Out-of-Phase Sync Event Analysis

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Generation System Protection

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Introduction

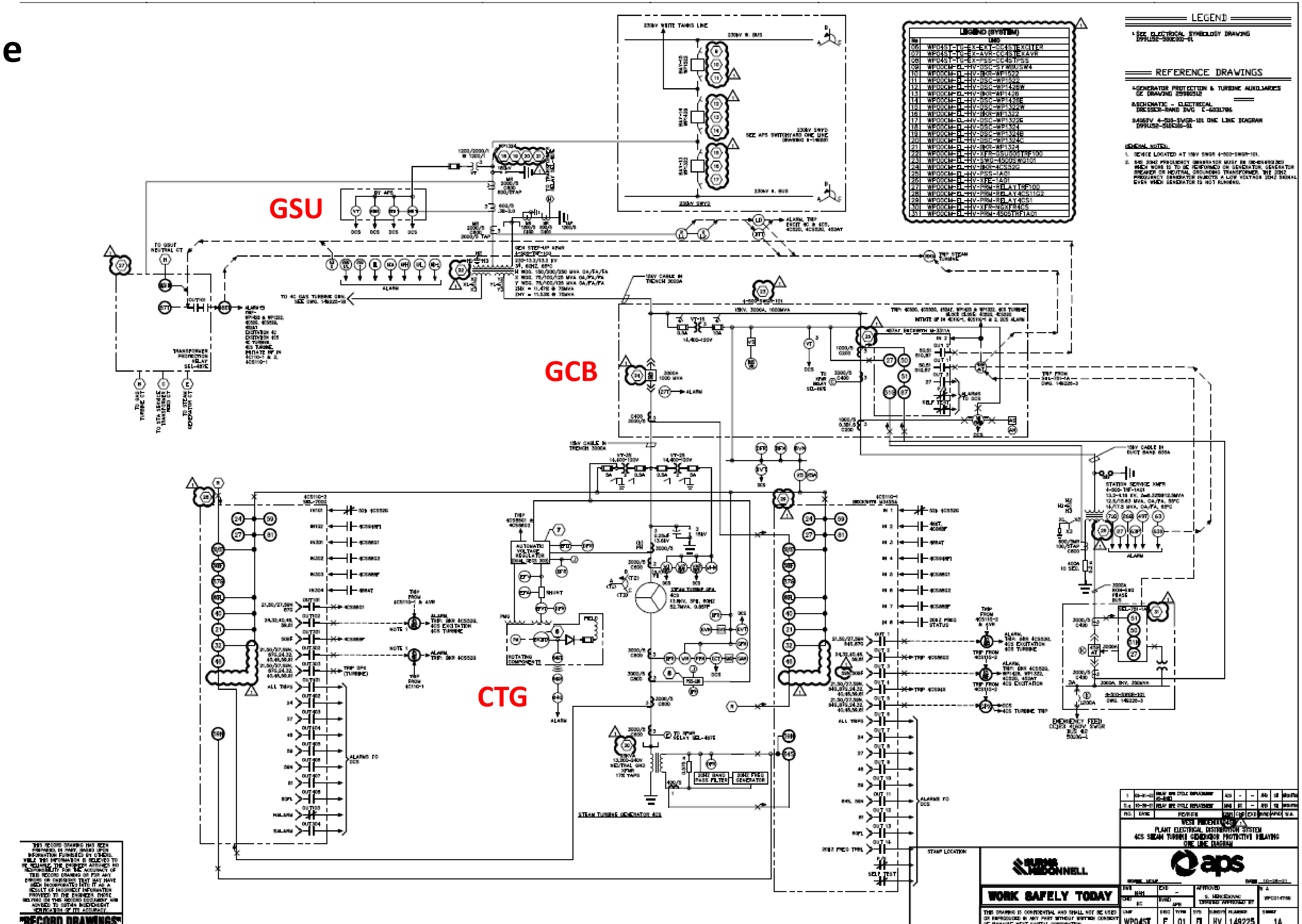
A major event occurred at a large APS power plant in Phoenix.

A new generator circuit breaker (**GCB**) had been installed for a combined cycle power block (**CCPB**) consisting of a gas turbine generator (**CTG**) and a steam turbine generator (**STG**).

