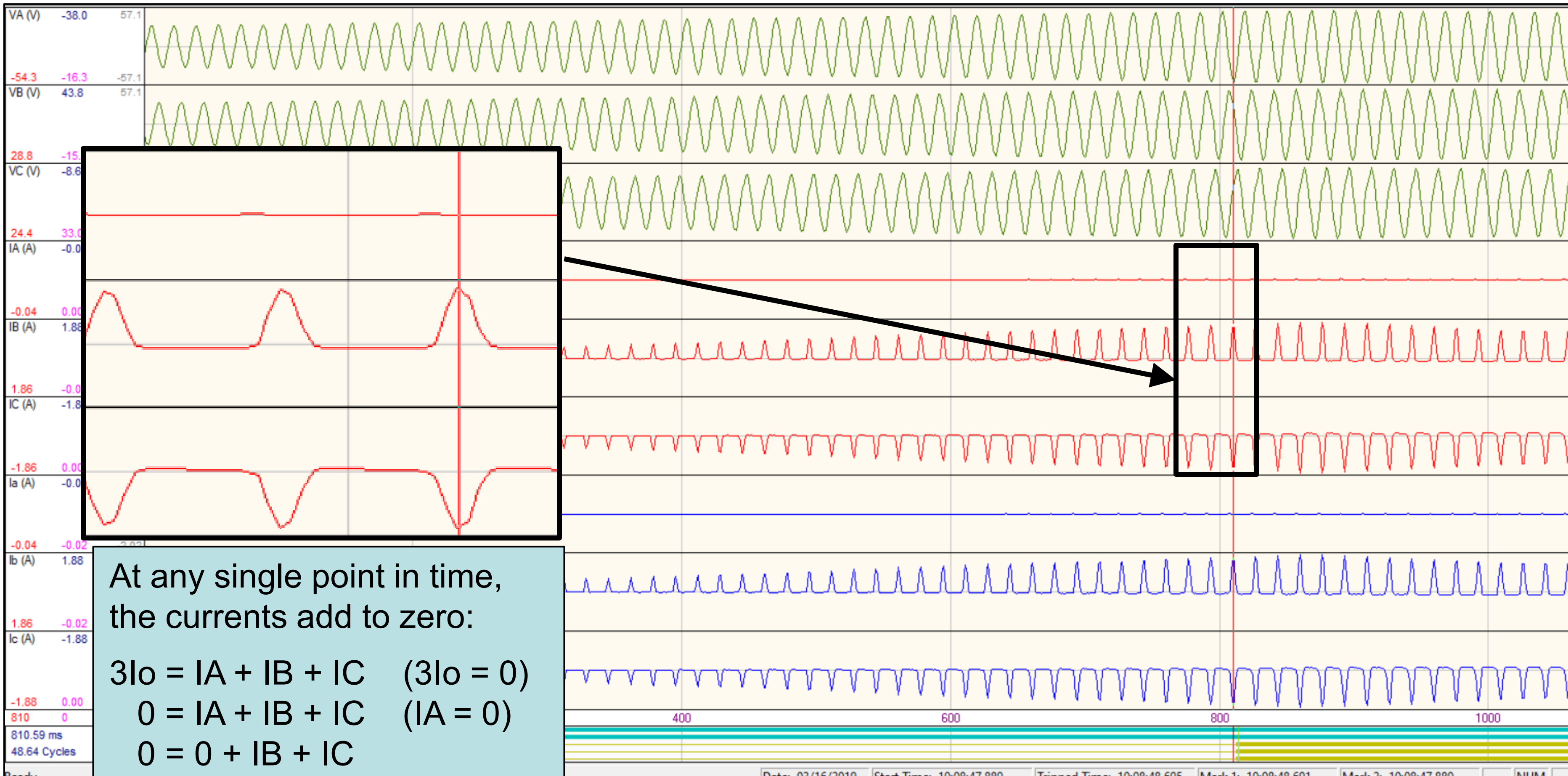
Blocking Inputs = FL

Protection for when the generator is accidently energized when off-line or during startup/shutdown.

50/27 Event Analysis

- (3) 50/27 trips during startup on unit connected applications:

- 1st 50/27 trip event:



At any single point in time, the currents add to zero:

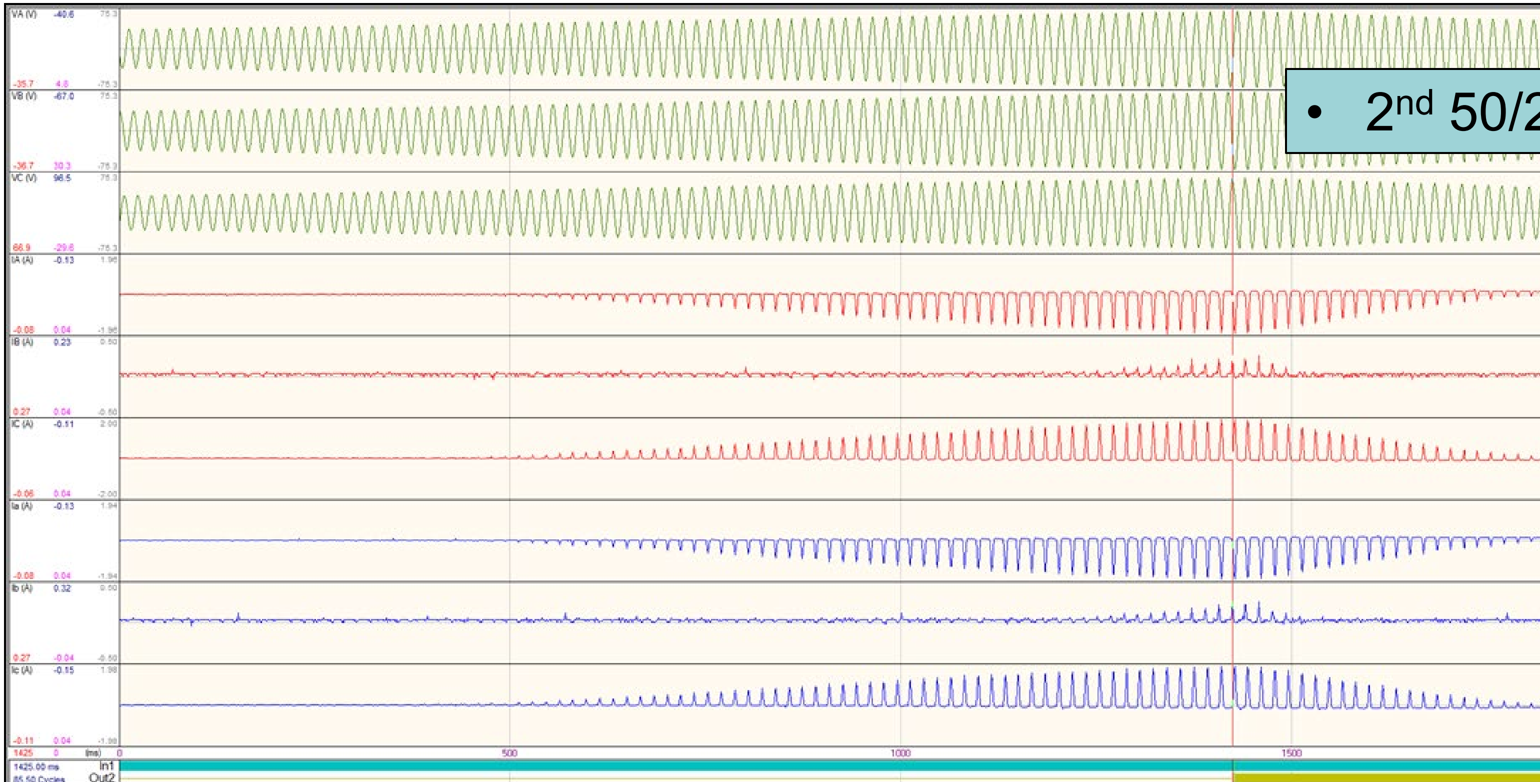
$3Io = IA + IB + IC \quad (3Io = 0)$

$0 = IA + IB + IC \quad (IA = 0)$

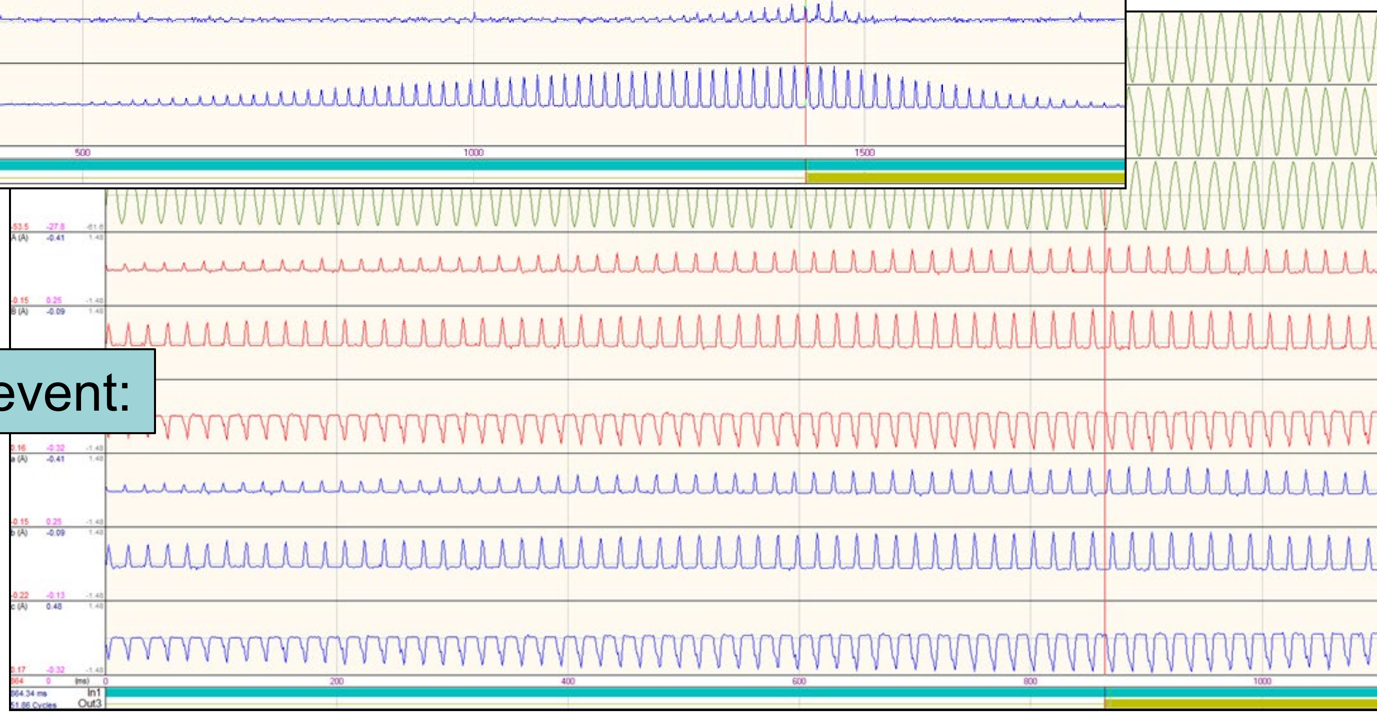
$0 = 0 + IB + IC$

$IB = -IC$

- 2nd 50/27 trip event:



- 3rd 50/27 trip event:

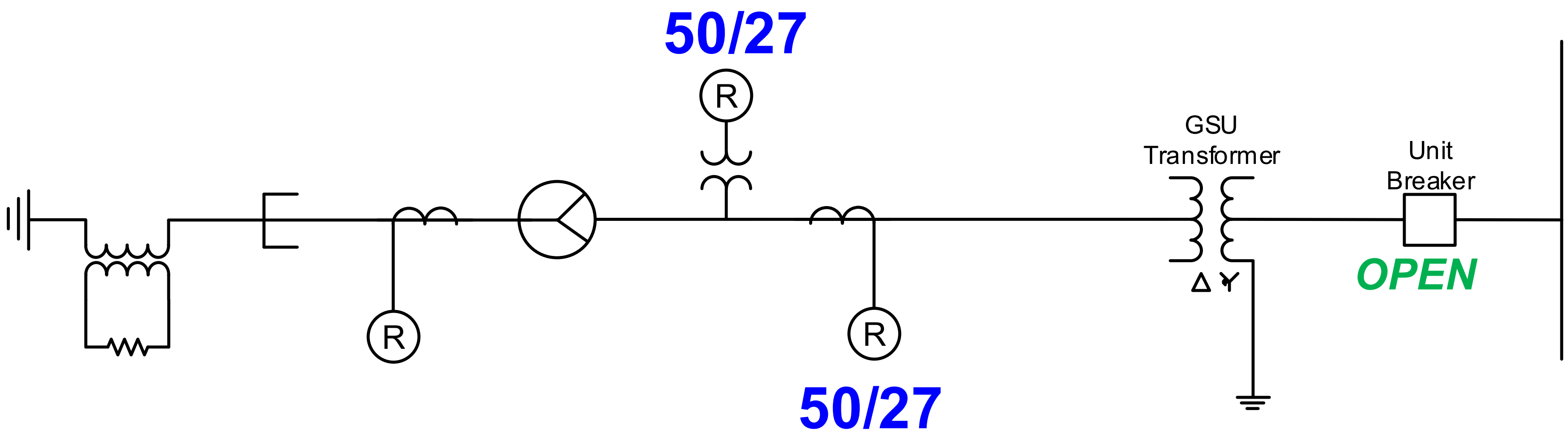


- What do all (3) events have in common?

- All 3 cases were unit connected, i.e. there was no LS generator breaker, they only had a HS unit breaker that was open at the time of the trips.

- All 3 cases occurred during startup i.e. they were coming back on-line (pre-sync period) after an outage where in one case the GSU had been replaced and in another case some GSU testing had been done.

- As the voltage was building up during startup to get ready to sync on-line, the 50/27 tripped the GSU HS unit breaker. Why?



- In all cases, the voltages were not yet built up to nominal – they were about 50-60% of nominal.

- In all cases, the currents were rich in harmonics and saturating heavily as this was pure GSU transformer magnetizing inrush current.

- At any single point in time, the current phasors add up to zero:
  - 3Io = IA + IB + IC
  - 0 = IA + IB + IC (as there was no 3Io)
  - –IA = IB + IC

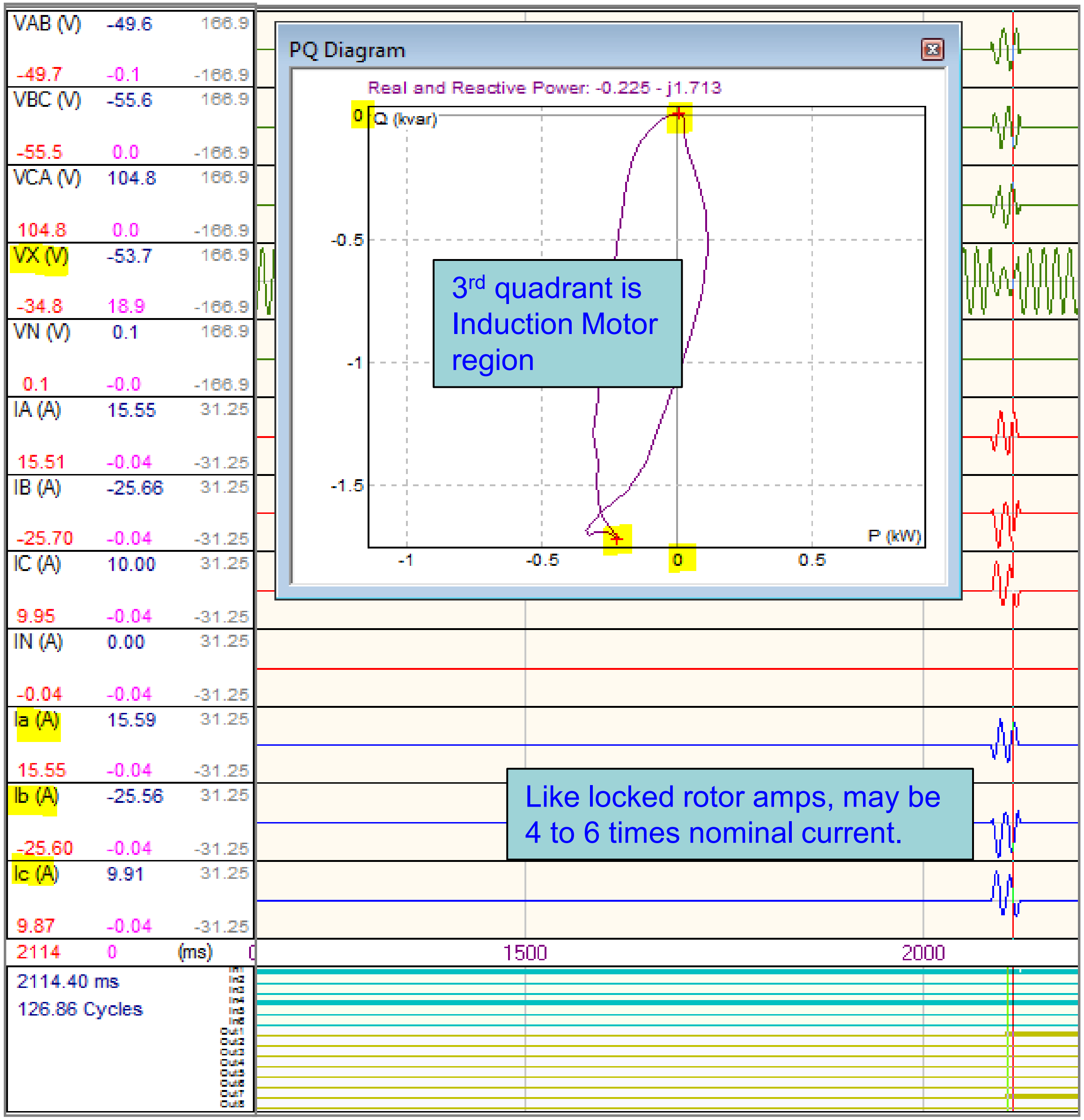
- All 3 cases had their 50 Pickup setting portion of the 50/27 setting set at minimum or 0.50 A.

- All 3 cases had their 27 Pickup setting portion of the 50/27 setting set too high.

50/27 Trip Event Analysis Conclusion

- These events were considered 50/27 mis-operations due to too sensitive settings for the Unit breaker applications, although relay operated correctly per applied settings.
- It may have helped to degauss the GSU after it was tested to remove remnant flux.
- In all cases, recommended to increase the 50 Pickup and decrease the 27 Pickup in their 50/27 settings.
- The 50/27, 50 Pickup in general should not be set at minimum for applications without a low side gen breaker. If you go thru the criteria shown in the Gen Calcs and Settings presentation, typically you can set this 50 Pickup with plenty of sensitivity at well above its minimum setting i.e. a setting closer to Inom or above may be appropriate for most applications.
- For applications that do have a low side generator breaker, then a 50 Pickup setting at minimum may be fine, although adding the extra security does not really sacrifice any needed sensitivity anyway.
- The 50/27, 27 Pickup should be set anywhere from 20% to 50% of Nominal Voltage as there are no disadvantages in setting it this low.

50/27 Trip – true accidental breaker closure when off-line



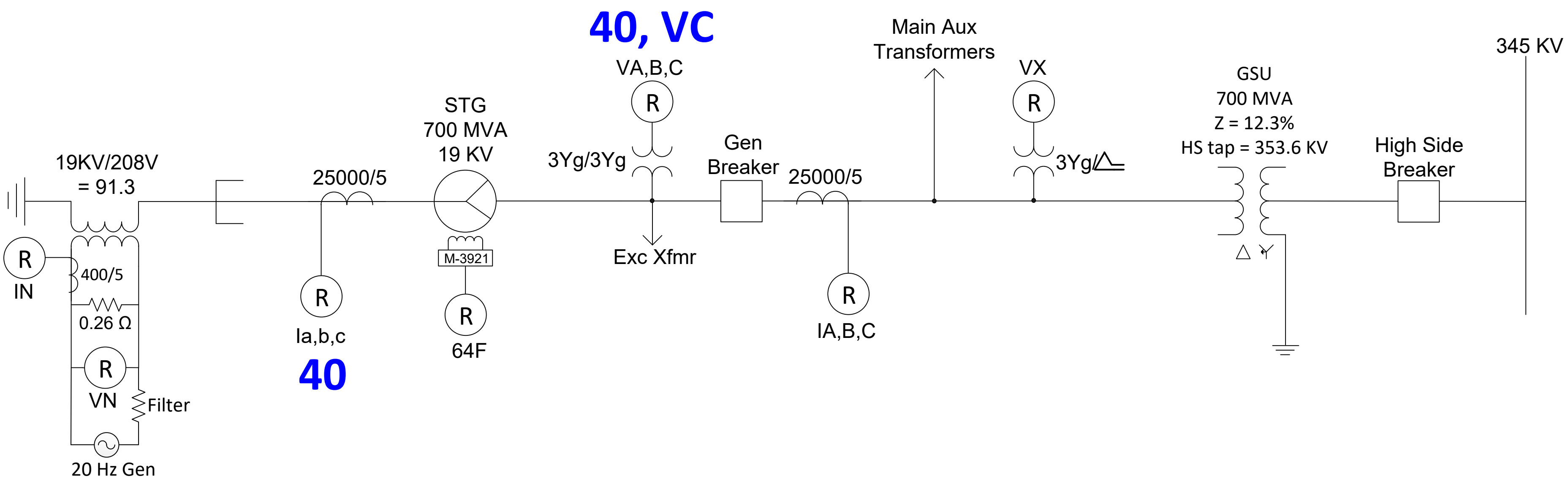
PRO TIP:

When machine is off-line do not disable protection:

- ✓ Do not open TCOs
- ✓ Do not remove AC fuses
- ✓ Do not remove DC or power supply voltage

This is when the 50/27 protection is needed.