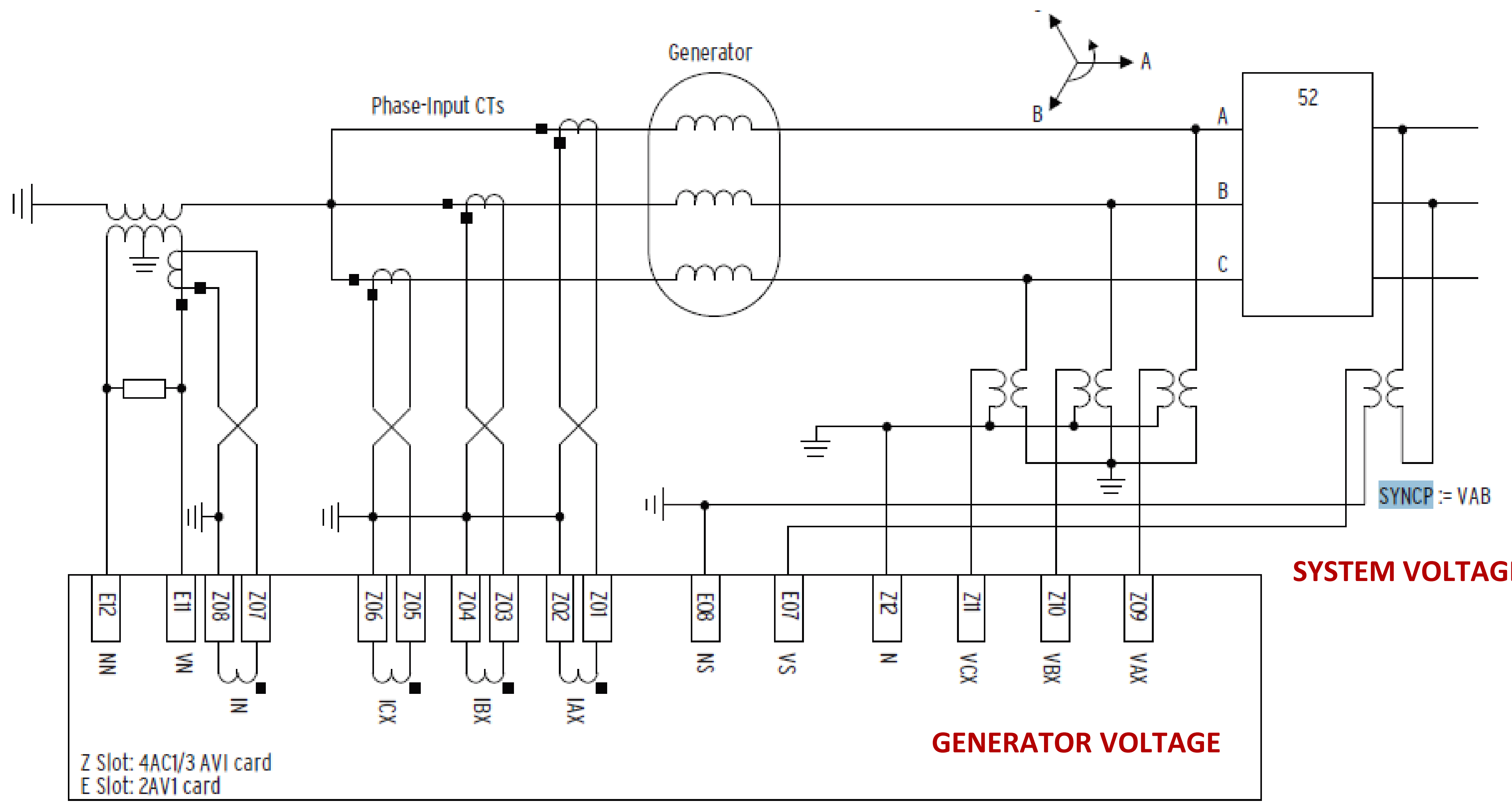
The new GCB is located on the low side of the GSU serving the CTG. The GSU has two low side delta windings, each serving one of the two generators.

Testing was being conducted for synchronization of the CTG via the new GCB.

One Line

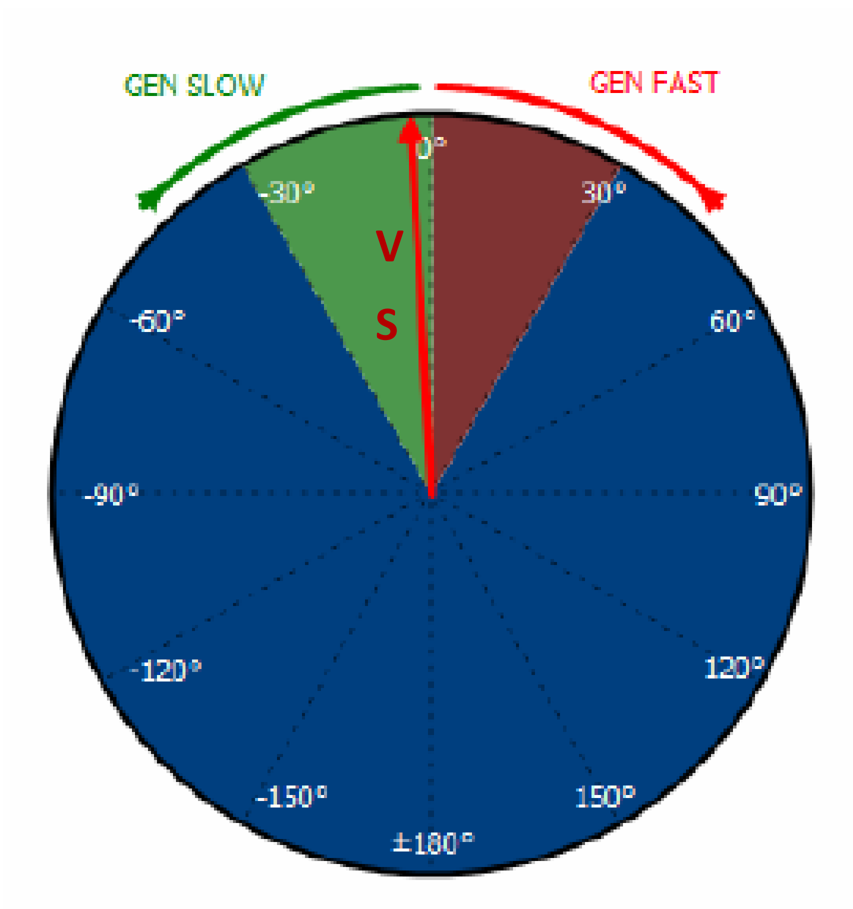

GSU
GCB
CTG
LEGEND
REFERENCE DRAWINGS
WORK SAFELY TODAY
"RECORD DRAWINGS"