40 – Loss of Field



Blocking Inputs = FL, 1

$$Z1 = \frac{V1}{I1}$$

$(uses\ positive\ sequence\ quantities\ for\ security\ during\ power\ swings)$

40 Event Analysis

Confirm Targets, SOE, and Oscillograph files agree on tripped function:

1. 09-Aug-2017 14:40:52.324

Inputs: Outputs: 1, 3

40 #1 Picked up: Yes Operated: Yes **40 #2** Picked up: Yes Operated:

Ia: 4.81 (A) **Ib:** 4.79 (A) **Ic:** 4.73 (A) **IN:** 0.00 (A)

Tripped Functions

Tripped at: 14:40:52.324

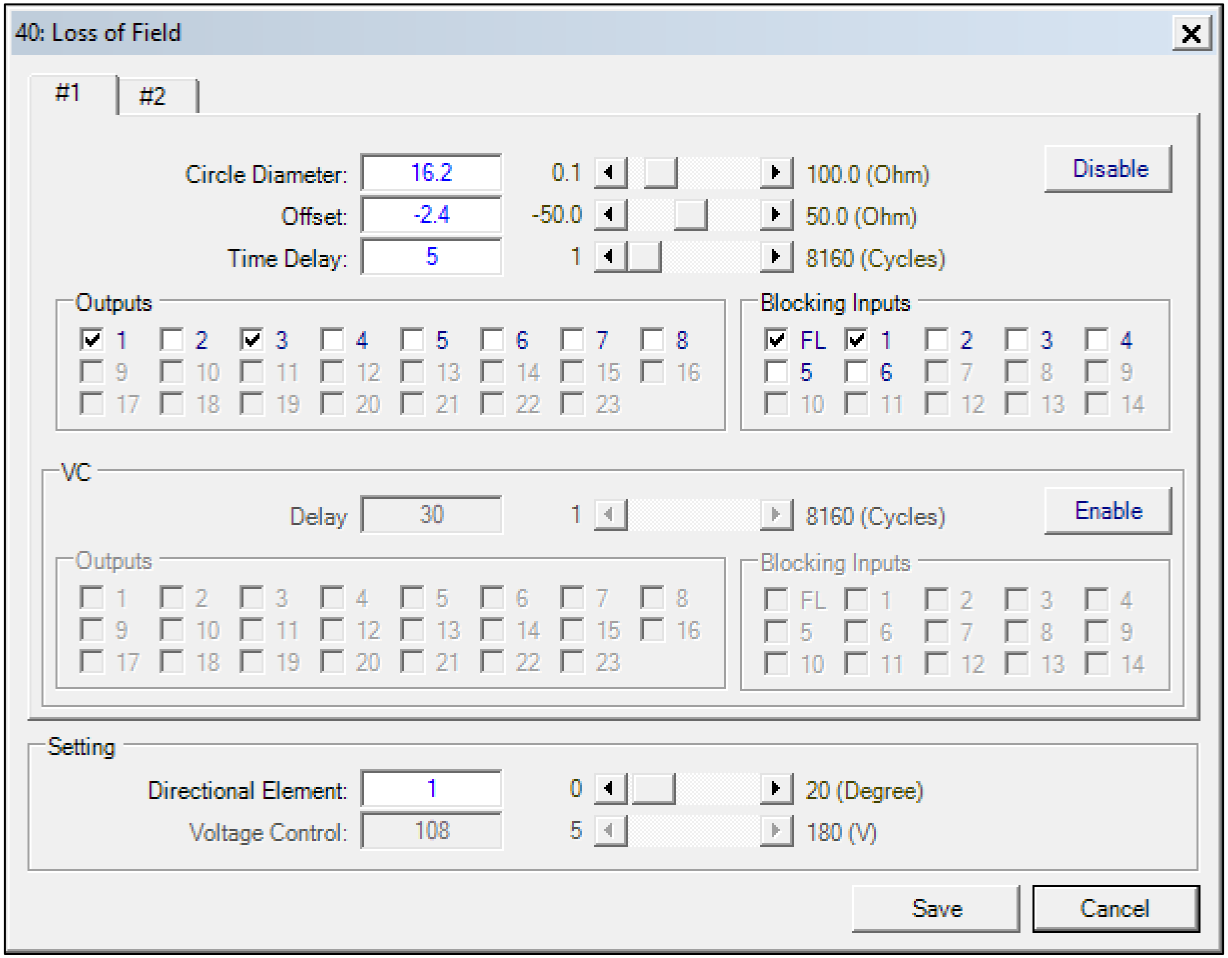
Pick up:	Tripped:
F40 #1	F40 #1
F40 #2	

32. 08/09/2017, 14:40:52.324

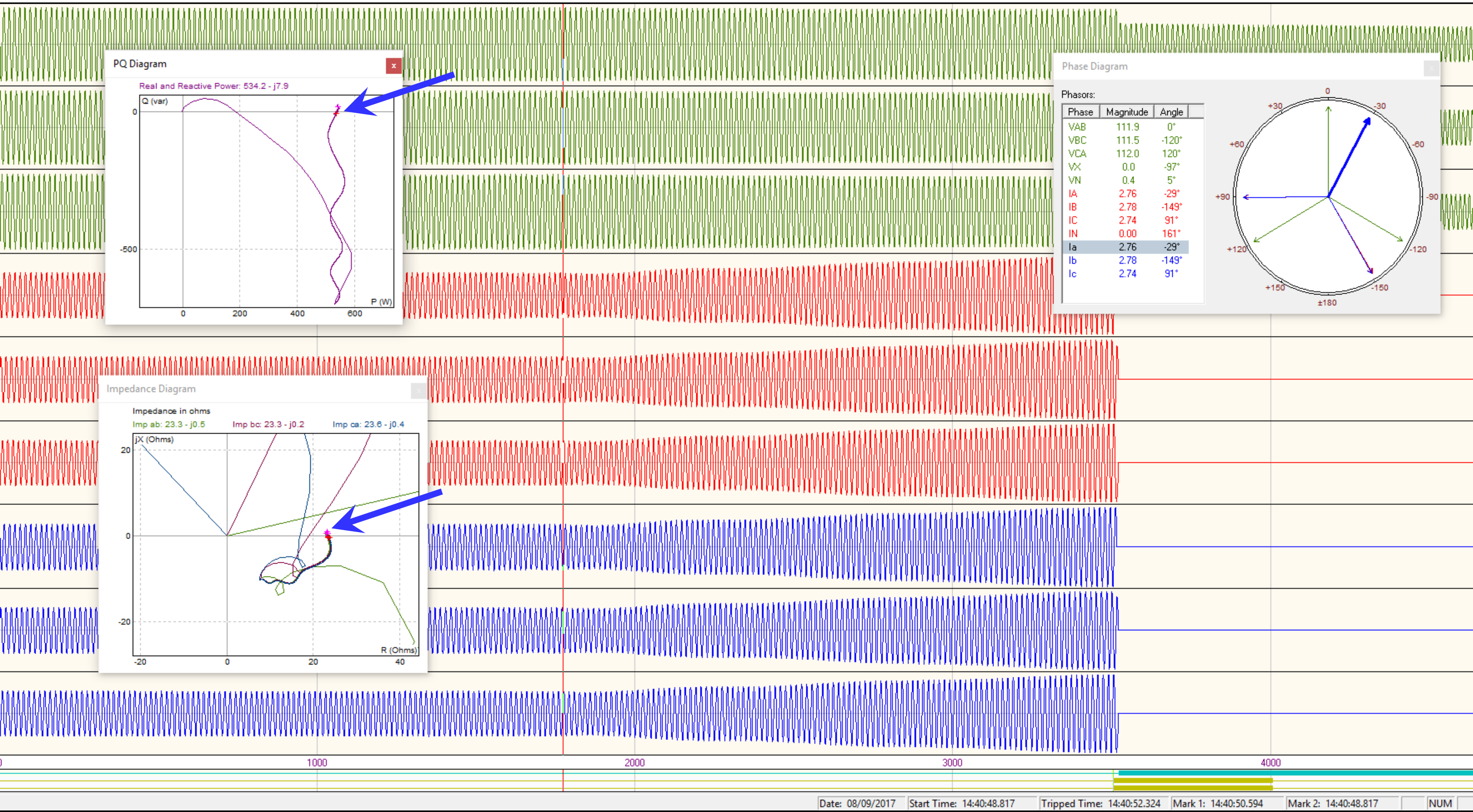
Picked up Inputs:		Dropped Inputs:	
Picked up Ouputs:	1, 3	Dropped Ouputs:	
40 #1:	Pickup/Timeout/	40 #2:	Pickup/

VA:	105.4 (V)	VB:	105.0 (V)	VC:	105.5 (V)	VN:	0.5 (V)
VX:	0.0 (V)	VPS:	105.2 (V)	VNS:	0.4 (V)	VZS:	0.0 (V)
IA:	4.81 (A)	IB:	4.79 (A)	IC:	4.73 (A)	IN:	0.00 (A)
Ia:	4.81 (A)	Ib:	4.79 (A)	Ic:	4.74 (A)	IPS:	47.76 (A)
INS:	0.25 (A)	IZS:	0.00 (A)	Ia Diff:	0.04 (A)	Ib Diff:	0.02 (A)
Ic Diff:	0.02 (A)	RAB:	7.74 (Ohm)	XAB:	-10.04 (Ohm)	RBC:	7.82 (Ohm)
XBC:	-10.06 (Ohm)	RCA:	7.74 (Ohm)	XCA:	-10.12 (Ohm)	Frequency:	59.99 (Hz)
V/Hz:	96.0 (%)	ROC Freq:	0.00 (Hz/s)	Real Power:	0.859 (PU)	React Power:	-1.108 (PU)
PS Real Imped:	7.89 (Ohm)	PS React Imped:	-10.03 (Ohm)	Phase Angle:	-45.1 (Degree)	Delta V:	105.3 (V)
Delta Freq:	3.000 (Hz)	VN 3rdH:	2.93 (V)	VX 3rdH:	0.01 (V)	59D ratio:	0.00
Field Insul.:	>100K (Ohm)	V Brush:	2163 (mV)	V Stator:	0.0 (V)	I Stator:	0.0 (mA)
Profile:	1						

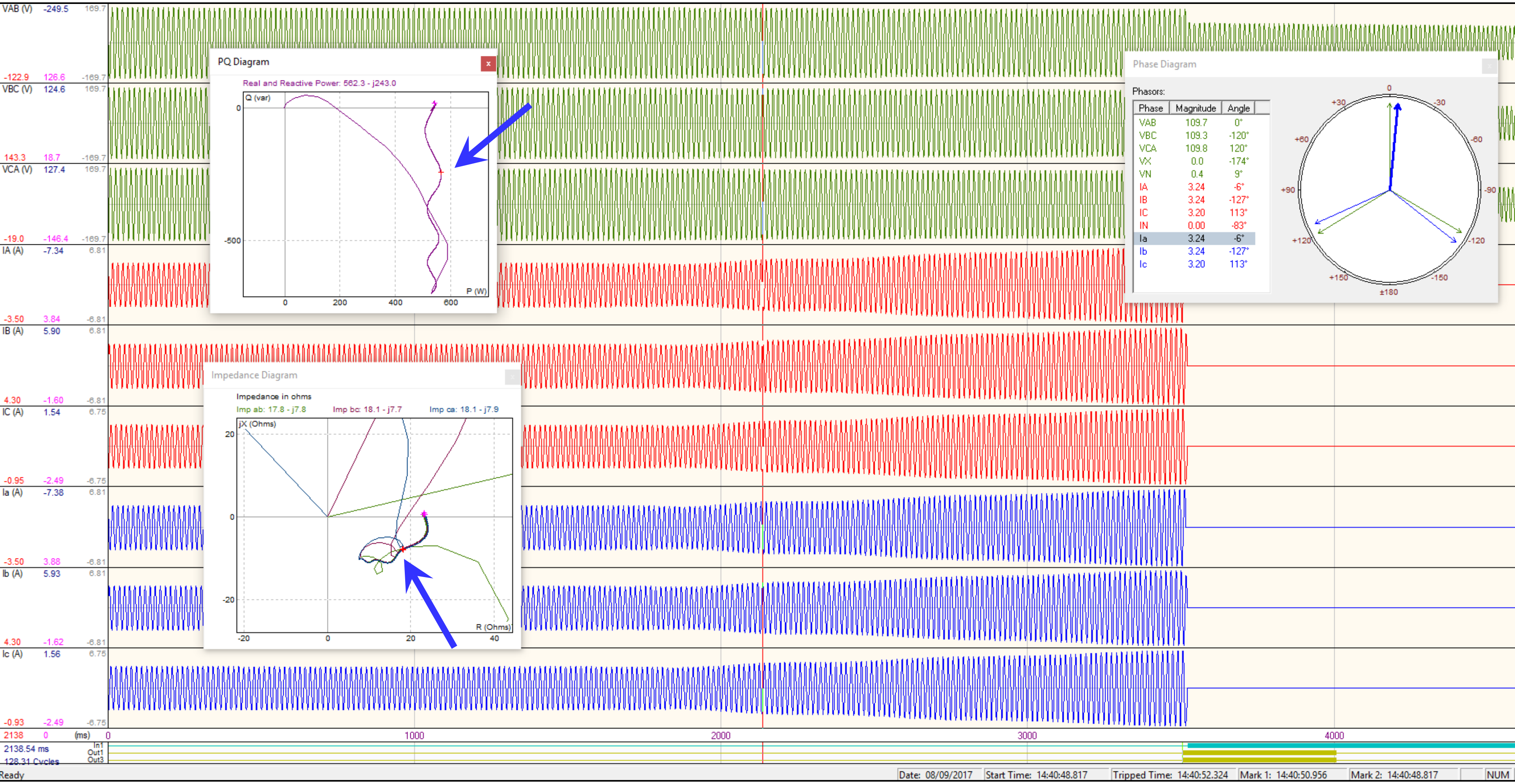
Ensure settings are correct (match indicated Trip Outputs, etc):



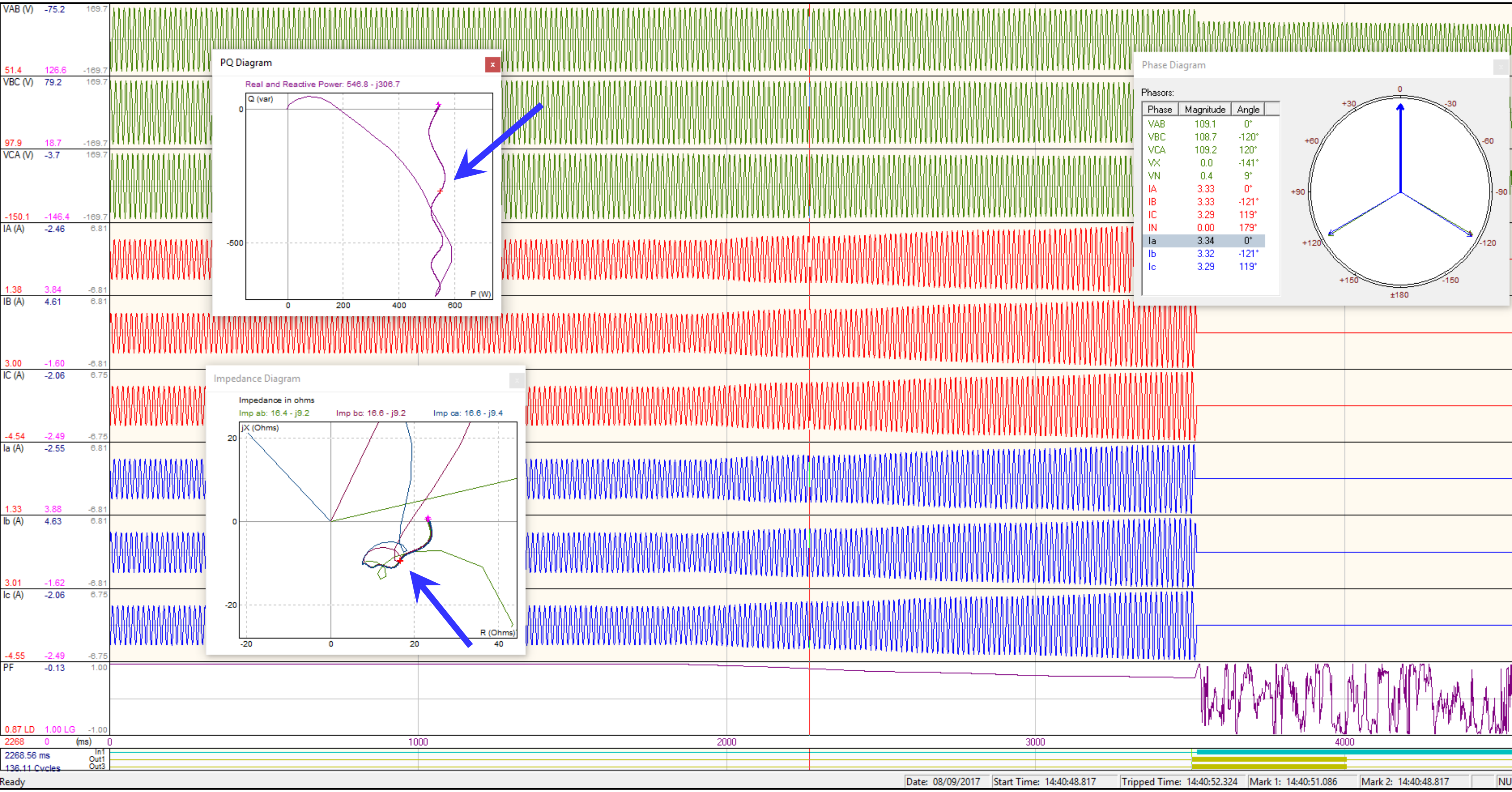
- Still normal, but starts heading towards leading region
- At unity PF, but 30 degree phase shift from VT Configuration = LL



- current phasor is heading towards voltage reference phasor
- Because of 30 degree phase shift, already in leading region on PQ and RX diagrams

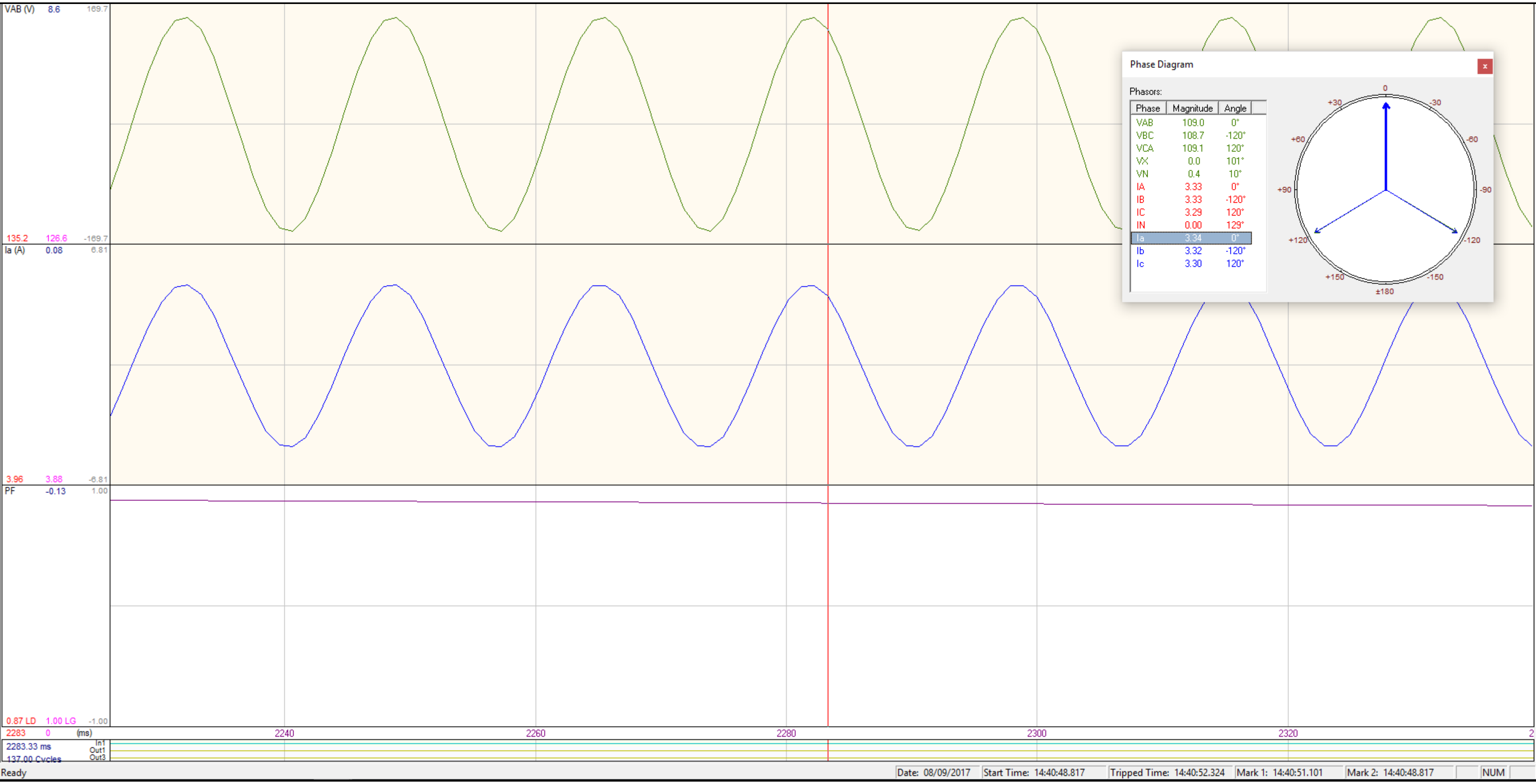


- current phasor on top of voltage reference phasor

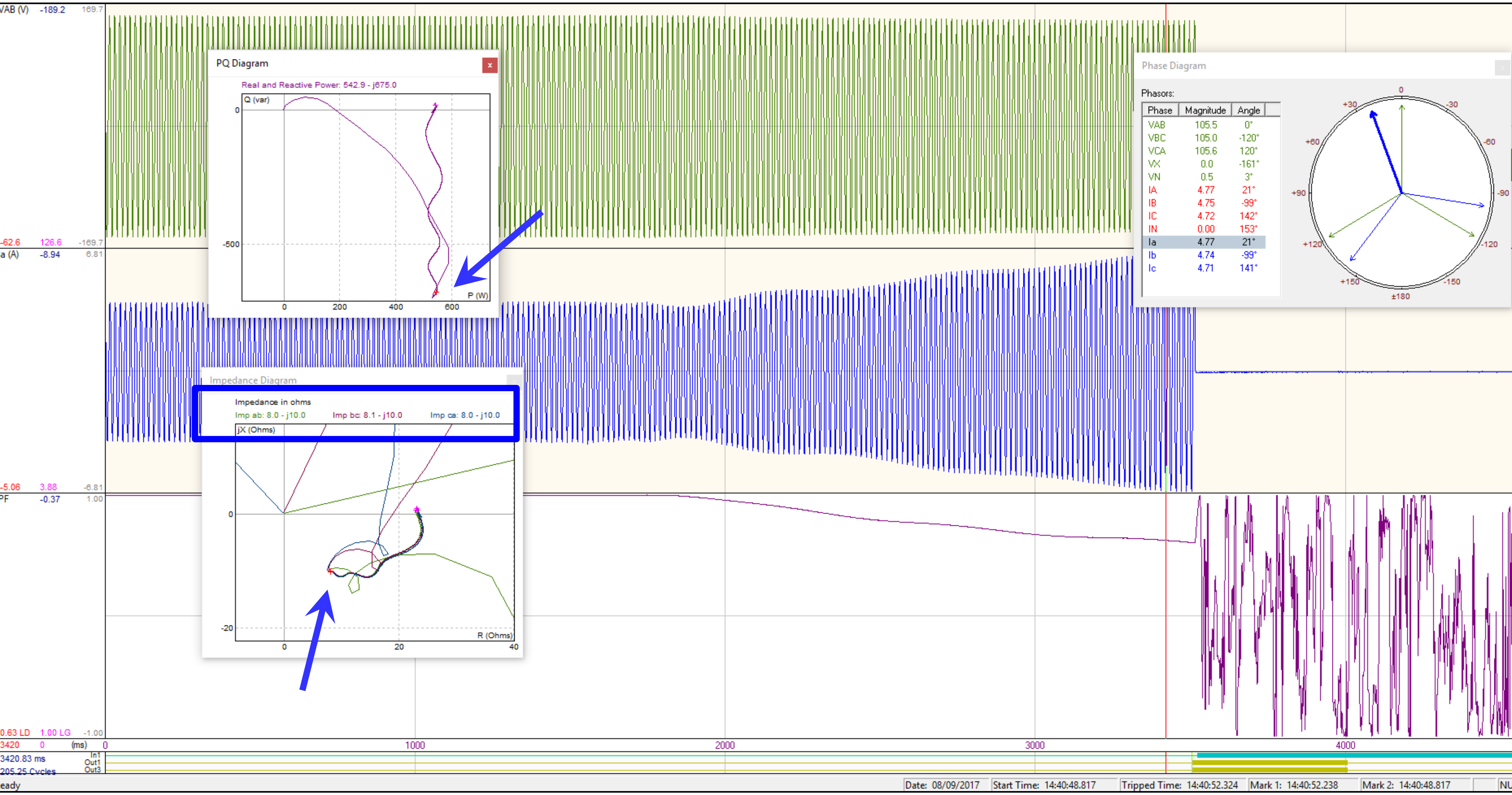


Phase	Magnitude	Angle
VAB	109.1	0°
VBC	108.7	-120°
VCA	109.2	120°
VX	0.0	-141°
VN	0.4	9°
IA	3.33	0°
IB	3.33	-121°
IC	3.29	119°
IN	0.00	179°
Ia	3.34	0°
Ib	3.32	-121°
Ic	3.29	119°

- PF = 0.87 leading, Inverse Cosine (0.87) = 30 degrees
- “Ia” in phase with “VAB”, so “Ia” leads “VAG” by 30 degrees



- Point at which the impedance enters zone 1 mho circle (5 cycles prior to trip)



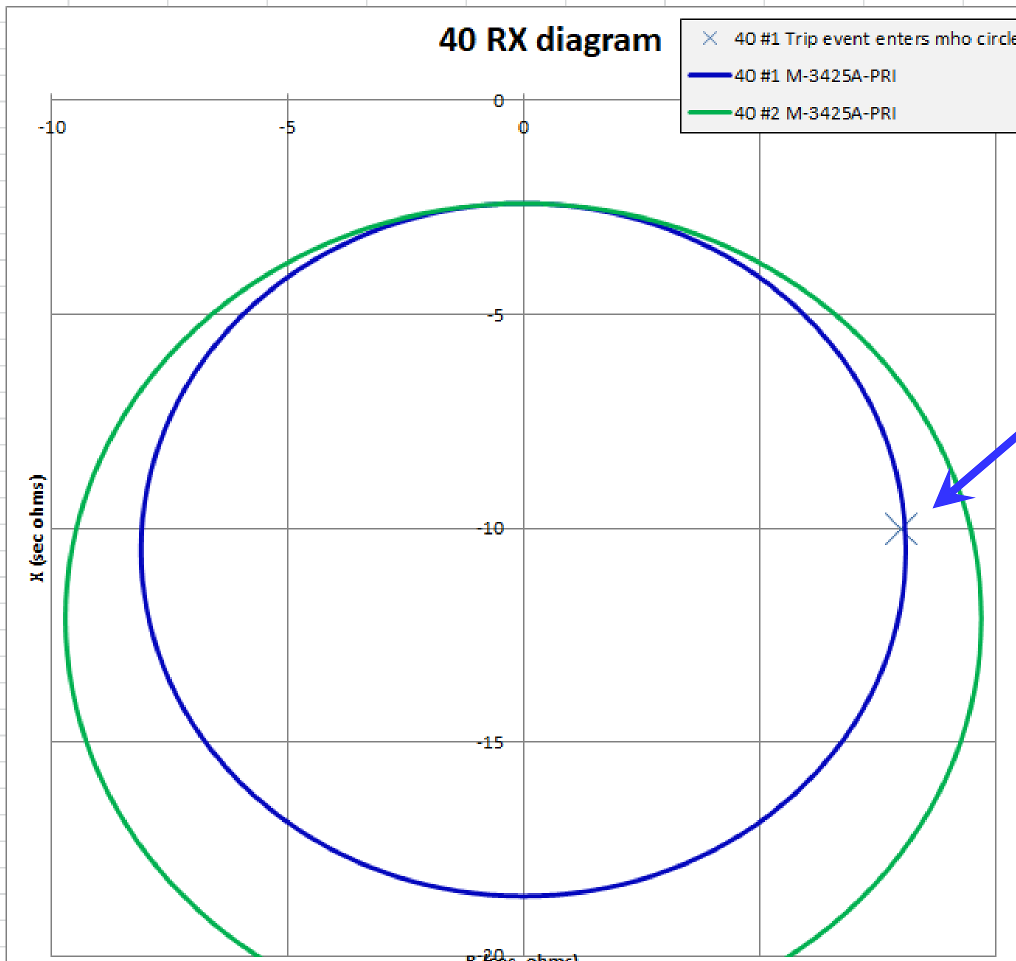
- Plot points from osc to ensure tripped correctly

40 - Loss of Field relay settings from M-3425A - negative offset zone 2 method

#1 Dia	16.2	sec ohms		Z1radius 8.1	R1circle center	0
#1 Offset	-2.4	sec ohms			X1circle center	-10.5
#1 Delay	5	cycles				
#1 VC Delay		cycles *				
#2 Dia	19.4	sec ohms		Z2radius 9.7	R2circle center	0
#2 Offset	-2.4	sec ohms			X2circle center	-12.1
#2 Delay	30	cycles				
#2 VC Delay		cycles *				
Dir		degrees **	DIR & VC are			
VC		volts ***	common to #1 & #2			

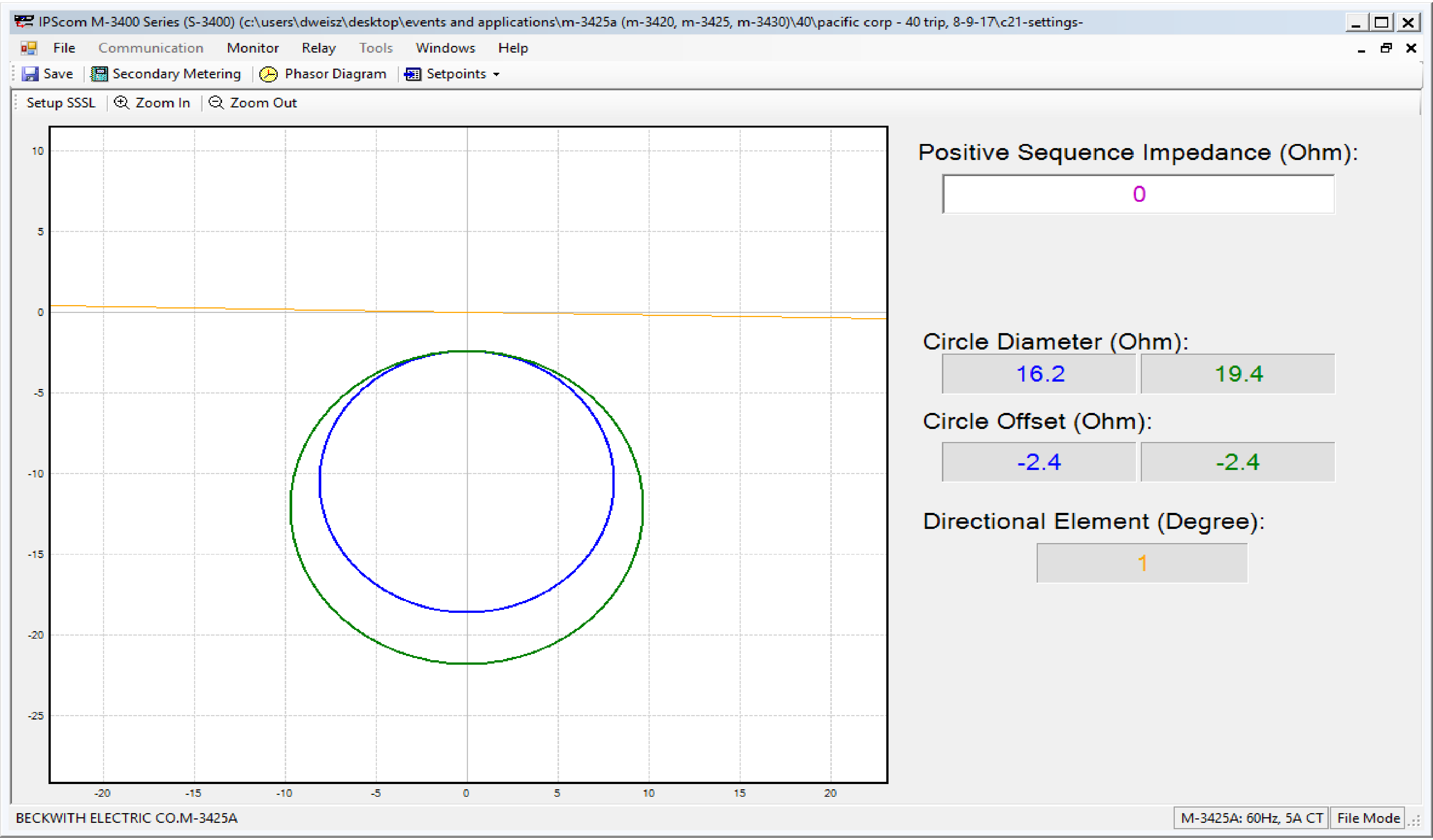
* accelerated tripping when accompanied by voltage dip
** n/a for negative offset
*** 80% of nominal voltage

	ZONE 1		ZONE 2	
angle	R1	X1	R2	X2
0	8.1	-10.5	9.7	-12.1
5	8.06917705	-9.79404	9.663089	-11.2546
10	7.9769428	-9.09345	9.552635	-10.4156
15	7.82399919	-8.40357	9.369481	-9.58946
20	7.61151023	-7.72964	9.115018	-8.7824
25	7.34109307	-7.07679	8.791186	-8.0006
30	7.01480577	-6.45	8.400446	-7.25
35	6.63513156	-5.85403	7.945775	-6.53631
40	6.20495999	-5.29342	7.430631	-5.86496
45	5.72756493	-4.77244	6.858936	-5.24106
50	5.20657964	-4.29504	6.23504	-4.66937
55	4.64596913	-3.86487	5.563691	-4.15423
60	4.05	-3.48519	4.85	-3.69955
65	3.42320792	-3.15891	4.099397	-3.30881
70	2.77036316	-2.88849	3.317595	-2.98498
75	2.09643427	-2.676	2.510545	-2.73052
80	1.40655024	-2.52306	1.684387	-2.54736
85	0.70596152	-2.43082	0.845411	-2.43691
90	4.9619E-16	-2.4	5.94E-16	-2.4
95	-0.7059615	-2.43082	-0.84541	-2.43691
100	-1.4065502	-2.52306	-1.68439	-2.54736
105	-2.0964343	-2.676	-2.51054	-2.73052
110	-2.7703632	-2.88849	-3.3176	-2.98498
115	-3.4232079	-3.15891	-4.0994	-3.30881
120	-4.05	-3.48519	-4.85	-3.69955
125	-4.6459691	-3.86487	-5.56369	-4.15423
130	-5.2065796	-4.29504	-6.23504	-4.66937
135	-5.7275649	-4.77244	-6.85894	-5.24106
140	-6.20496	-5.29342	-7.43063	-5.86496
145	-6.6351316	-5.85403	-7.94577	-6.53631

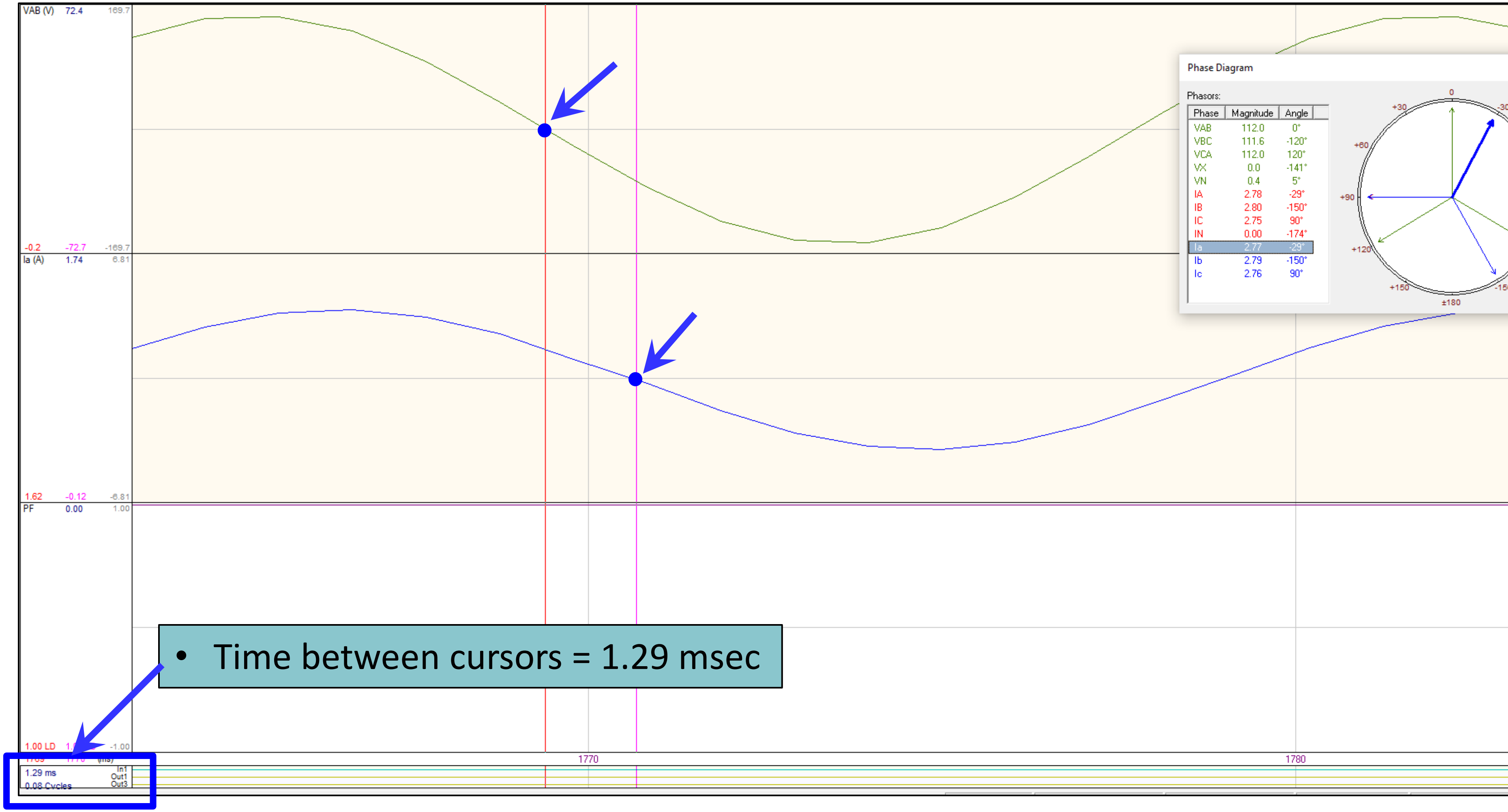


trip points from osc 5 cyc prior to trip	
8	-10
8	-10

- Compare to Loss of Field diagram via Monitor in IPScom
- With comtrade file, could play event in relay via Test Set (shows Z path on diagram)



- At start of event, prove that Ia lags VAB by 30 degrees:



- *How many seconds are in 1 sample, knowing that the M-3425A takes 16 samples per cycle:*

$$\frac{x\ seconds}{1\ sample} = \frac{1\ second}{60\ cycles} * \frac{1\ \text{cycle}}{16\ \text{samples}}$$

$$x\ seconds = 1\ sample * \frac{1\ second}{60\ cycles} * \frac{1\ \text{cycle}}{16\ \text{samples}}$$

$$x\ seconds = \frac{1}{60 * 16} = \frac{1}{960} = 0.00104\ seconds\ or\ 1.04\ msec$$

- *Now, how many degrees are in the 1.29 msec between the zero crossing of "Ia" versus the zero crossing of "VAB":*

$$\frac{x\ degrees}{1.29\ msec} = \frac{360\ degrees}{1\ cycle} * \frac{1\ \text{cycle}}{16\ \text{samples}} * \frac{1\ \text{sample}}{1.04\ \text{msec}}$$

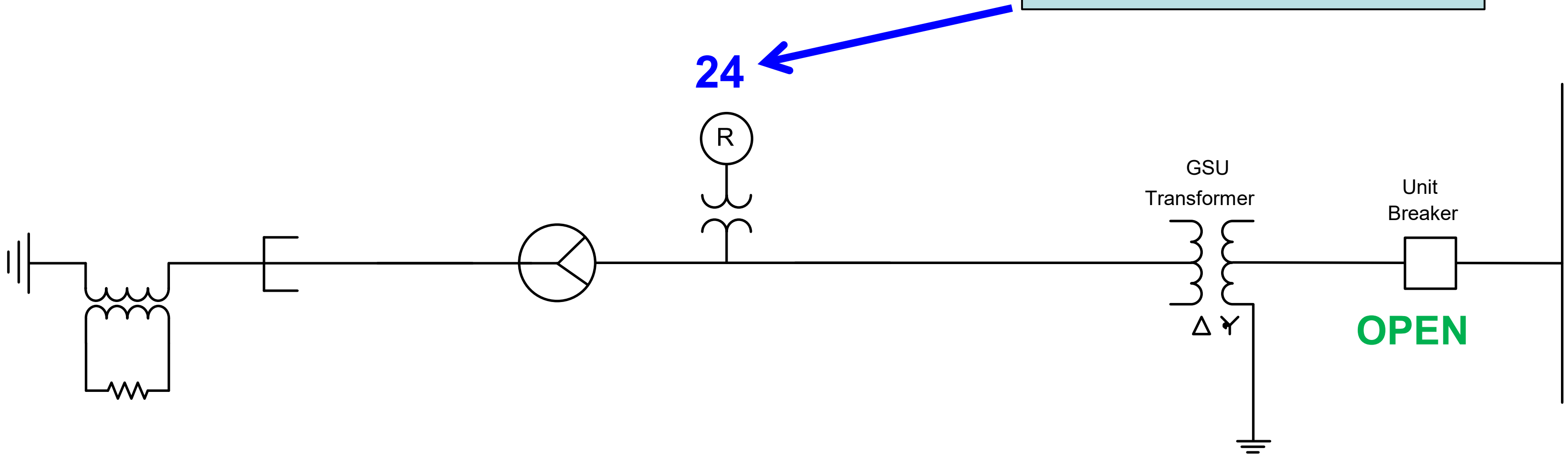
$$x = \frac{1.29*360}{16*1.04} = 28\ degrees \approx 30\ \text{degrees}$$

40 Event Analysis Conclusion

- Reported and showed customer, relay operated correctly.
- Relay tripped 5 cyc after locus entered the zone 1 mho circle.
- There was an issue with the AVR (no more details than that).
- When moving the event forward in time, whenever you see the current phasor change from lagging to leading on the Phasor Diagram that is pretty telling of a true Loss of Field event.
- Additionally, it is easy to see via the PQ and RX diagrams on the Oscillography Analysis Software.