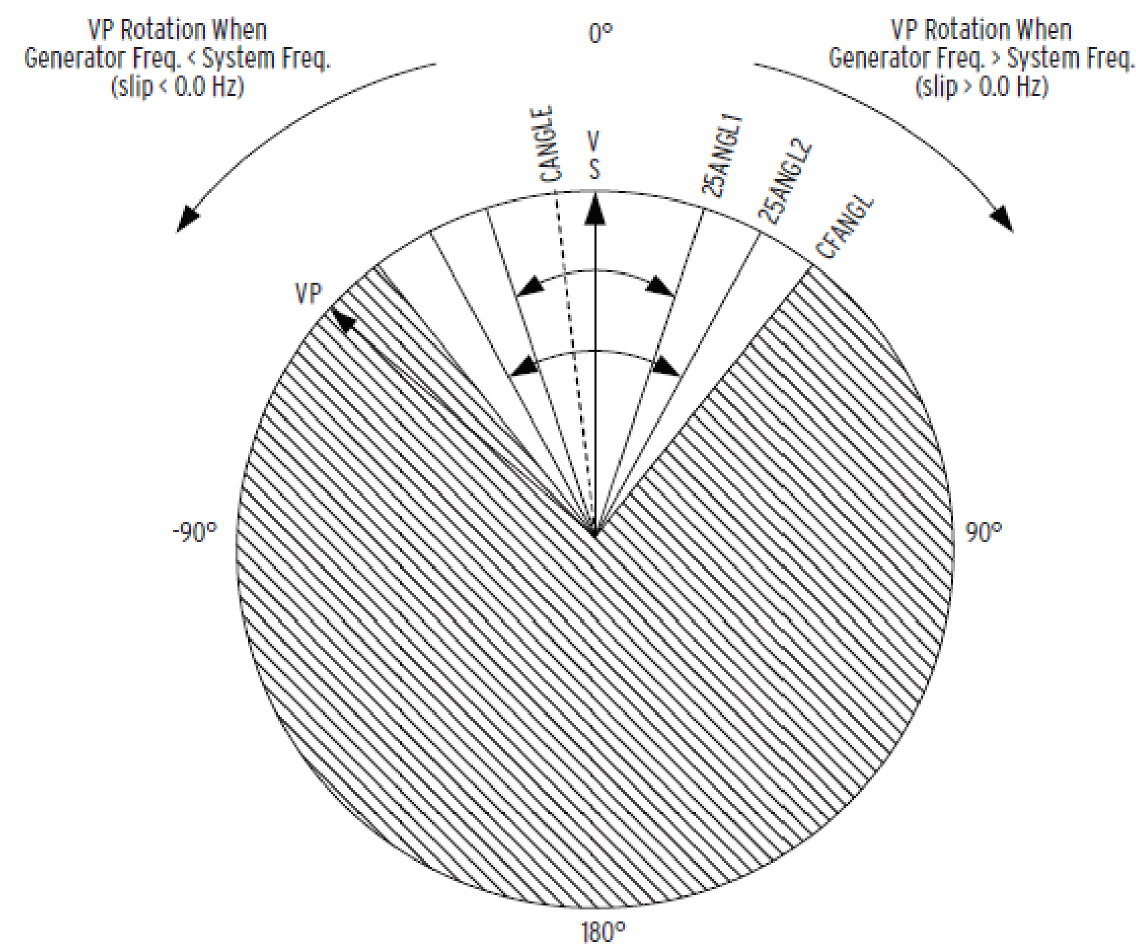
Synchronization



NOTE - BREAKER (52) IS OPEN PRIOR TO SYNC

Synchronization



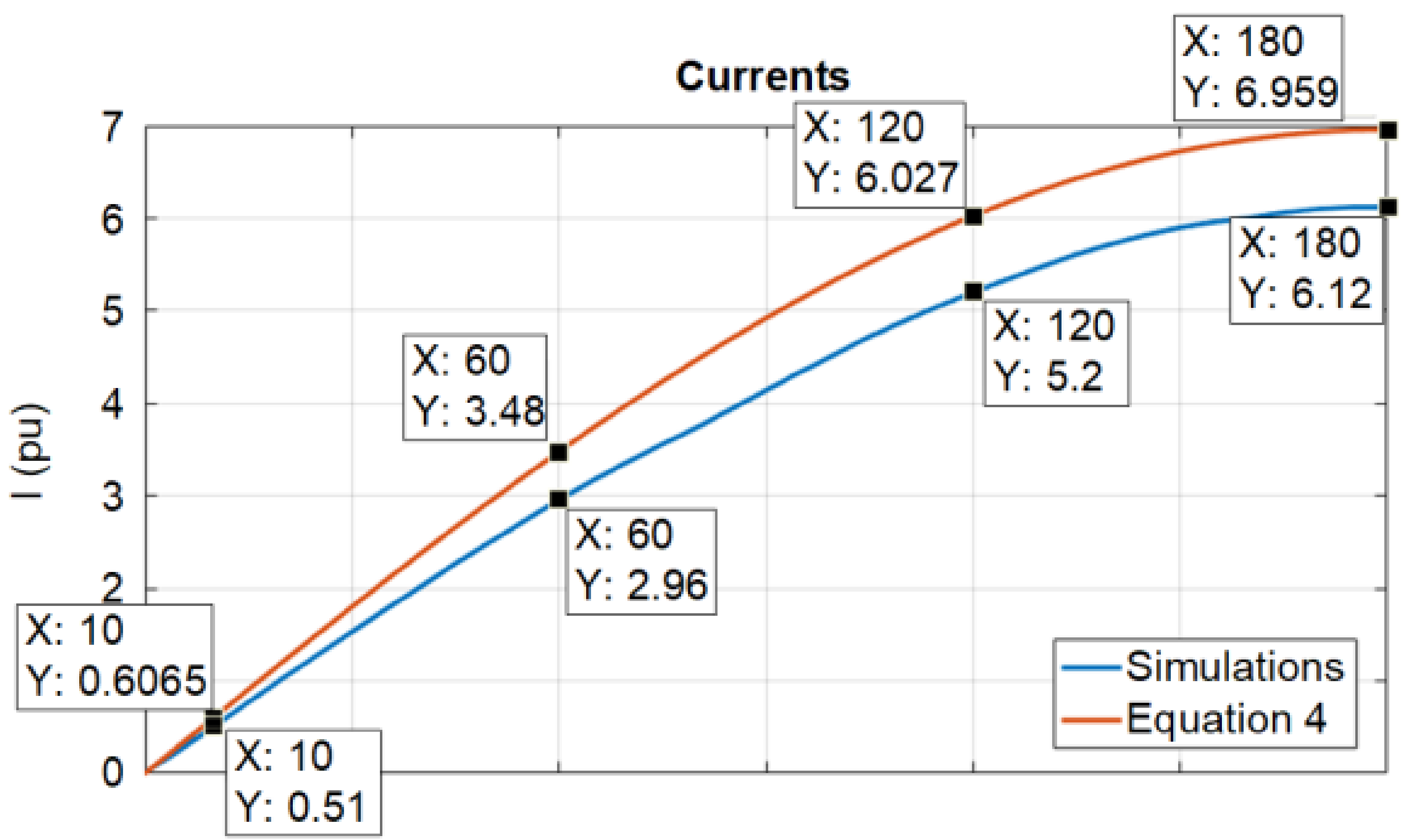


VS = SYSTEM VOLTAGE

Synchronization

- The lower the angle between the generator voltage and system voltage, the better.
- Electrically worst case is 180 degrees separation.