24 – Volts/Hz (Overexcitation)

from gen relay or GSU relay or both



$$B = \frac{Volts}{Hz}$$

- *Excessive B (magnetic flux density) causes overexcitation*
- *frequency measured from voltage waveform*
- *Recommend to set both 24 and 59 functions.*

24 Event 1

gen running at rated freq (59.99 Hz) and rated voltage (69.3 V so VT Config = LG) so V/Hz should be 100% i.e. V/Hz=(69.3/69.3)/(60/60) = 1 pu. However, it shows V/Hz = 57.8 %:

99. 05/12/2020, 09:35:31.897

Picked up Inputs:
Picked up Ouputs:
32 #1: Pickup/
32 #3: Pickup/

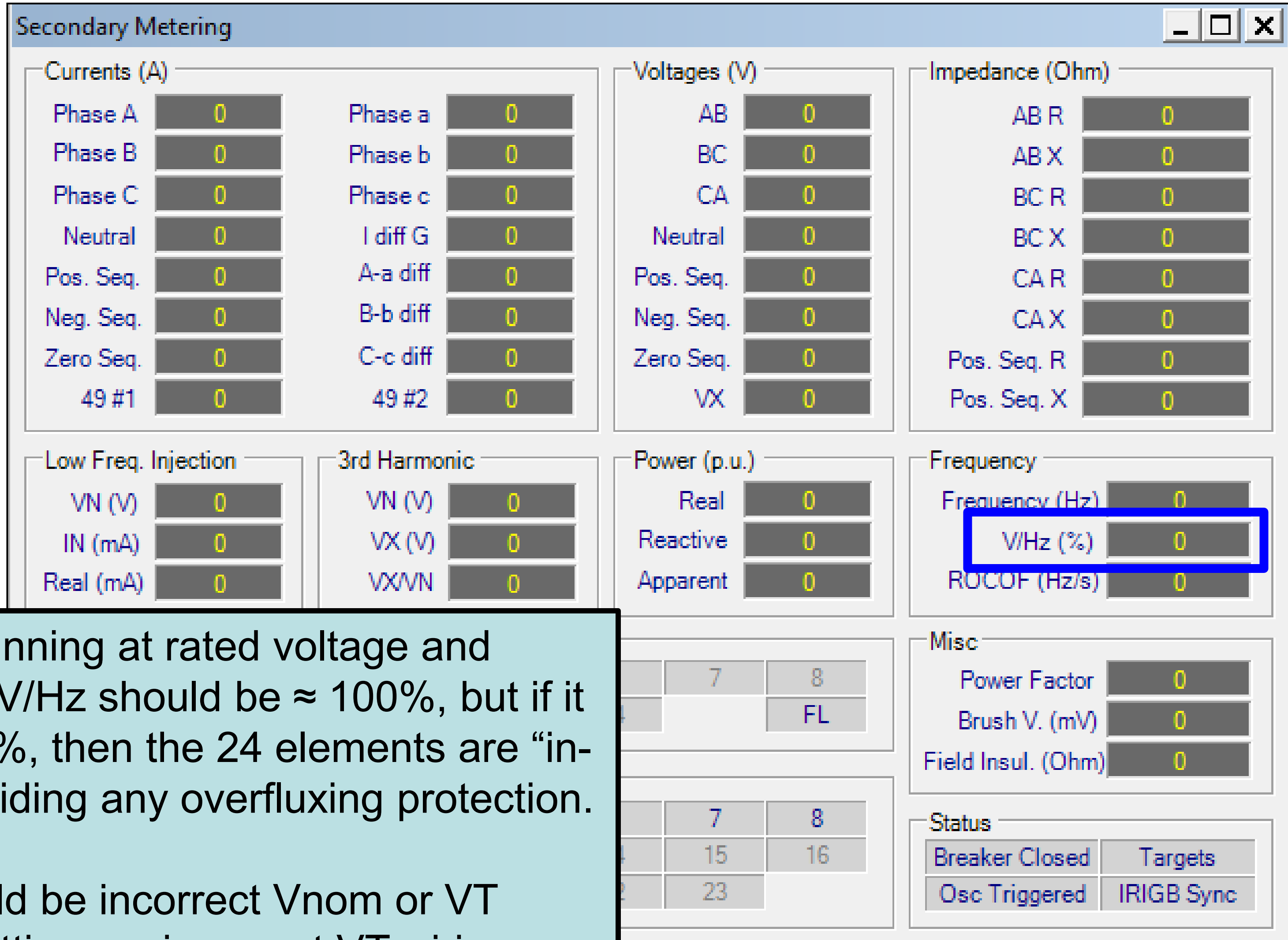
Dropped Inputs:
Dropped Ouputs:
32 #2: Pickup/

VA:	69.3 (V)	VB:	69.4 (V)	VC:	69.3 (V)	VN:	0.3 (V)
VX:	0.0 (V)	VPS:	69.3 (V)	VNS:	0.2 (V)	VZS:	0.4 (V)
IA:	0.16 (A)	IB:	0.18 (A)	IC:	0.17 (A)	IN:	0.00 (A)
Ia:	0.17 (A)	Ib:	0.19 (A)	Ic:	0.17 (A)	IPS:	0.17 (A)
INS:	0.02 (A)	IZS:	0.00 (A)	Ia Diff:	0.01 (A)	Ib Diff:	0.01 (A)
Ic Diff:	0.01 (A)	RAB:	-198.40 (Ohm)	XAB:	-310.02 (Ohm)	RBC:	-115.76 (Ohm)
XBC:	-327.68 (Ohm)	RCA:	-224.08 (Ohm)	XCA:	-327.68 (Ohm)	Frequency:	59.99 (Hz)
V/Hz:	57.8 (%)	ROC Freq:	0.02 (Hz/s)	Real Power:	-0.010 (PU)	React Power:	-0.021 (PU)
PS Real Imped:	327.67 (Ohm)	PS React Imped:	327.67 (Ohm)	Phase Angle:	-45.1 (Degree)	Delta V:	69.3 (V)
Delta Freq:	3.000 (Hz)	VN 3rdH:	3.03 (V)	VX 3rdH:	0.00 (V)	59D ratio:	0.00
Field Insul.:	<1K (Ohm)	V Brush:	247 (mV)	V Stator:	0.0 (V)	I Stator:	0.0 (mA)
Profile:	1						

- Why? Because Vnom was set at 120 V: V/Hz=(69.3/120)/(60/60) = 0.58 pu.
- Vnom should have been set at 69.3 V or could change VT = LG-LL and leave Vnom at 120 V but then must change all other voltage-based settings to LL voltage as well.
- **This relay was in-service for 12 years without any 24 protection.**

24 Event 1 – check step when unit first goes on-line:

- **When generator VTs are first energized, check V/Hz on Metering screen:**



When gen is running at rated voltage and frequency, the V/Hz should be ≈ 100%, but if it is instead ≈ 58%, then the 24 elements are "in-effect" not providing any overfluxing protection.

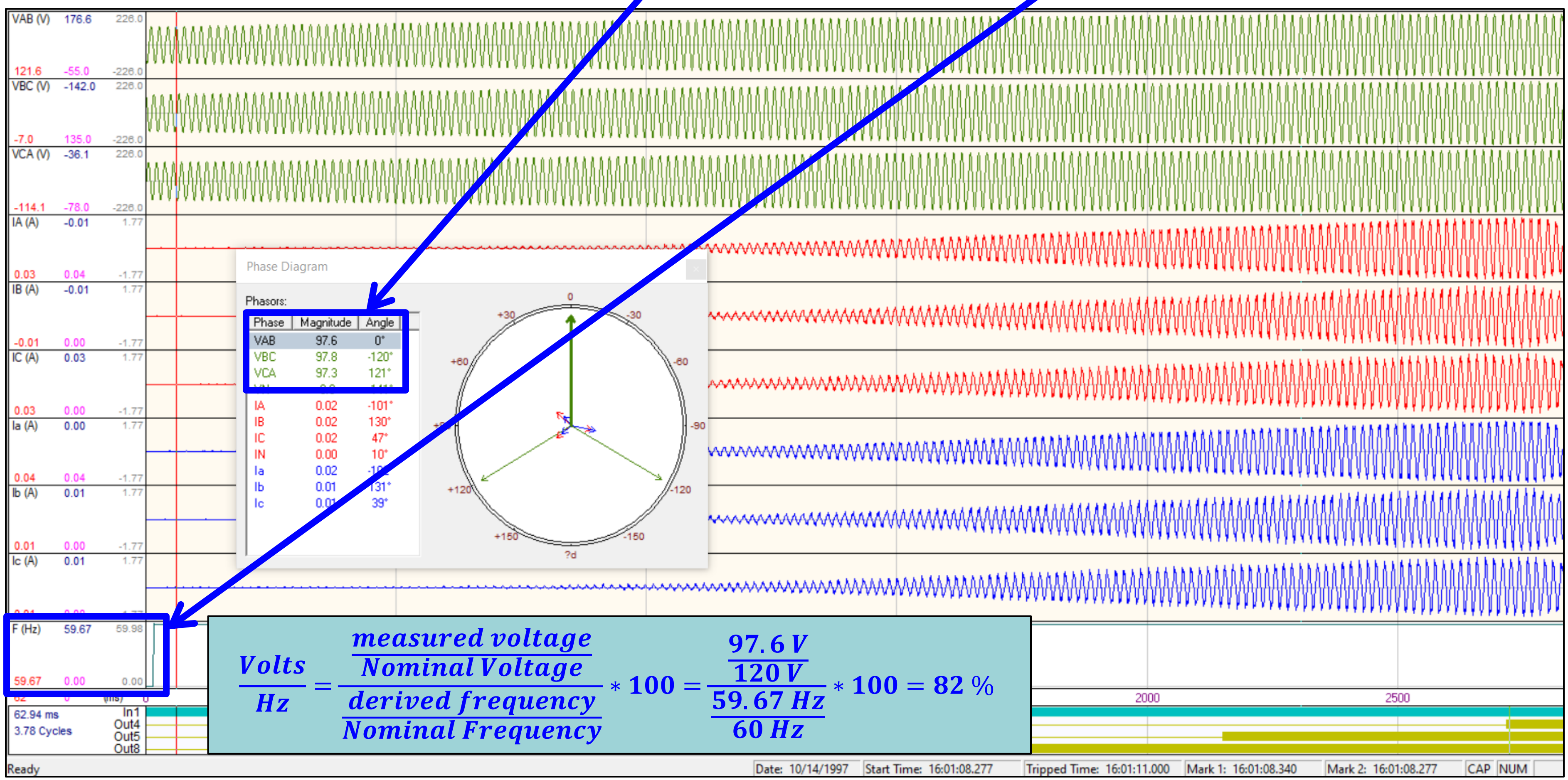
The cause could be incorrect Vnom or VT Config relay settings or incorrect VT wiring.

24 Event 2

Event: 24 Trip while off-line in the pre-synchronizing period

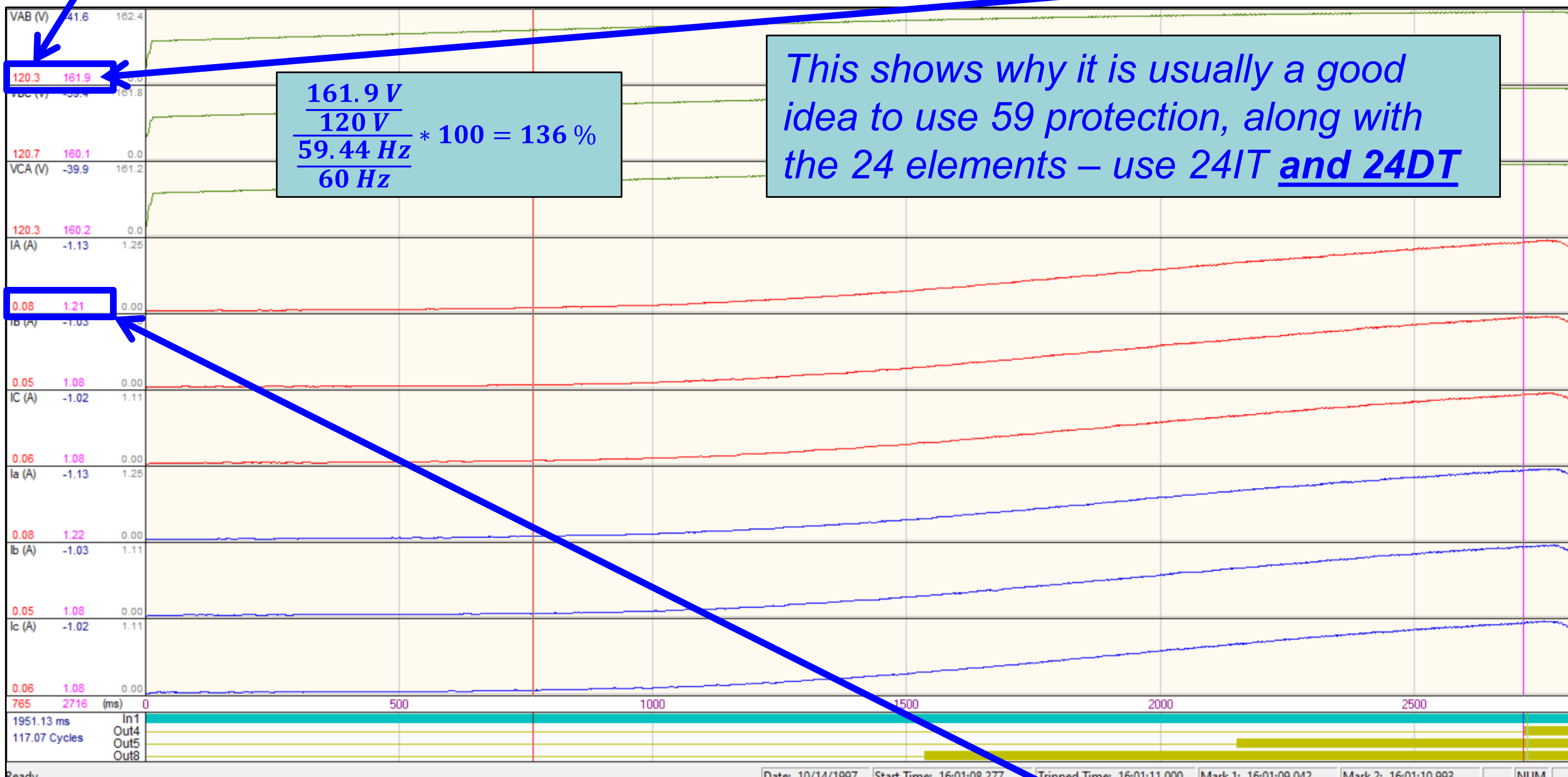
- Unit connected generator (no low side gen breaker).
- High side breaker is open.
- Excitation is boosted to get ready for the synch closure.

- At start of event, LL phase voltage was 97.6 V and frequency was at 59.67 Hz.
- And the current was zero at that point as one would expect with the GSU HS breaker open.
- But the current will increase a bit just strictly as magnetizing current into the GSU.



$$\frac{Volts}{Hz} = \frac{\frac{measured\ voltage}{Nominal\ Voltage}}{\frac{derived\ frequency}{Nominal\ Frequency}} * 100 = \frac{\frac{97.6\ V}{120\ V}}{\frac{59.67\ Hz}{60\ Hz}} * 100 = 82\ \%$$

- At 120 V nominal voltage (red cursor) it should have stopped boosting, and at that time the GSU magnetizing current was very low, just 0.08 A.
- At the time the trip occurred, the voltage had boosted all the way up to **161.9 V**.

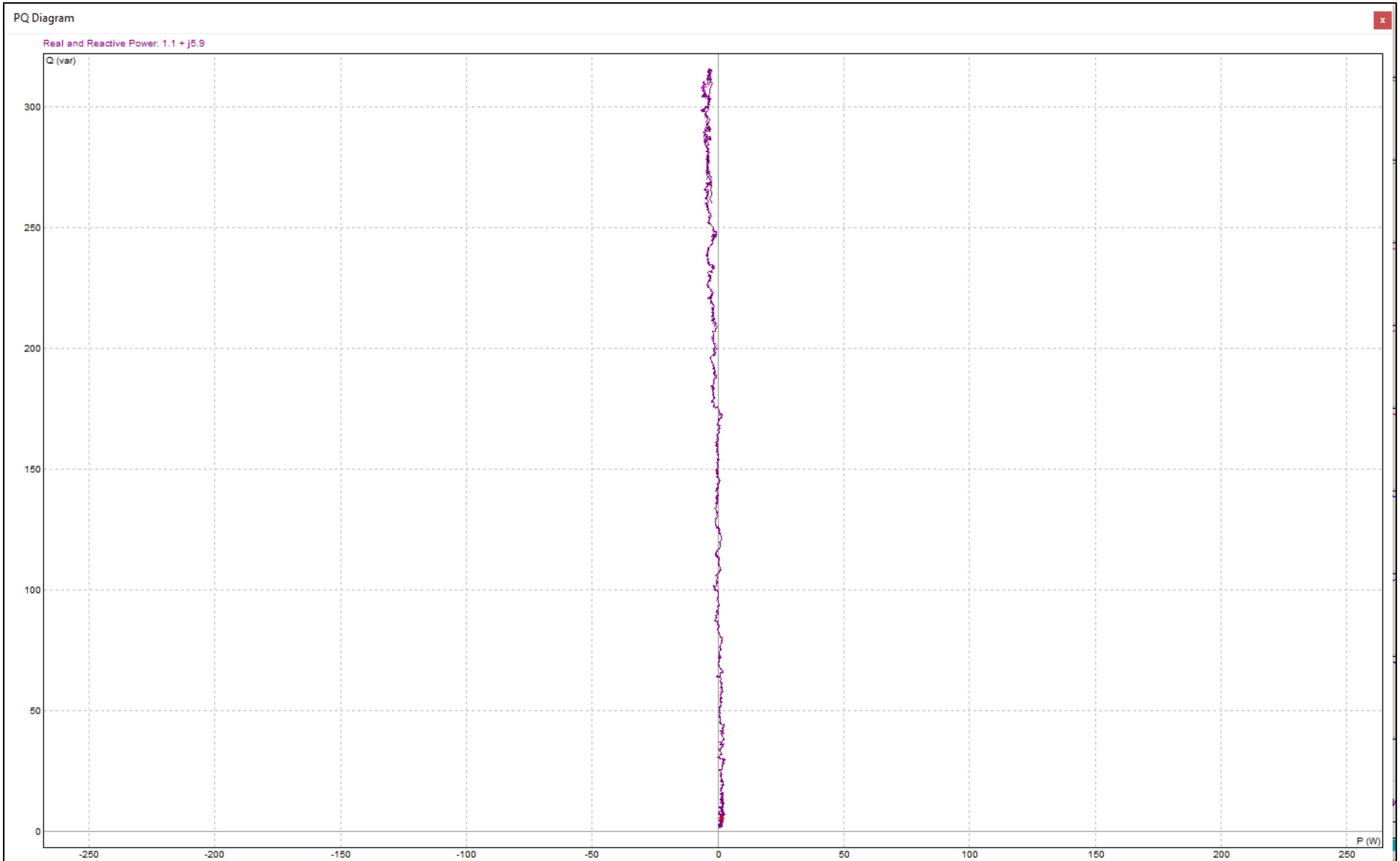


$$\frac{\frac{161.9\,V}{120\,V}}{\frac{59.44\,Hz}{60\,Hz}} * 100 = 136\,\%$$

This shows why it is usually a good idea to use 59 protection, along with the 24 elements – use 24IT ***and 24DT***

Once the voltage gets high enough to cause overexcitation, 1.21 A of current flows into the GSU and flux spills over into and heats non-laminated parts of the GSU.

- By the time it tripped, it was pushing a lot of Vars into the GSU:



24 Event 2 – Conclusion

- Cause was found to be a runaway excitation system due to blown fuse and the excitation control system had no such blocking for blown fuse so as it saw no volts, it kept trying to boost the voltage.

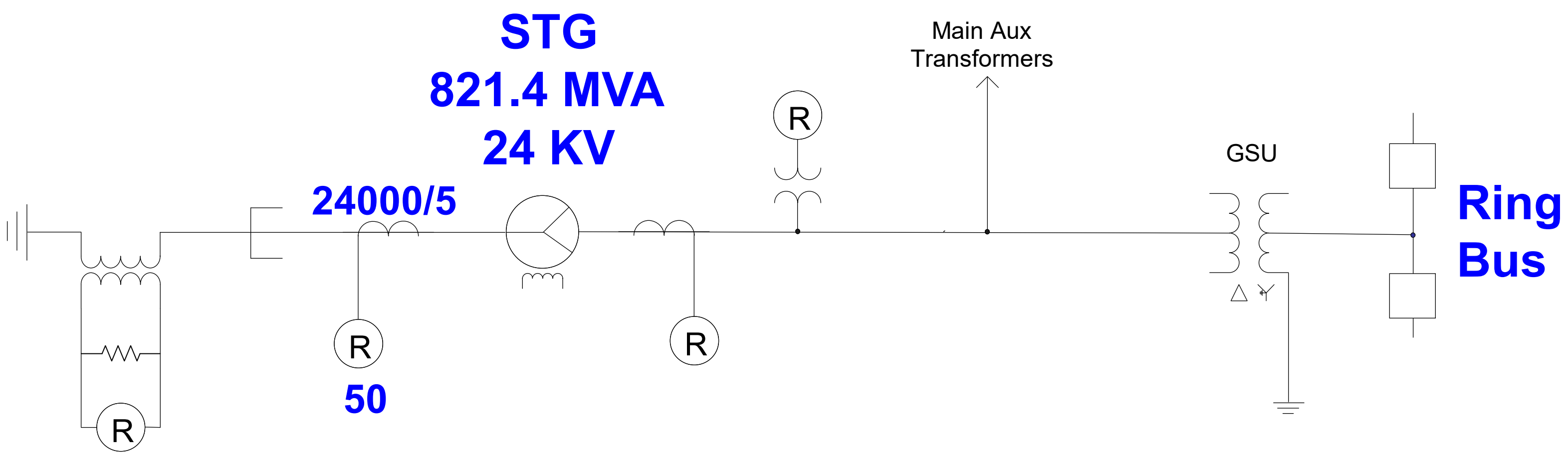
- This shows why I always preferred not to block 24 with FL because if excitation and relay are driven from the same VTs, then the relay's 24 protection would not have tripped if FL blocking were implemented.

- Where did the current go if the GSU HS breaker is open?

- Into the GSU and then out as heat.

- Conservation of energy…….electricity in, heat out.

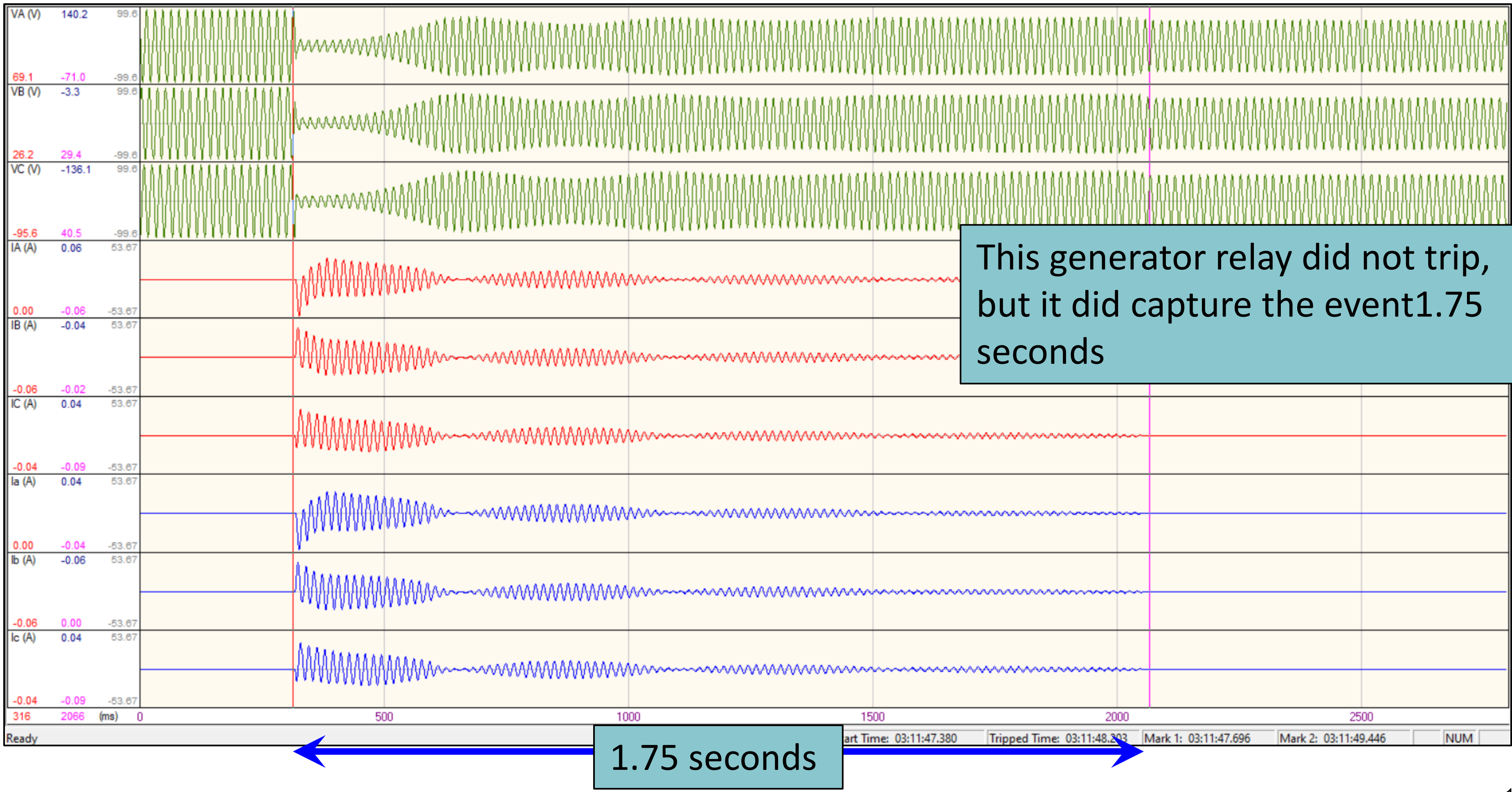
50 with IPSlogic (Isync Trip)

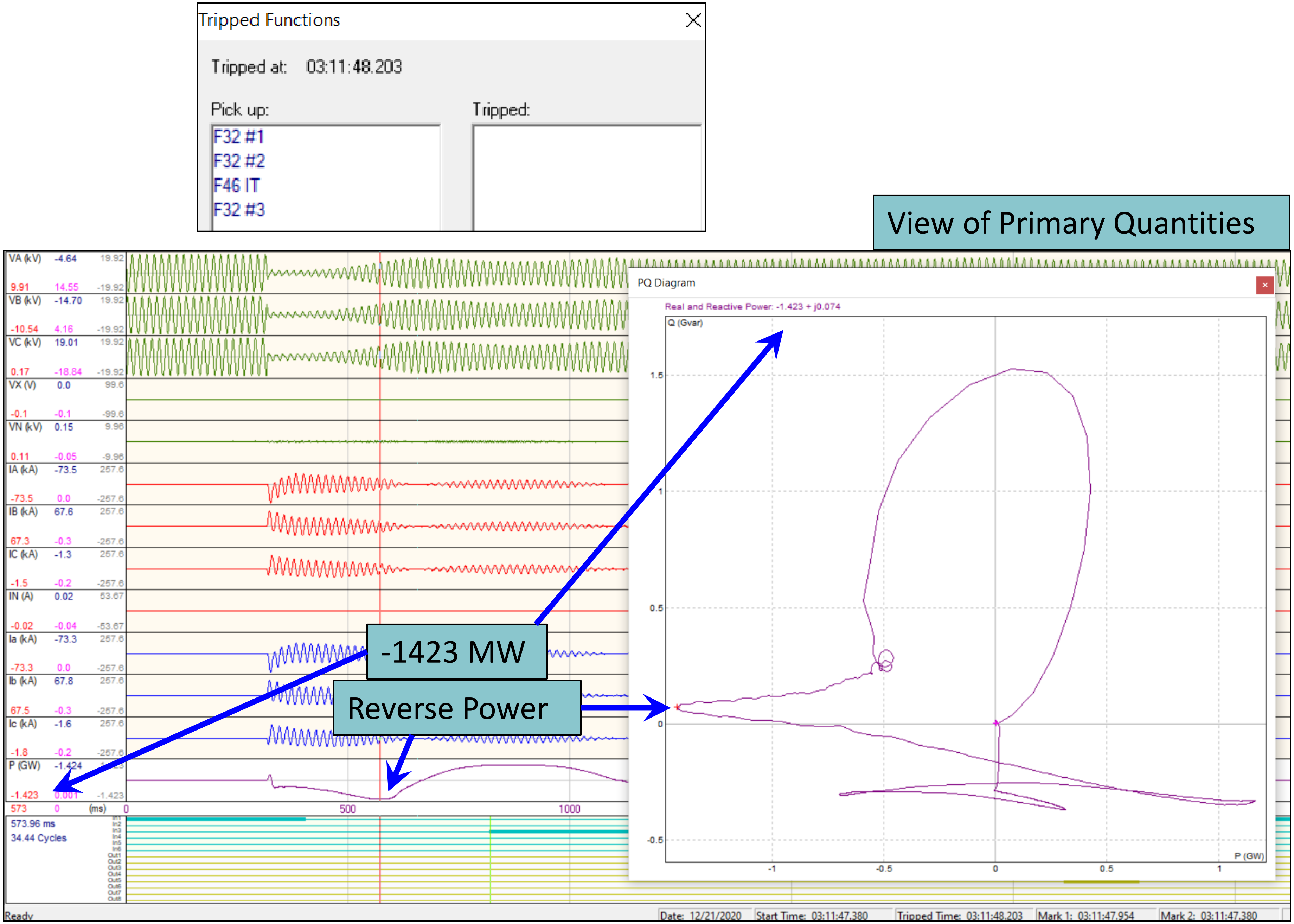


- Some type of a current-based Isync Trip scheme or Out-Of-Phase Synch (OOPS) protection could have been helpful to detect this event and shorten the amount of time before tripping.
- **However, a current-based Isync Trip scheme would not have prevented this event from occurring i.e. it can only detect it after it has already occurred but still helpful to limit extent of damage.**

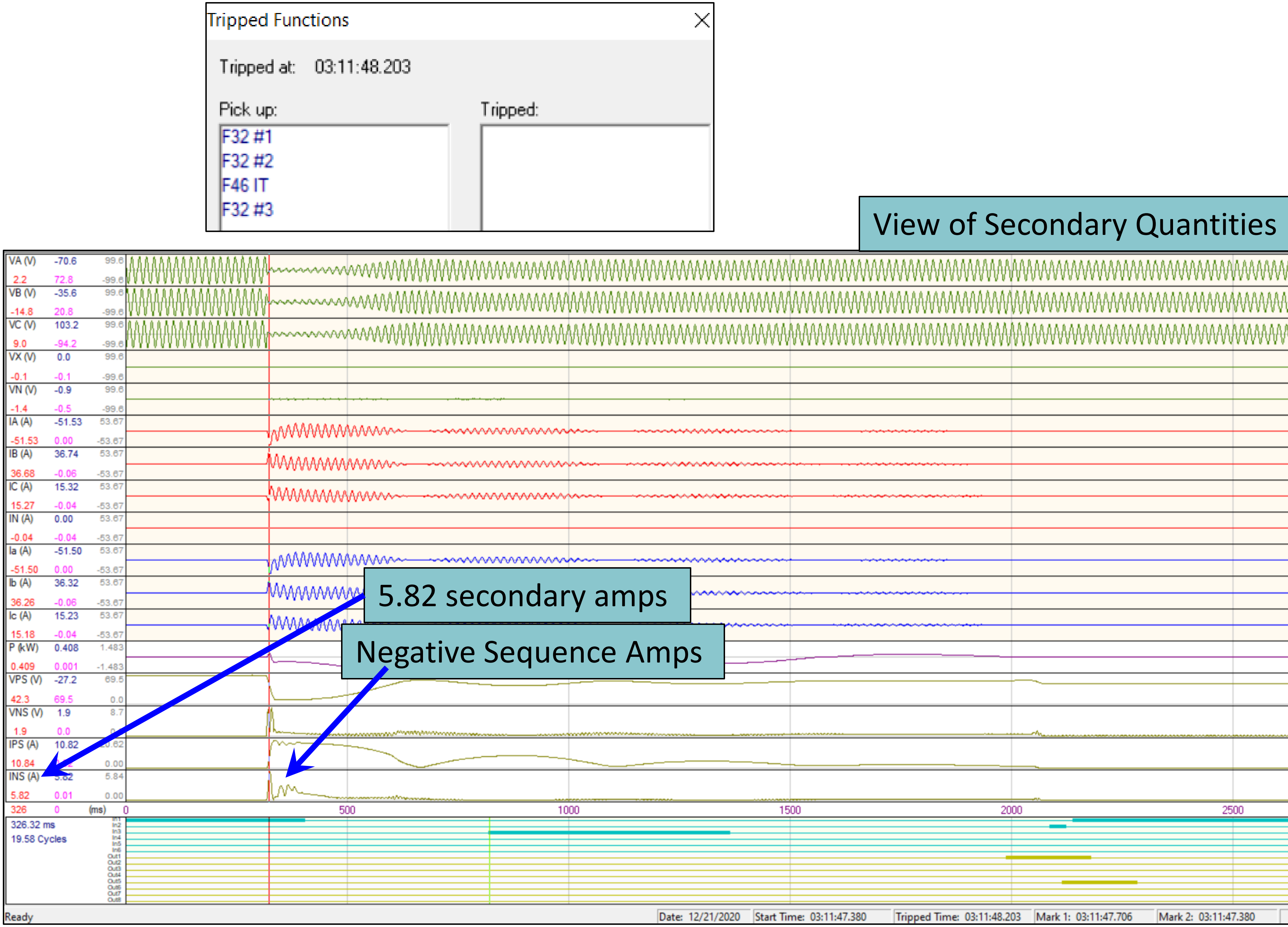
Out-of-Phase Closure Event Analysis

- Customer reported this occurred during a **manual sync** when they closed in the GSU high side breaker out-of-phase causing the “building to shake” and resulting in extensive rotor damage and a long outage.

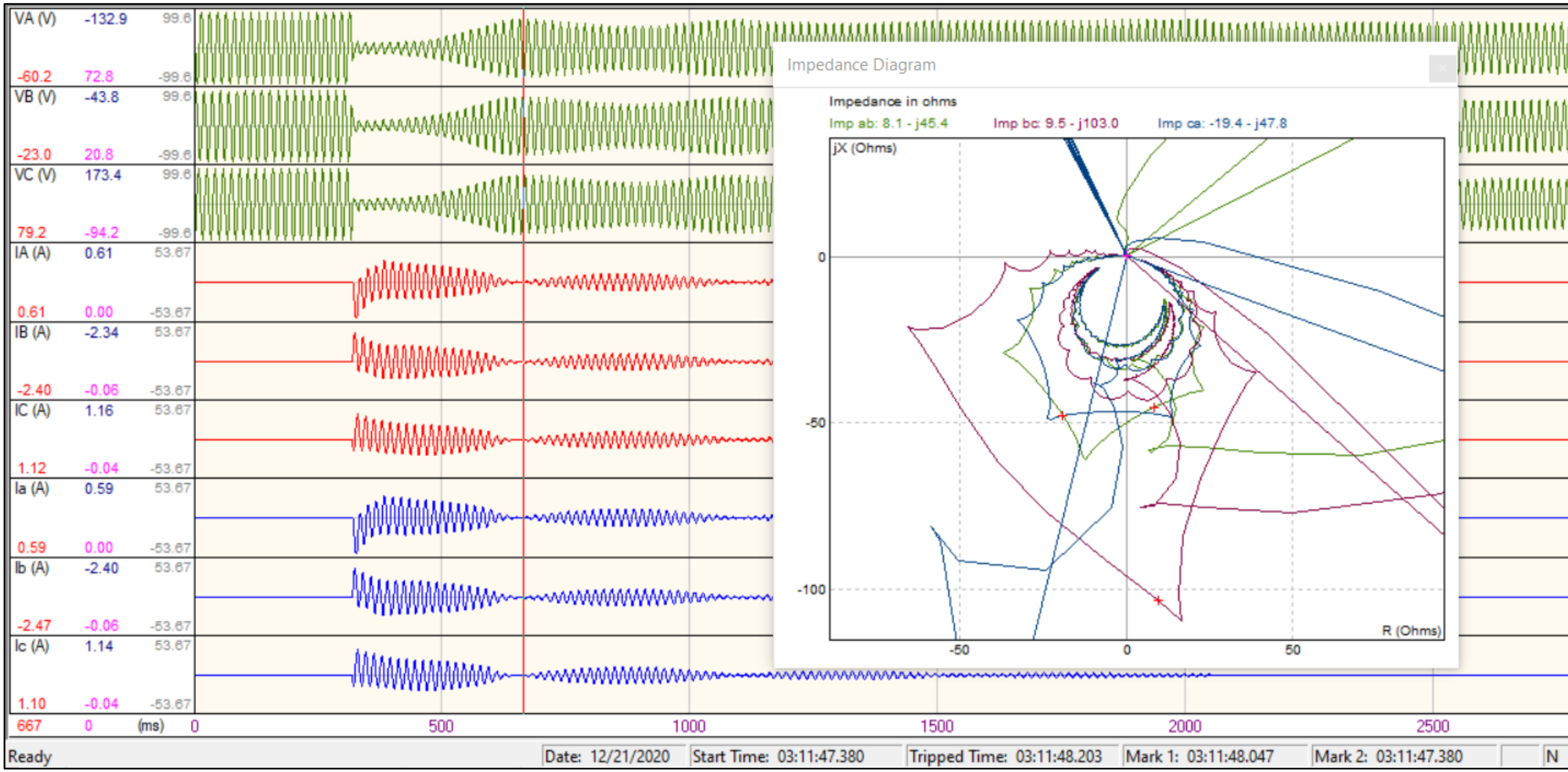



Tripped Functions
Tripped at: 03:11:48.203
Pick up:
F32 #1
F32 #2
F46 IT
F32 #3
Tripped:
View of Primary Quantities
PQ Diagram
Real and Reactive Power: -1.423 + j0.074
Q (Gvar)
P (GW)
-1423 MW
Reverse Power
573.96 ms
34.44 Cycles
Ready
Date: 12/21/2020
Start Time: 03:11:47.380
Tripped Time: 03:11:48.203
Mark 1: 03:11:47.954
Mark 2: 03:11:47.380

View of Secondary Quantities



78 Out of Step protection was disabled in this application; however, even if it was enabled and if it was set using typical criteria it would not have seen this event as the event locus would not have entered a 78 permissive mho circle and traverse both 78 blinders in sequence i.e. the electrical center of the swings below do not pass thru the gen/GSU zone.



- The max current from the oscillography showed 21.64 Asec.
- $I_{pu} = \frac{Iactual}{Ibase} = \frac{21.64}{4.12} = 5.25\, pu \quad (5.25\ times\ nominal\ current)$
- This is like locked rotor amps to start an induction motor.