Out-of-Phase Synchronization



$$I_{AC} \approx \frac{V \bullet |1 - \angle\delta_0|}{X_{total}} = \frac{2 \bullet V}{X_{total}} \sin\left(\frac{\delta_0}{2}\right) \qquad (4)$$

where:

I_{AC} is the maximum ac current magnitude.

V is the generator and system voltage magnitude (typically 1 pu).

X_{total} is the sum of X_d'', X_T, and X_S.

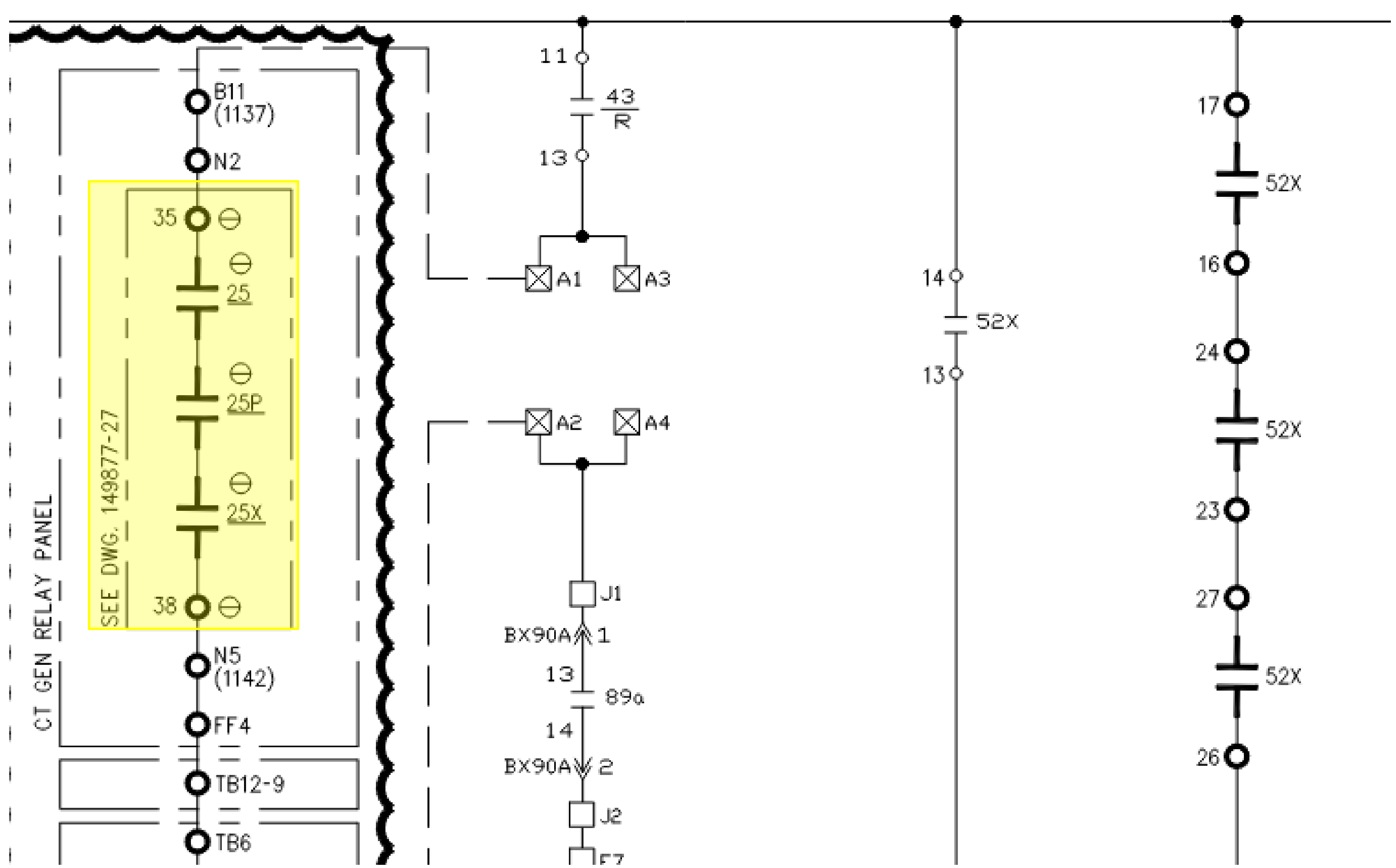
δ_0 is the synchronizing angle (the initial angle difference across the breaker).

Event

- The GCB closed out-of-phase because a high impedance input of a fault recorder monitoring the output of the sync check relay shorted, providing a positive path to the GCB close coil.
- Protective relaying operated and opened the switchyard breakers, isolating the CCPB.