- 21.64 Asec * 24000/5 = 103,872 Apri
- $I_{fault} = I_{pu} * I_{base} = \frac{v}{Xd"} * \frac{S}{\sqrt{3} * V_{LL}} = \frac{1}{0.16} * \frac{821.4M}{\sqrt{3} * 24K} = 123{,}499\ Apri$
- 50/27, inadvertent energization protection will typically not see this event as the voltage is at nominal voltage approximately in this pre-synchronizing period.

- Convert this out-of-phase closure amps to an angle via eqn:

$$Iac := \frac{\sqrt{Es^2 + Eg^2 - 2 \cdot Es \cdot Eg \cdot \cos(\delta s)}}{Xg1subunsat + Zt + Zs1} \cdot \frac{Sbase \cdot 1000}{\sqrt{3} \cdot VbaseLS}$$

- Solve for angle:

$$\delta s := \operatorname{acos}\left(\frac{Es^2 + Eg^2 - \left(\dfrac{Iac \cdot (Xg1subunsat + Zt + Zs1)}{\dfrac{Sbase \cdot 1000}{\sqrt{3} \cdot VbaseLS}} \right)^2}{2 \cdot Es \cdot Eg} \right) \cdot \frac{180}{\pi}$$

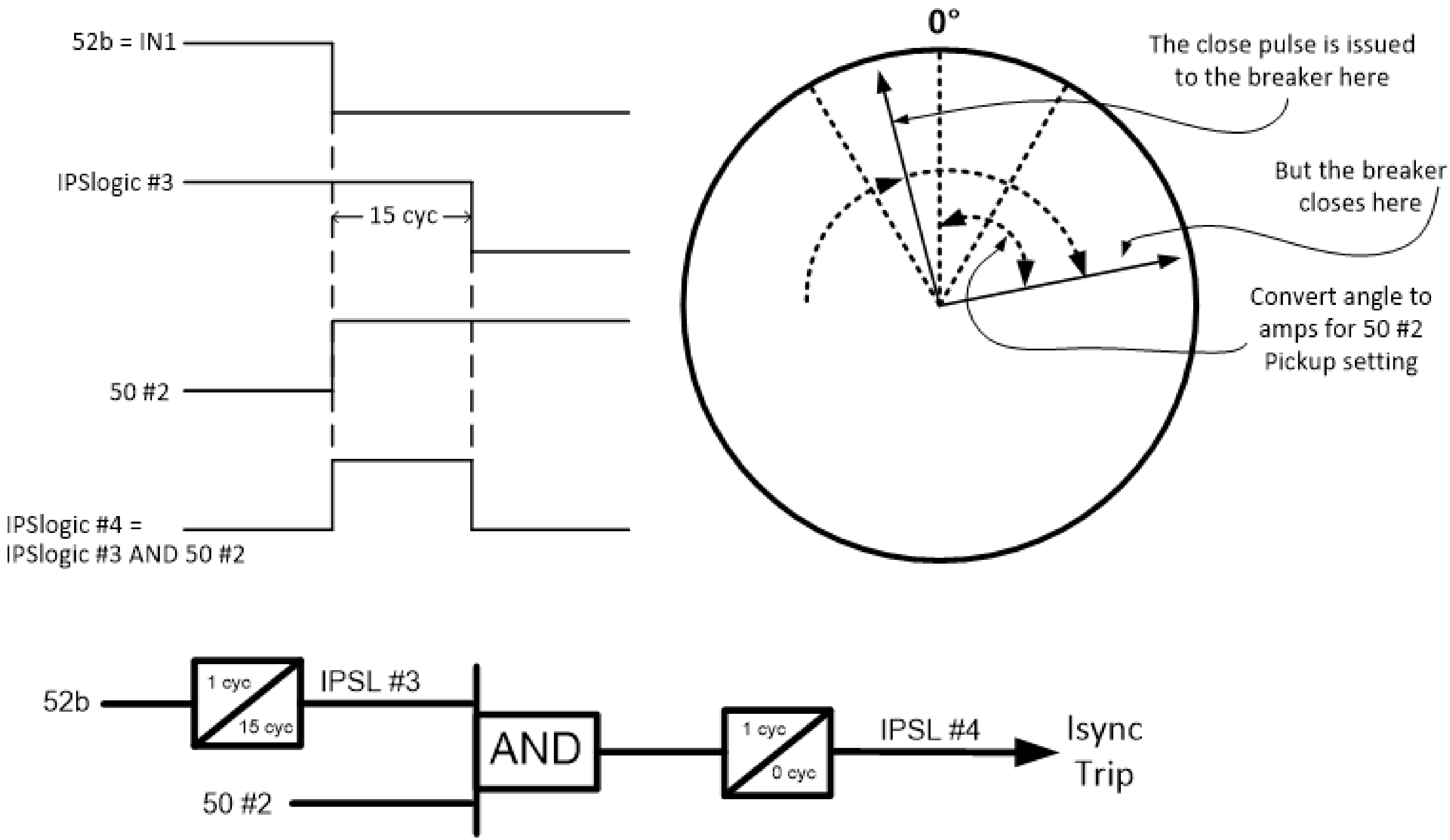
- Worst case fault amps occurs at 180°
- Worst case Torque occurs at 120°

1. Phase Angle Difference between VB_kV and VS_kV phasors at time of event
2. Waveform showing difference between System and Generator at time of event
3. OUT102 command to Breaker Close coil is not supervised by the 25A1 element which is shown with the 52A feedback

- A **current-based** out-of-phase synch close protection will immediately trip after the breaker closes out of phase.
- It is not necessary to BF trip back a zone as the closure has already occurred so can just trip the subject breaker itself.

- An **angle-based** out-of-phase synch close protection is another method which operates based on the measured angle after the final 25A close pulse is issued.
- BF trip back a zone once the “damage” angle is measured.
- Saves damage as it does not have to wait for the breaker to close and once it does close, it closes onto a dead bus.
- Should be programmed in the same device that is doing 25A.
- Could cause unnecessary outage if the breaker never does close so tripping back a zone is unnecessary.

- **Current-based** Isync Trip protection scheme:



Sync Panel

SYNC SLIP FREQ OK
SLOW
FAST
SYNCHROSCOPE
SYNC VOLTS OK
SYNC PHASE ANGLE OK
REVERSE POWER TRIP TIMING
GENERATOR BREAKER SYNC SWITCH
GENERATOR BREAKER
GENERATOR BREAKER SYNC SWITCH
GENERATOR BREAKER

FAST
SYNCHROSCOPE
SYNC SLIP FREQ OK
SYNC VOLTS OK
SYNC PHASE ANGLE OK

2 causes of the event:

- The manual sync check relay (solid state) failed in the closed position due to circuit board level component failure.
- Also, the pistol grip switch to manually sync close the breaker was forcibly held in the closed position.

Recommendations:

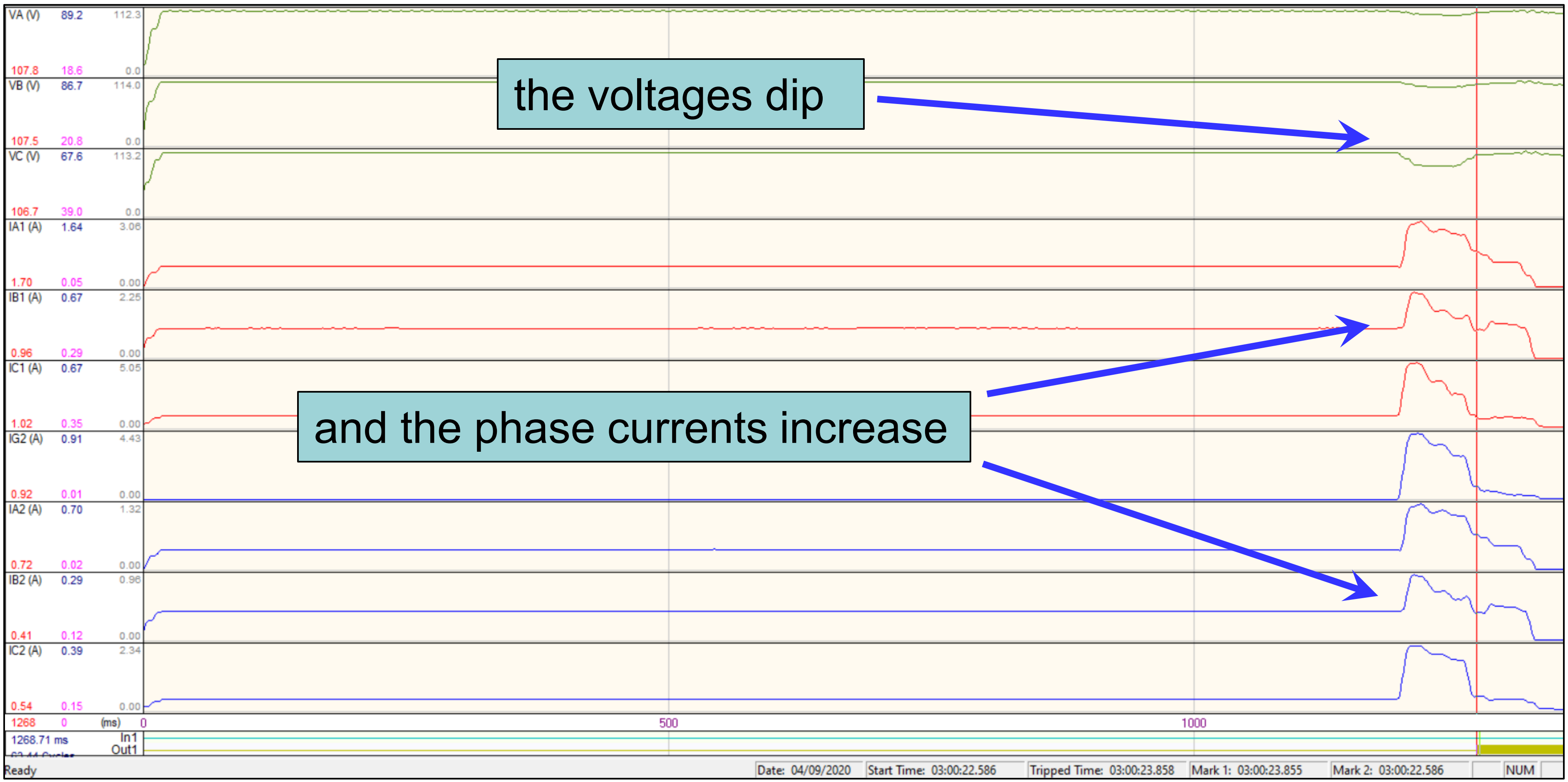
- When manually syncing a generator on-line, only "momentarily" turn the pistol grip switch to the close position just prior to when the sync scope reaches 12 o'clock noon. Then release the handle immediately to allow it to freely spring back to center position.
- Never hold the breaker close switch in the close position and trust that the "25" sync check relay will only allow a close at 0 degrees or 12 noon.

Considerations:

1. Backup protection from breaker control relays
2. Redundancy vs. coordination
3. Utilize a Close Out of Sync Detection (25/50) Element to reduce duration and consequence of event (Does Not Prevent Event)
4. Importance of data from quality protective relaying, excitation controls, fault recorders
5. Active Field Ground Detection
6. Information Available to Operators
7. Lessons Learned and Sharing

Bonus Event – any guesses?

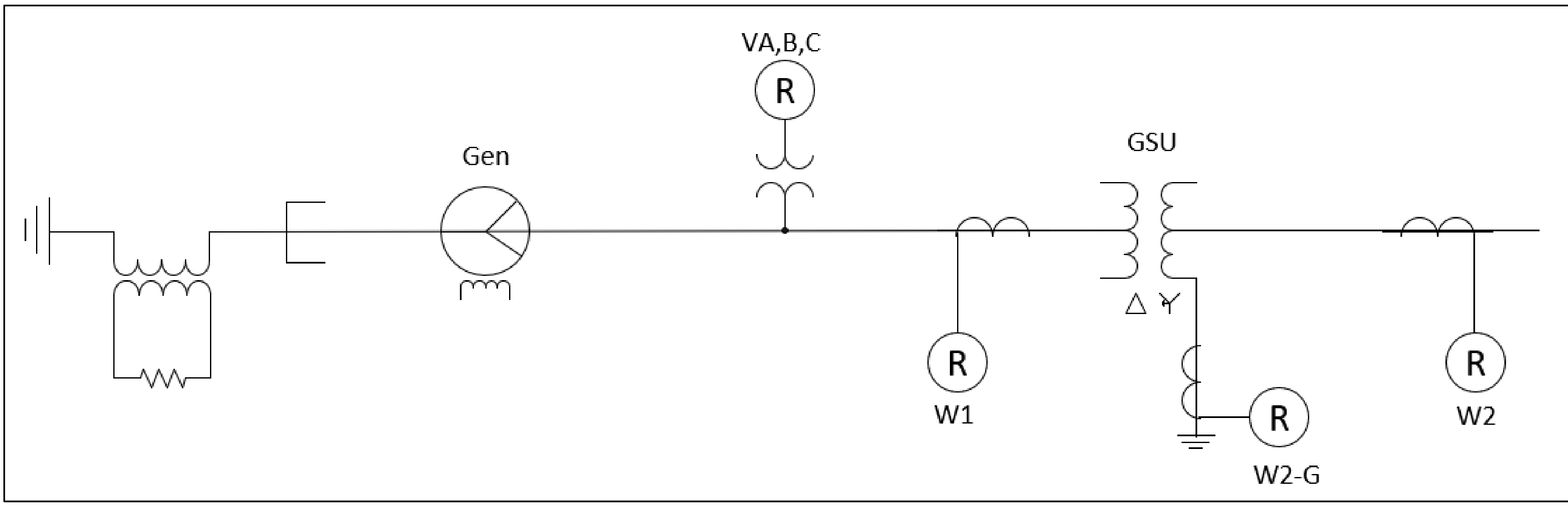
Looking at the RMS tracings of the waveforms, the current and voltages are running per normal, then:



This was an 87T trip from an M-3310 relay on a GSU:

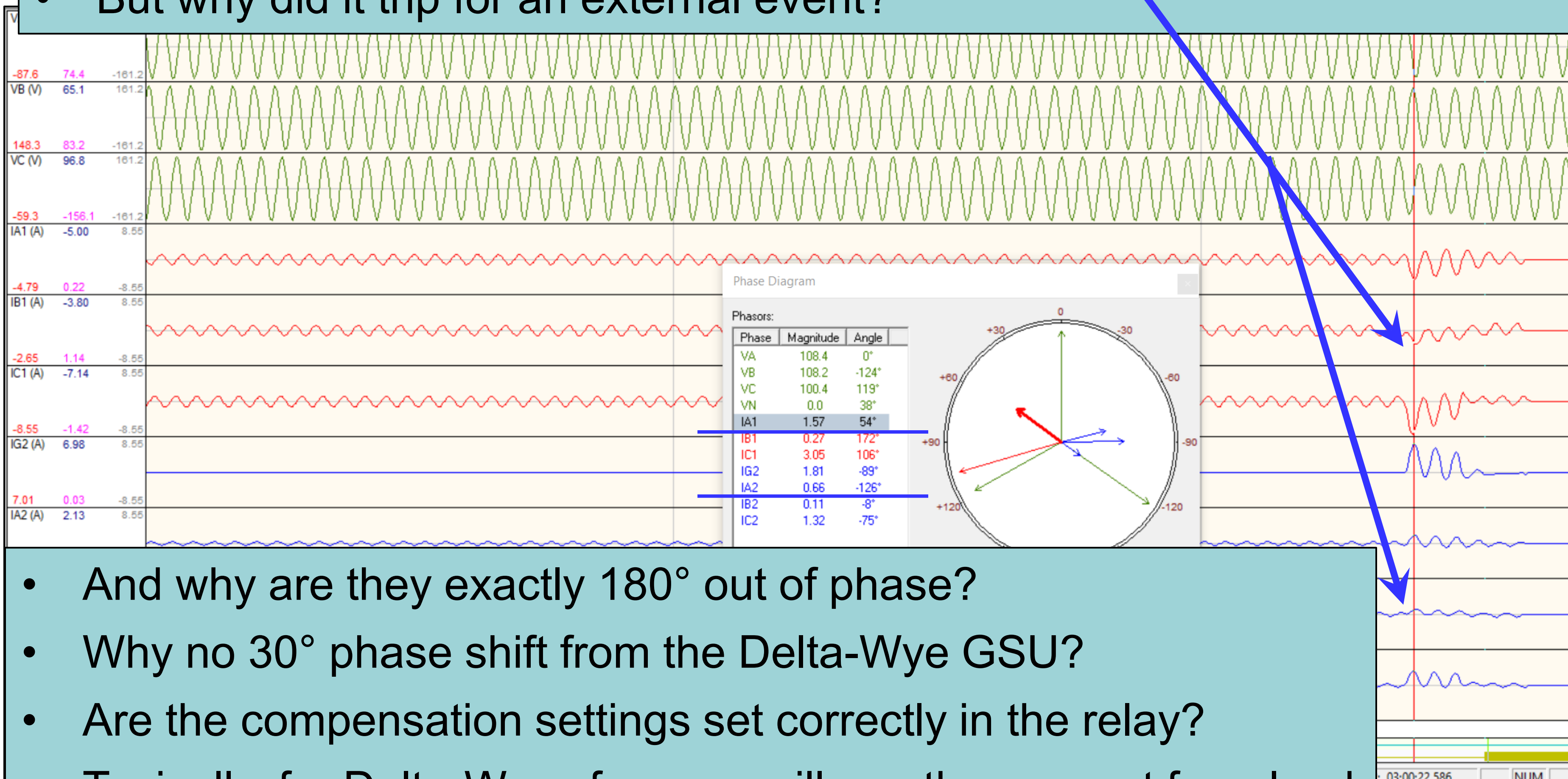
09-Apr-2020 03:5 1 (51W2)Inv. Time Phase Overcurrent - Phase A Picked Up
(51W2)Inv. Time Phase Overcurrent - Phase C Picked Up
(51G) Inv. Time Neutral Overcurrent Picked Up
(87T) Phase Differential Current - Phase C Operated

INPUTS: OUTPUTS: 1
W1 Currents: 1.98 A (A), 1.29 A (B), 0.90 A (C)
W2 Currents: 0.88 A (A), 0.56 A (B), 0.50 A (C), 1.56 A (N)



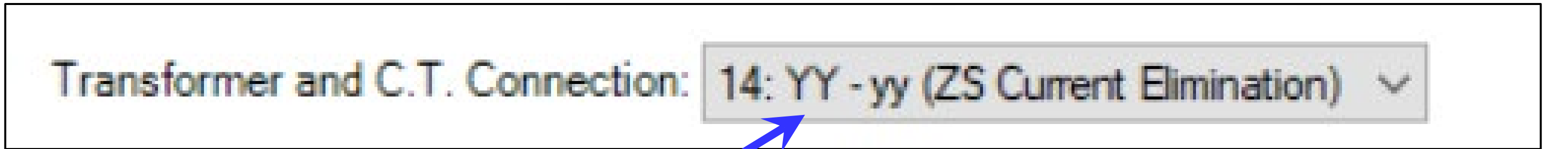
- Why did it trip?
- Was it an internal GSU fault?

- Here we can see that the phase currents are 180° out of phase which would be consistent with some type of an external event.
- But why did it trip for an external event?