Event

- The 25 sync contacts are shown below, they pick up the 52X.
- The 52X contacts pick up the 52CC close coil.



Purpose

Verify that the protective relaying properly operated.

*Provide a solution that addresses this type of an event (that is, **o**ut-**o**f-**p**hase **s**ync (**OOPS**) protection).*

SEQUENCE OF EVENTS

- The CTG was ready to be brought online that morning for a live test of the new GCB to commission the breaker.
- The generator breaker closed at 9:11 AM and tripped 6.8 cycles later due to the main generator protection relay, which initiated an 87-phase differential protection trip.
- This trip triggered a direct transfer trip (DTT) of both switchyard breakers, which in turn de-energized the GSU.
- This trip was due to the high magnitude fault level current flowing through the GSU resulting from the out-of-phase synch; that is, the system and CTG were close to 180 degrees out-of-phase when the GCB closed.
- *An effort was made to close one of the switchyard breakers at 9:24 AM to recover auxiliary load since the GSU was de-energized.*
- The main GSU protection then tripped again, and the switchyard breaker was tripped via DTT 5.4 cycles later.

SEQUENCE OF EVENTS

A final attempt to close the same switchyard breaker was made at 9:33 AM with the same result; this time the main GSU protection tripped on 87 phase differential protection three cycles later. The GSU was severely damaged due to a low voltage winding fault as a result and would have to be replaced.

1^{st} Trip

Main GSU Protection Trips

- The GSU was damaged during the first event.
- The output from the sudden pressure relay (SPR) asserts the main GSU protection input IN102 three cycles into the first event, as shown in Figure 1, which in turn triggers the trip output OUT101 and sends a DTT to the switchyard breakers.
- It is assumed that there was significant transformer winding movement due to the high magnitude fault level current flowing through the GSU, resulting from the out-of-phase synch.
- The currents were interrupted three cycles later by the GCB, resulting in the generator breaker being closed for a total of 6 cycles.

1st Trip Cont'd

Color	Name	Mag	Angle
Red	IAT.Phasor	96.2601 A	124.85°
Green	IBT.Phasor	100.125 A	2.86°
Blue	ICT.Phasor	97.5295 A	-118.14°

1st Trip Cont'd

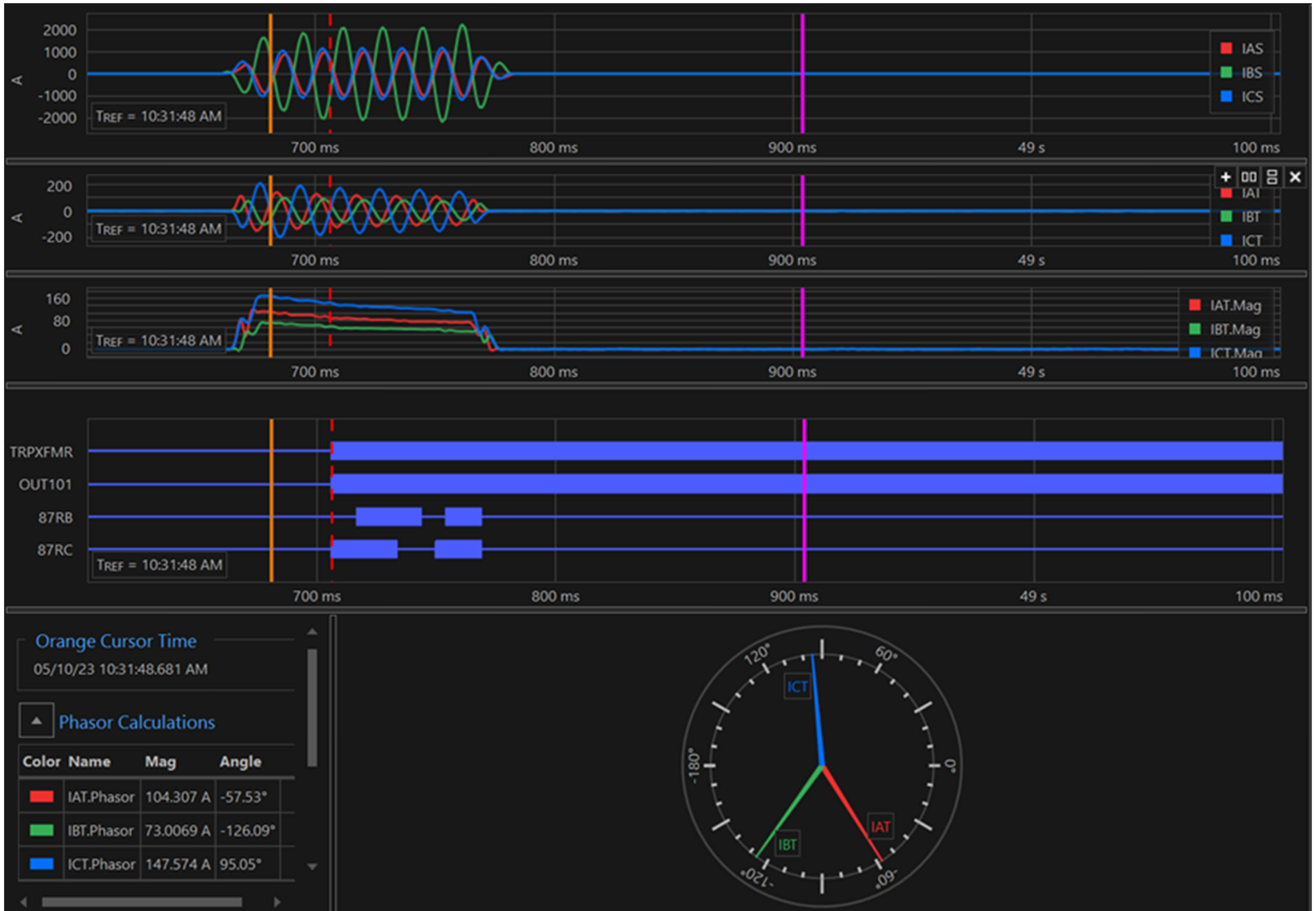
- Given the short assertion time and the fact that the SPR did not assert during the subsequent re-energizations of the GSU, the SPFR chatter was due to the extreme forces in the GSU while the large fault current magnitude current was flowing.
- This is a known behavior of SPFR for high magnitude current through faults.
- The dissolved gas analysis (DGA) indicated there was a high energy electrical discharge within the transformer.
- This damage led to the internal fault on the GSU low voltage winding serving the CTG.