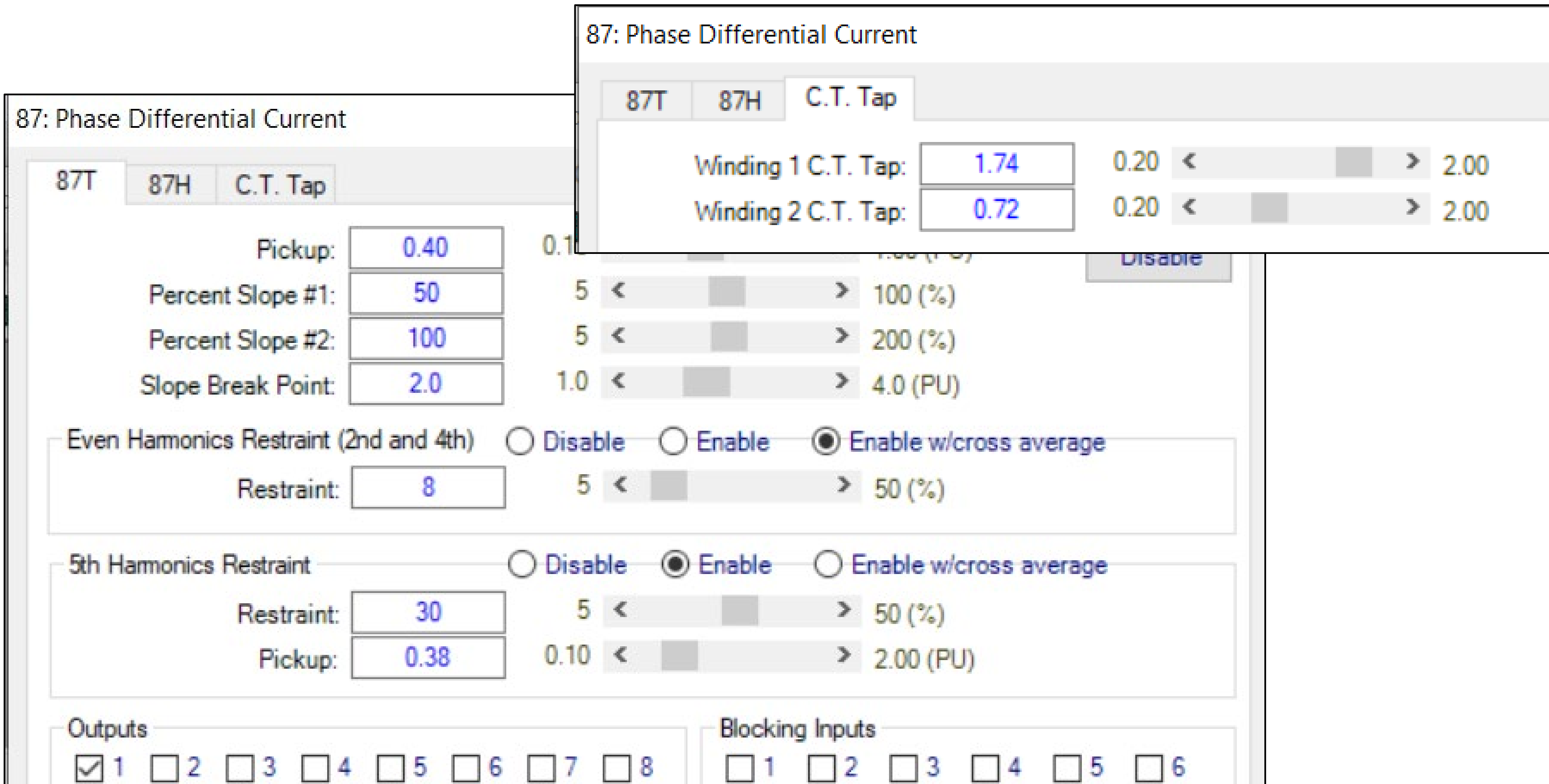


- And why are they exactly 180° out of phase?
- Why no 30° phase shift from the Delta-Wye GSU?
- Are the compensation settings set correctly in the relay?
- Typically, for Delta-Wye xfmr, you will see thru current from load or external event be 150° (Dab) or 210° (Dac) apart – HS Wye leads LS Delta by 210°.

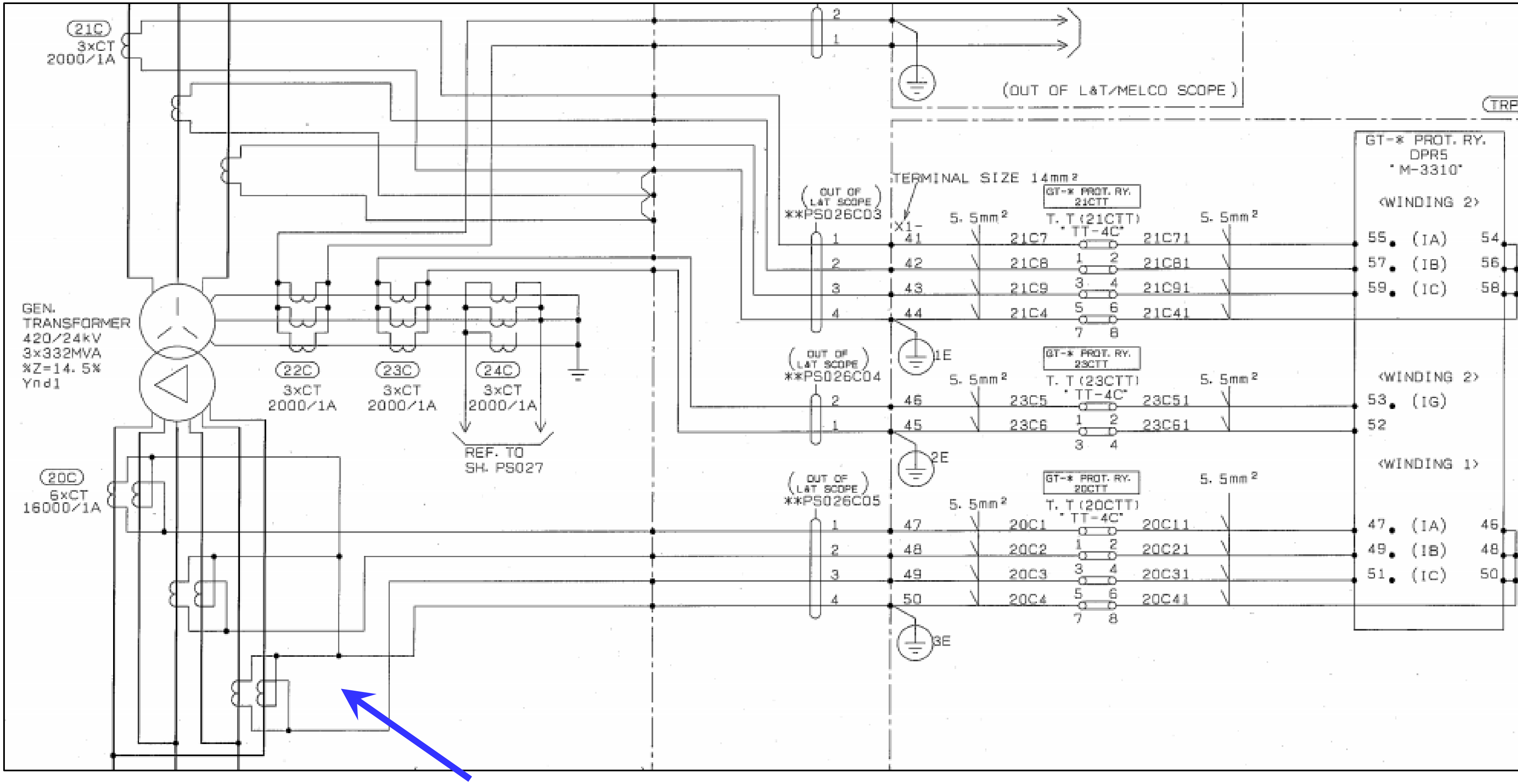
Check the 87T Transformation/CT compensation, CT Tap settings, etc:



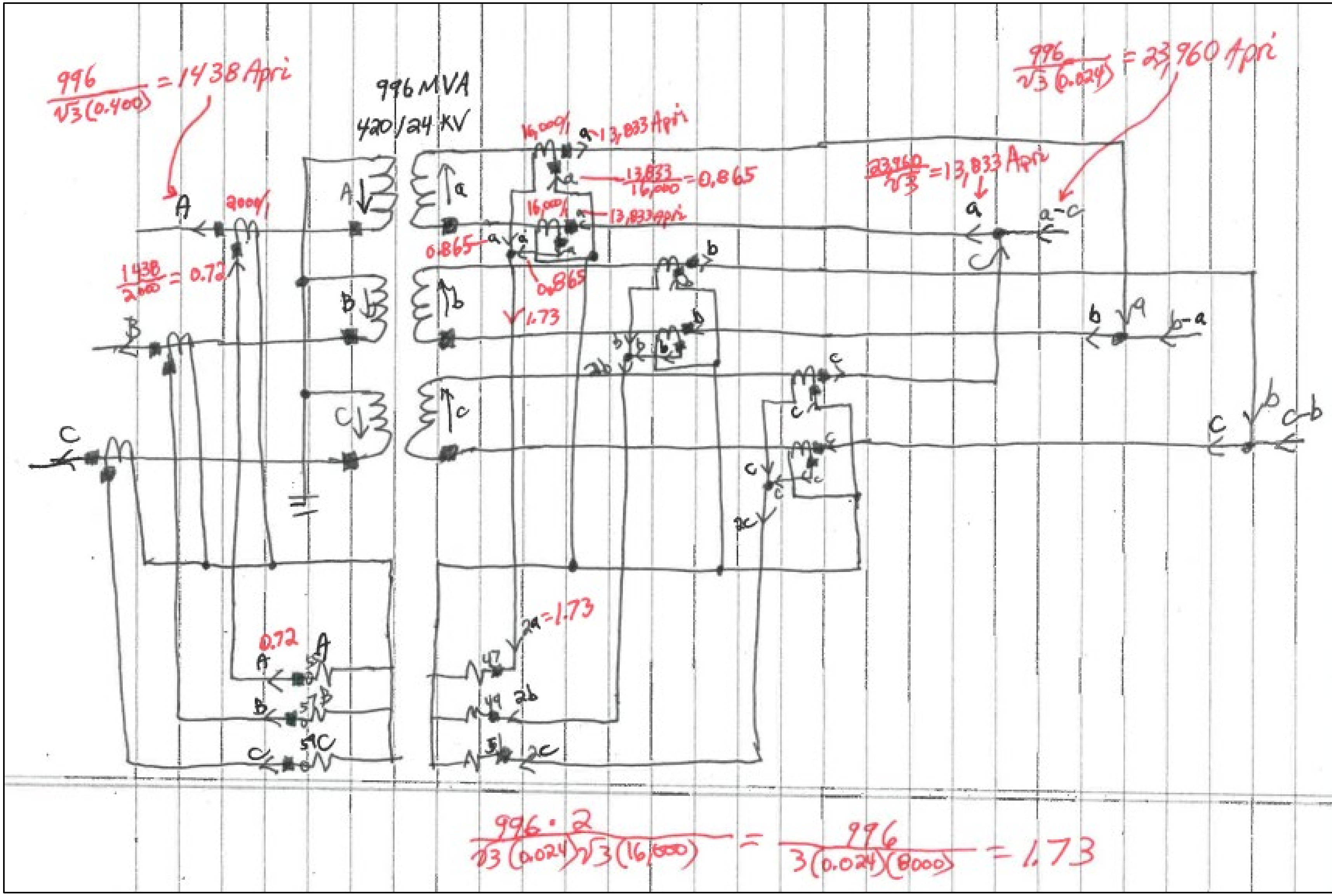
No 30° phase shift was set, why not?



- 3-line:

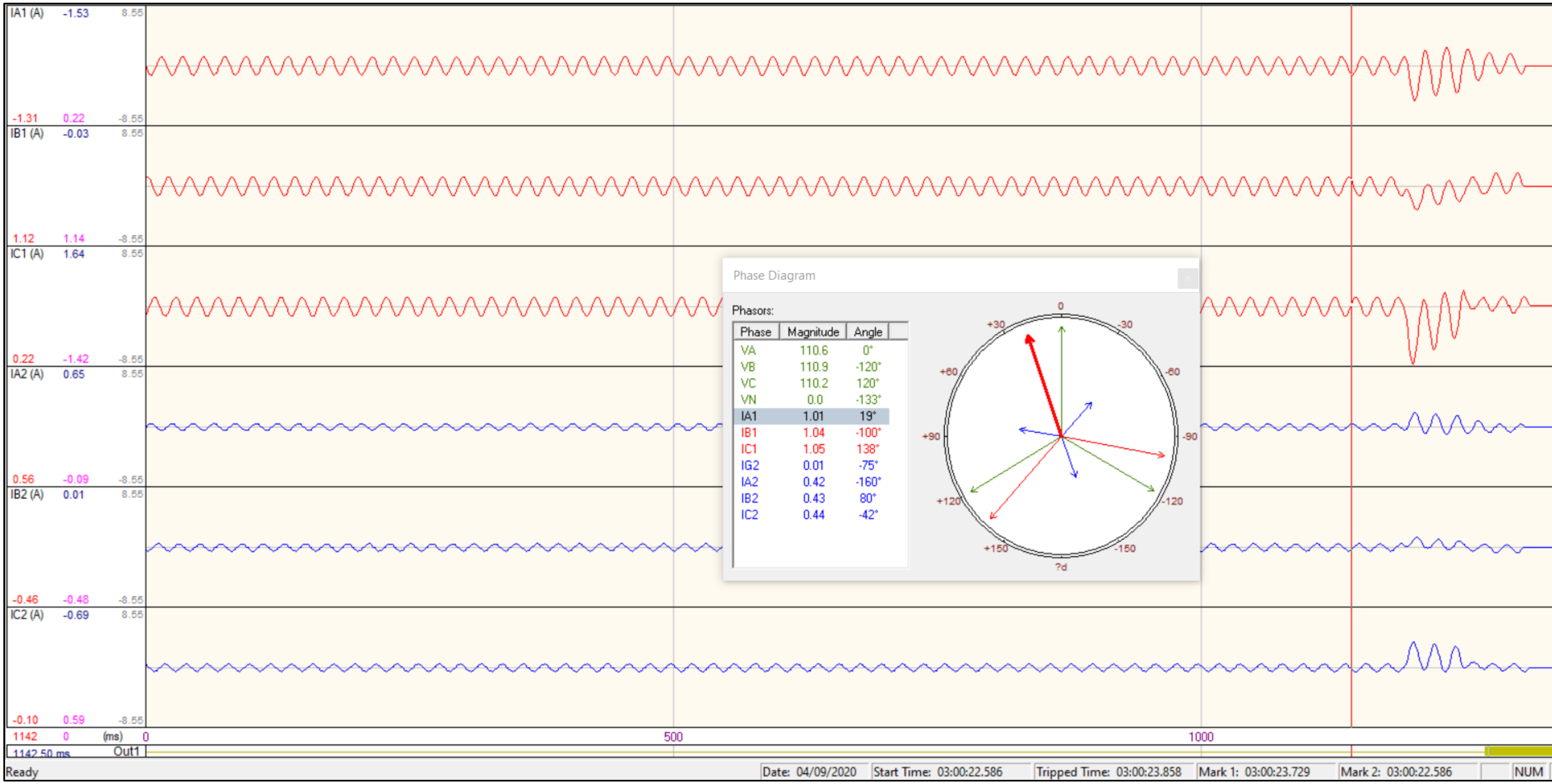


- Delta side CTs are inside the Delta: **that's why no 30° phase shift was set**
- Now, check if the CT Tap settings are correct.



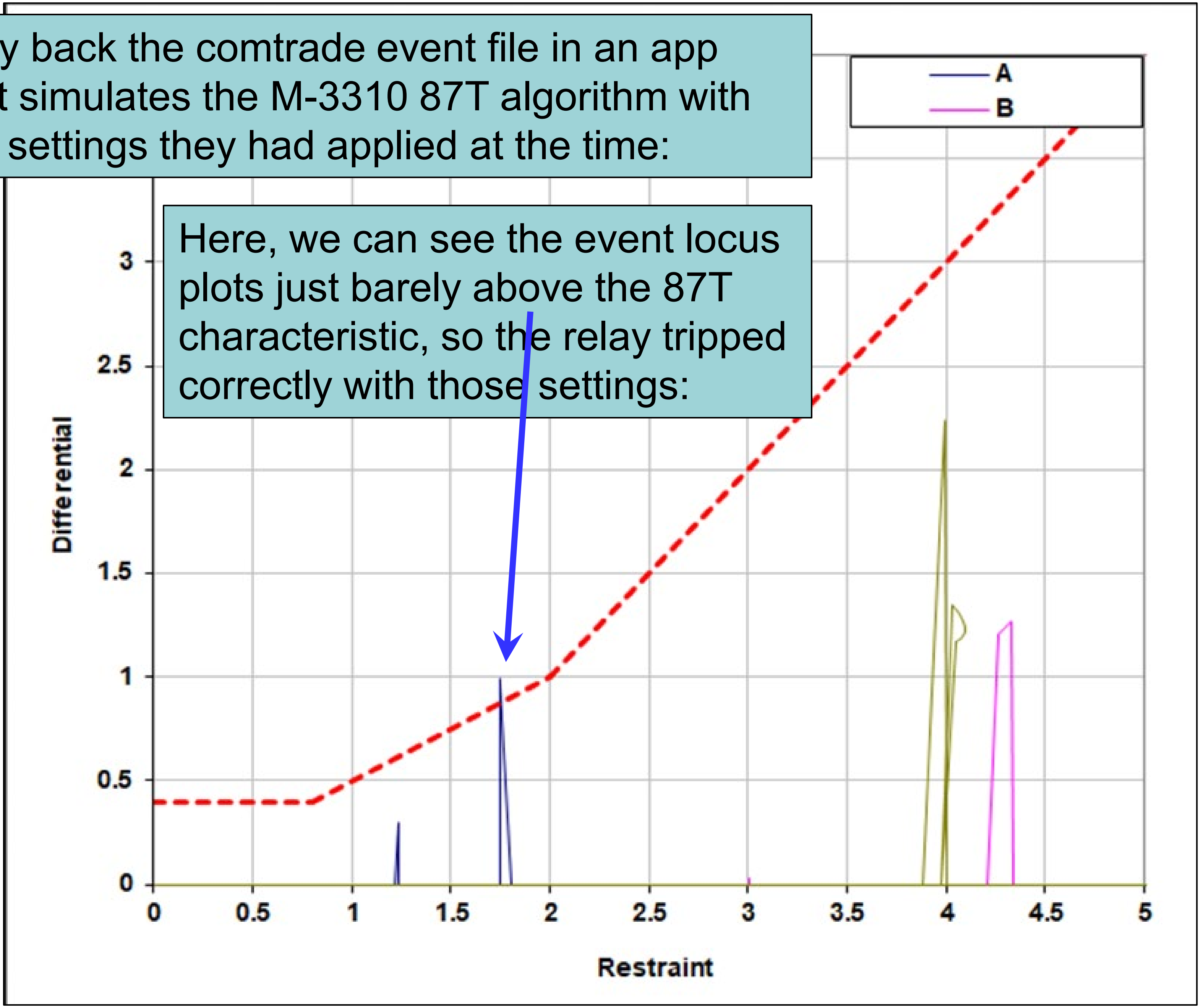
- So yes, the CT Tap settings appear to be set correctly as well.

- Look at pre-fault area to confirm CT Tap settings are correct.



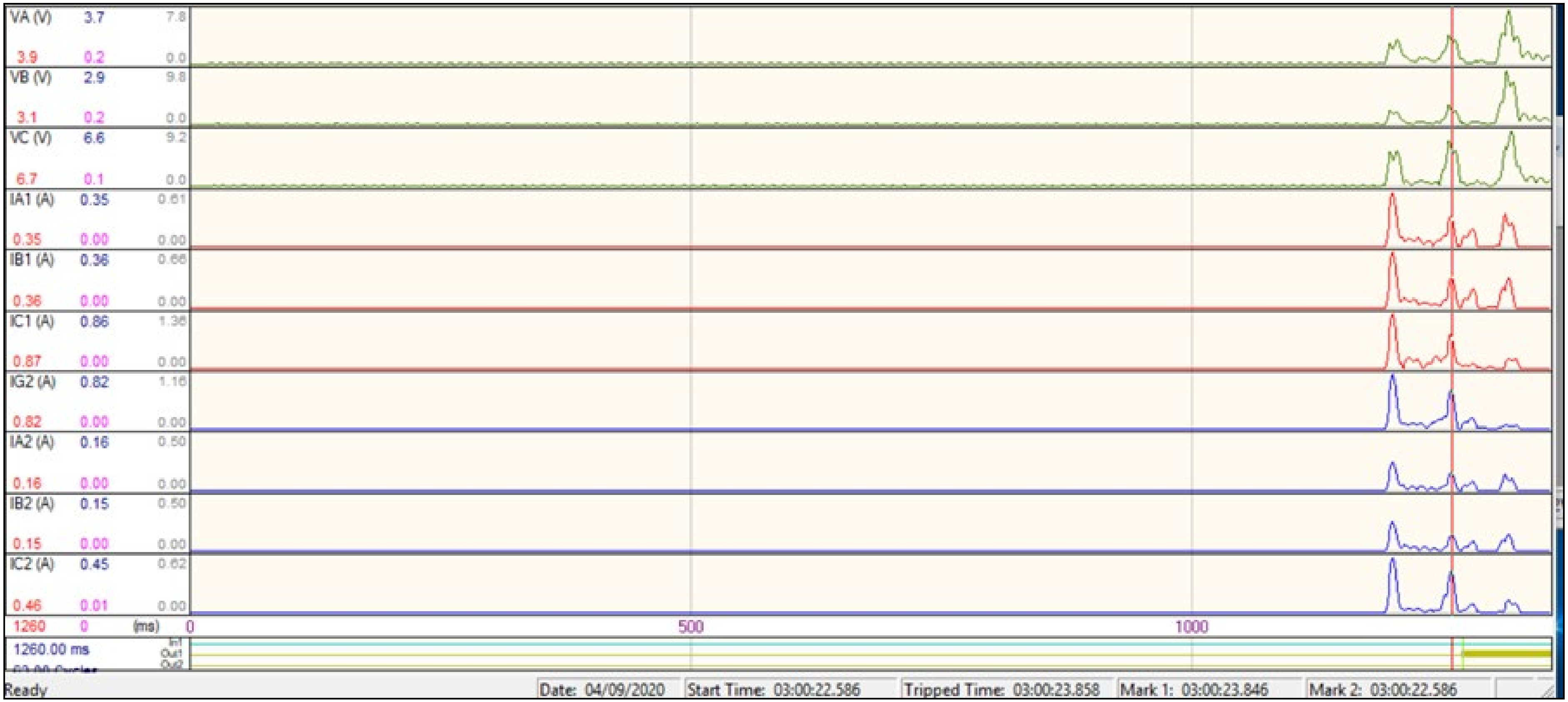
- $1.01 * \frac{0.72}{1.74} = 0.42\ A, so\ yes$ Tap settings are correct.

- Play back the comtrade event file in an app that simulates the M-3310 87T algorithm with the settings they had applied at the time:

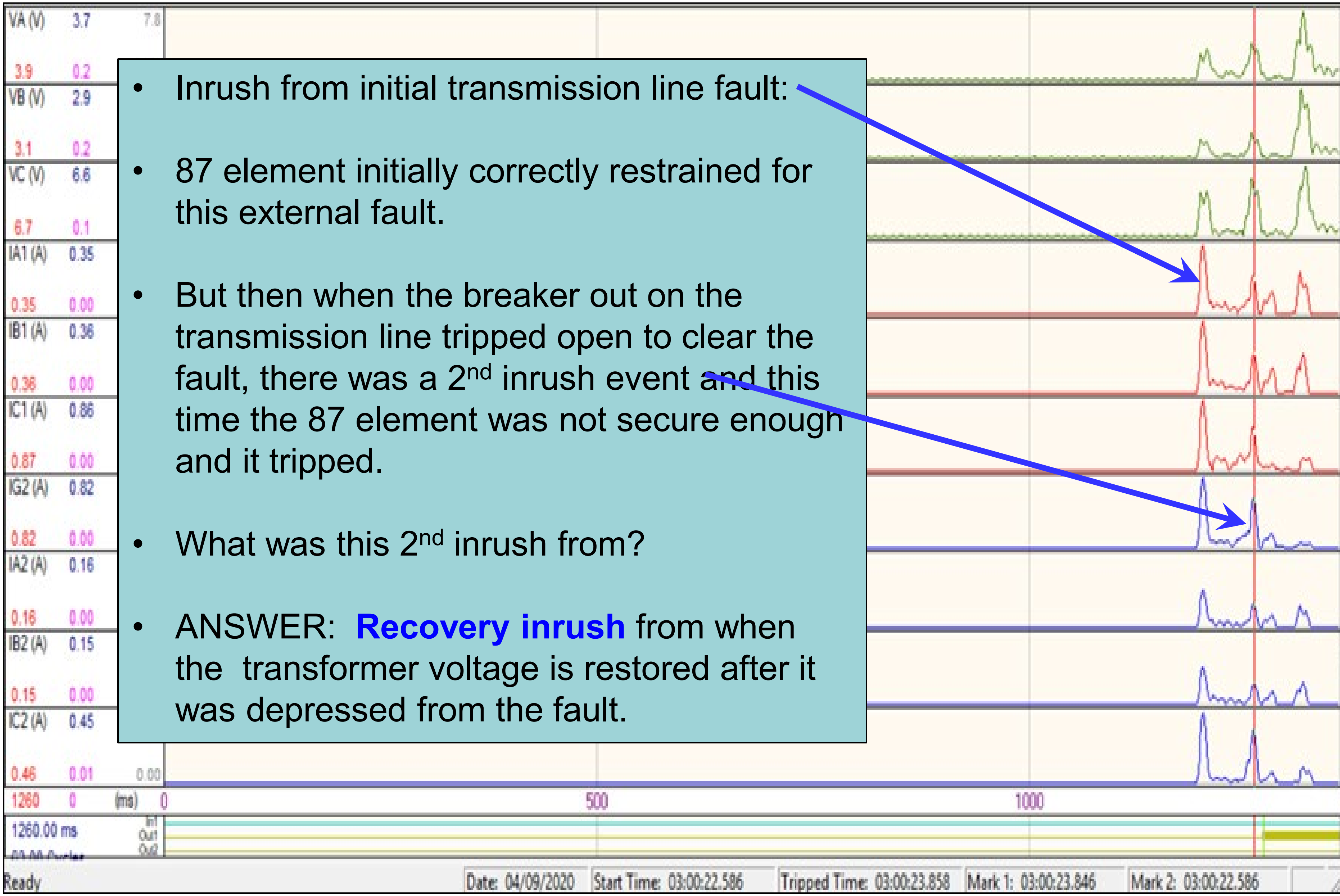


Here, we can see the event locus plots just barely above the 87T characteristic, so the relay tripped correctly with those settings:

- Look at the 2nd harmonic signature:



- Clue – trip occurred when there was a fault out on the transmission system.
- So why did this GSU protection relay trip for a transmission line fault?



- Inrush from initial transmission line fault:

- 87 element initially correctly restrained for this external fault.

- But then when the breaker out on the transmission line tripped open to clear the fault, there was a 2nd inrush event and this time the 87 element was not secure enough and it tripped.

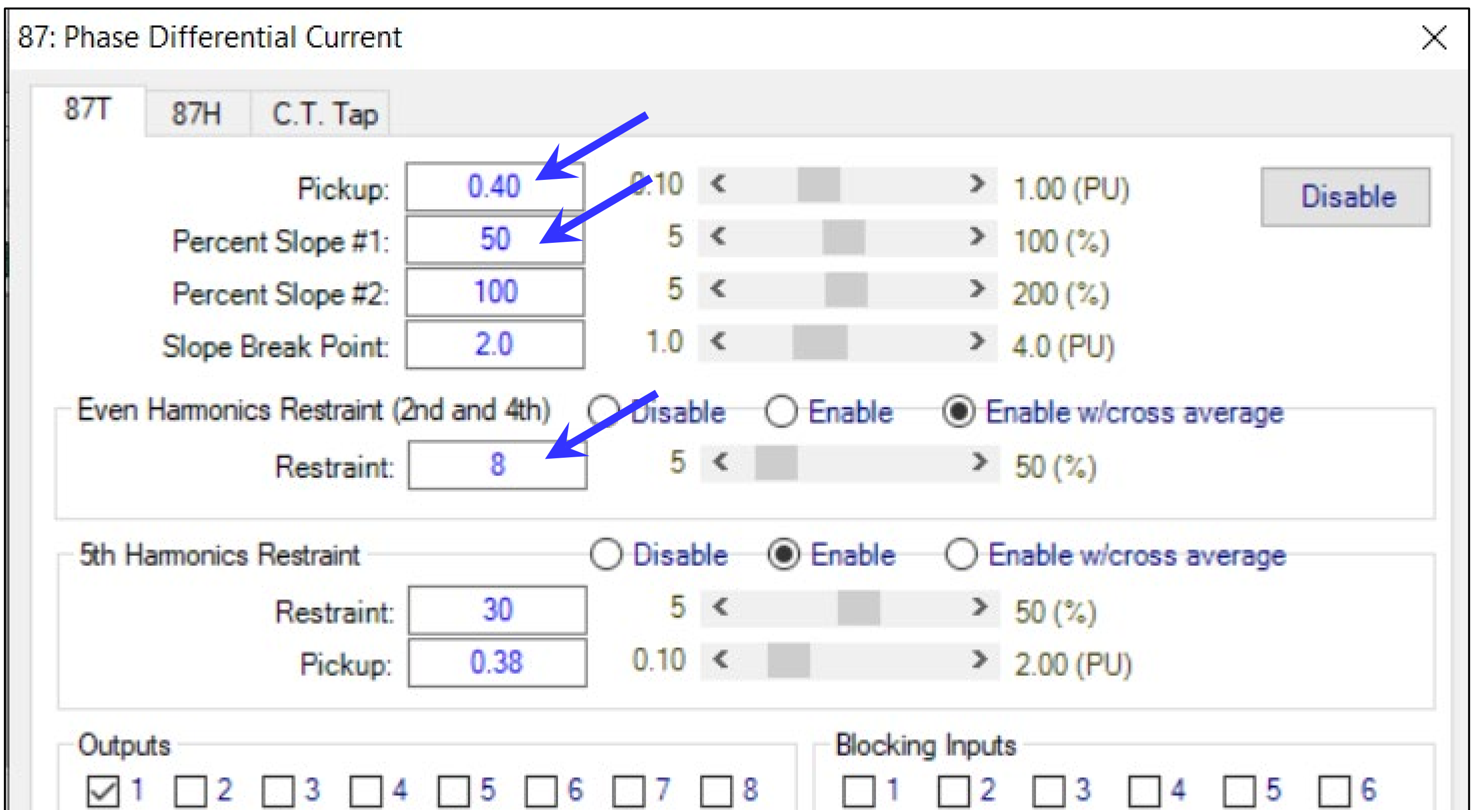
- What was this 2nd inrush from?

- ANSWER: **Recovery inrush** from when the transformer voltage is restored after it was depressed from the fault.

- Recommended they consider desensitizing the 87T settings: Pickup and/or Slope and/or Even Harmonic Restraint.

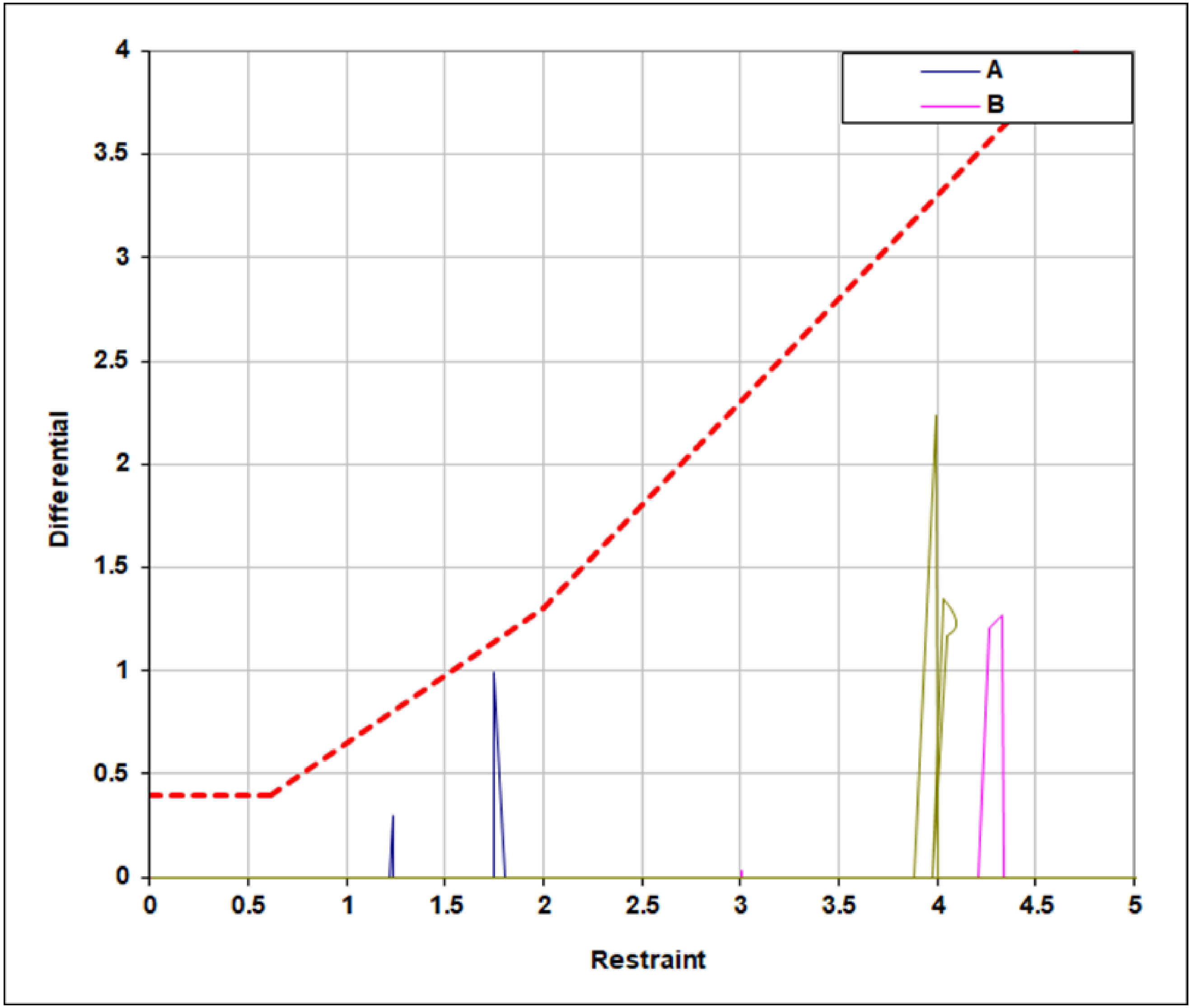
- The settings had already been desensitized per my recommendations from an 87T trip a couple years earlier where it had tripped for a transmission line fault.

- The CT Saturation performance matching is likely not that great.

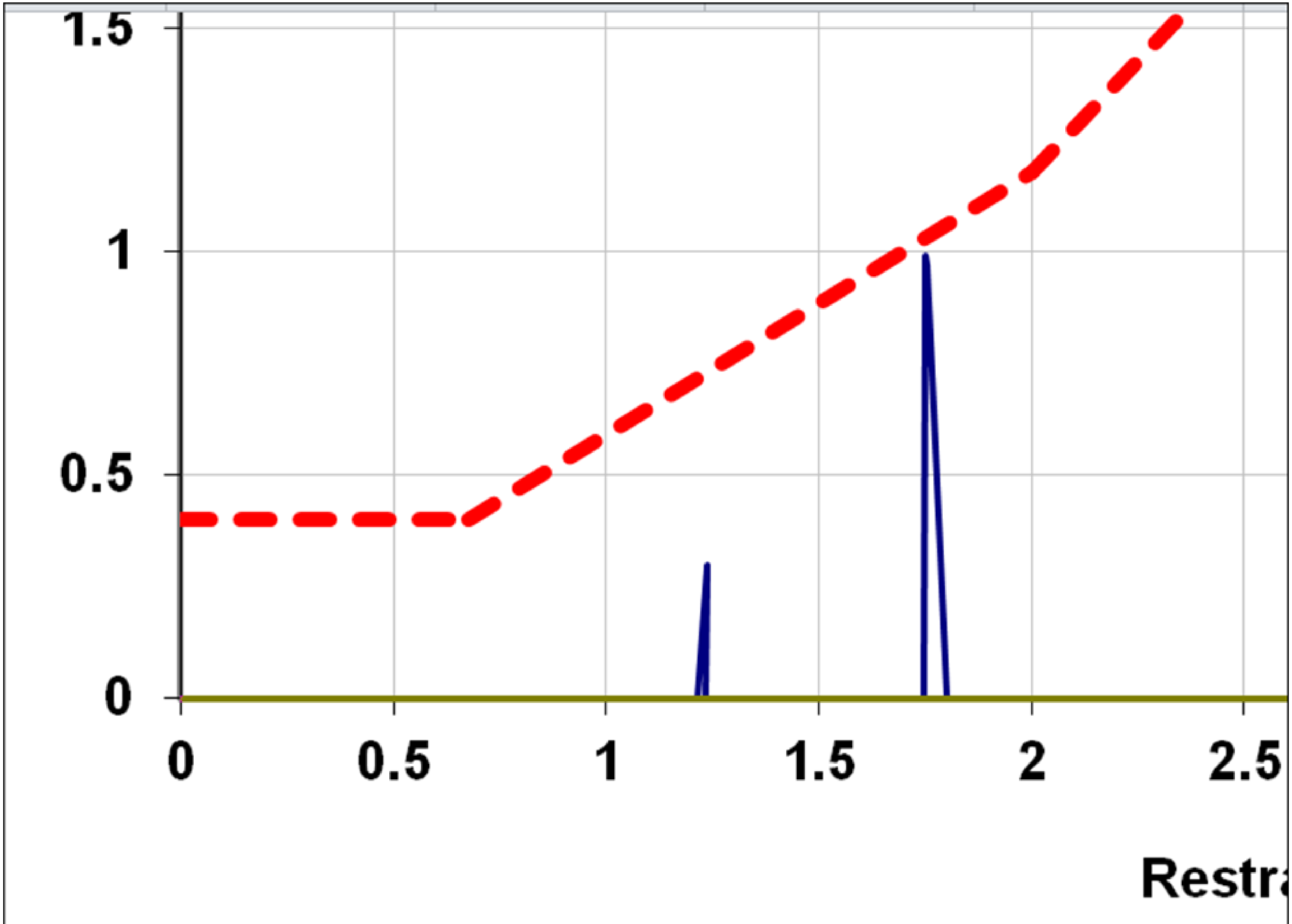


- Showed several options to customer for settings changes to make it more secure:

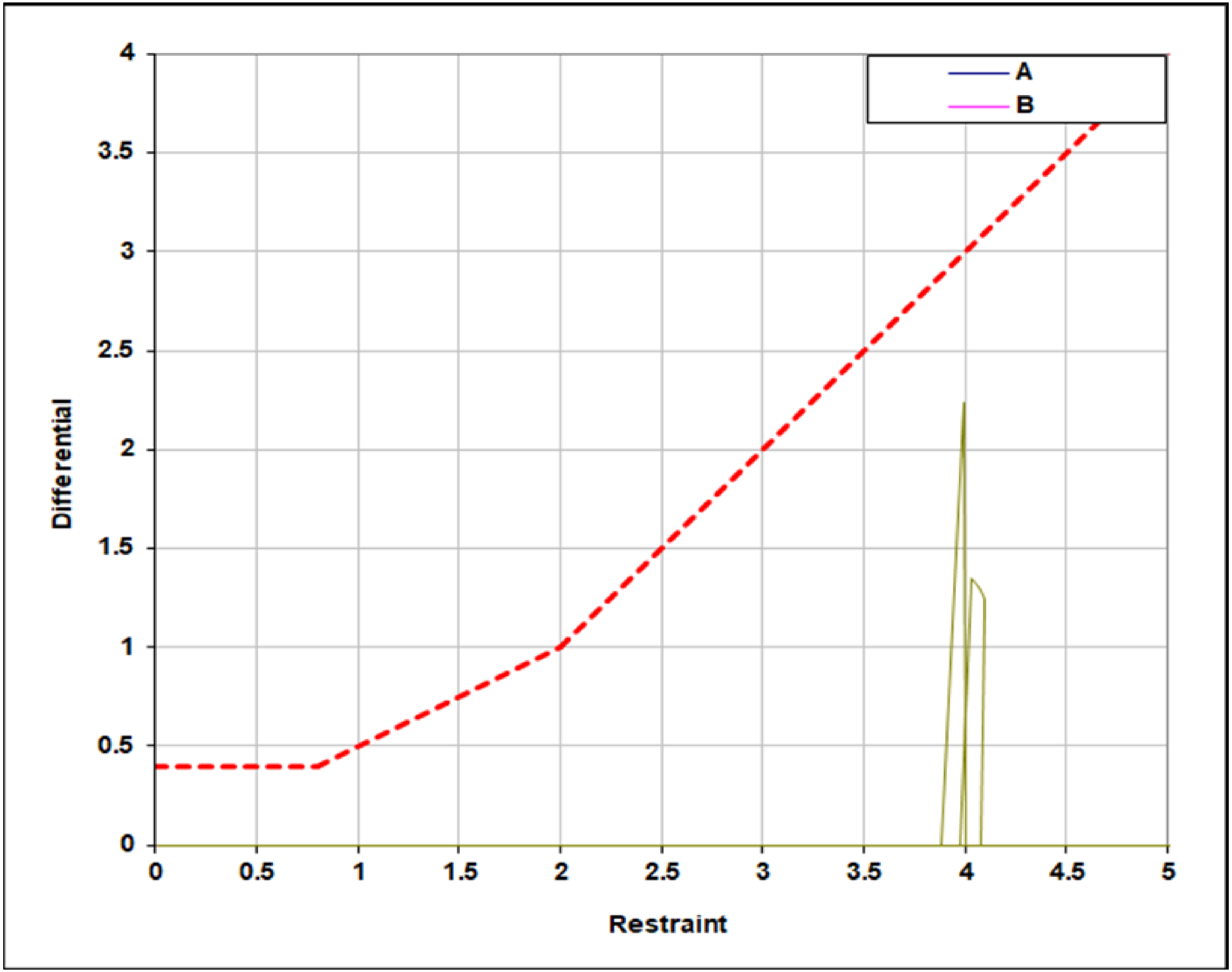
1) Adjust Slope 1 setting from 50% to 65%, in which case the event locus then plots below your operating characteristic:



Zoomed in with a Slope 1 setting of 59%:



2) Leave Slope 1 set at 50% and decrease the even harmonic restraint from 8% to 6%, in which case tl



- I would probably choose increasing Slope 1 to 65% and leave the even harmonic restraint at 8%.

- Transformer simulations show that magnetizing inrush current usually yields more than 30% of IF2/IF1 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 required for sufficient security for some modern transformers**; however, this additional security must be weighed against the risk of inadvertently restraining for internal faults with this lower Even Harmonic Restraint setting.

- Shows the importance of proper CT Dimensioning, CT Saturation Calculations, and CT Performance Modelling by the initial power plant designer.

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Questions?