2nd & 3rd Trips

- Figures 2 and 3, to follow, are for the second and third main GSU main protection trips, due to the 87-transformer differential protection.
- The first fault was phase-to-ground, which evolved into a phase-to-phase-to-ground fault the third time the GCB was closed.

Main GSU 2nd Protection Trip

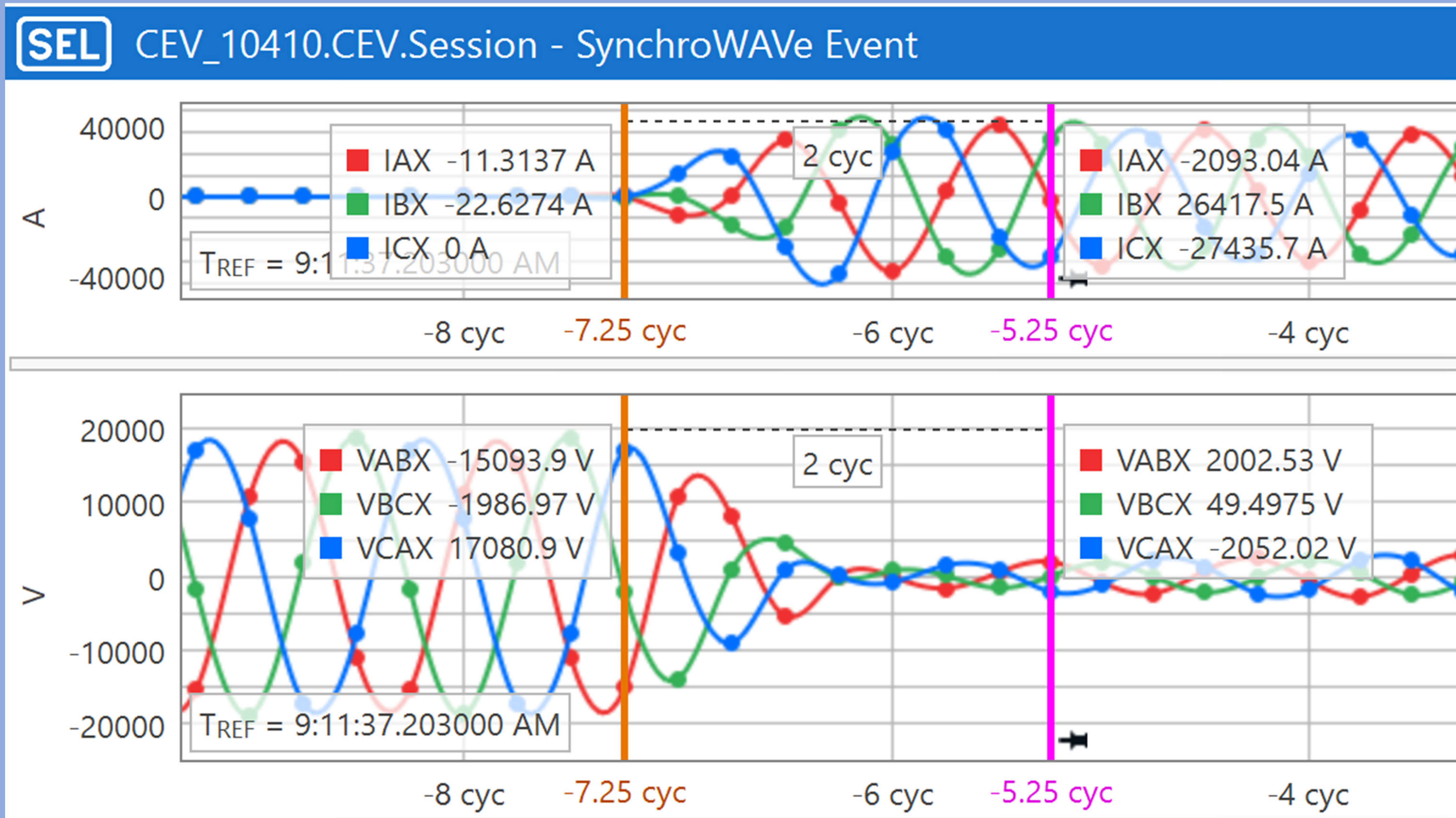
Main GSU 3rd Protection Trip



Out-of-Phase Sync (OOPS)

- The GCB was closed when the machine was **180 degrees out-of-phase** with the system.
- This was verified using oscillography from the second main generator protection. VCAX voltage goes in-phase with the system in only 2 cycles.
- This is because the system is much stronger, and it almost instantly rotated the shaft of the generator 180 electrical degrees to force it in-phase with the system.
- See Figure 4.

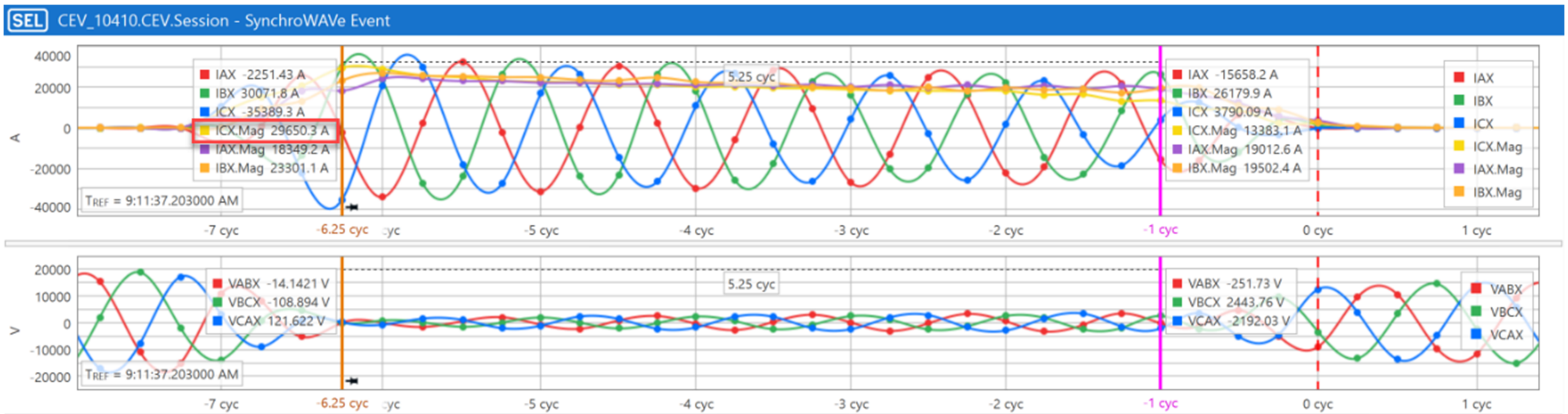
Out-of-Phase Sync (OOPS)



Out-of-Phase Sync (OOPS)

- The stator phase current grew extremely high in magnitude when the GCB was closed out-of-phase.
- The filtered current on C-phase recorded by the second main generator protection relay rose as high in magnitude as 29,650 Amps.
- A three-phase fault at the terminals of the CTG would produce 28,335 Amps based upon the saturated subtransient reactance (Xd”) of 0.158 per unit and a nominal current of 4,477 Amps.
- Based upon IEEE C50.13, IEEE Standard for Cylindrical-Rotor 50 Hz and 60 Hz Synchronous Generators Rated 10 MVA and Above, generators are built to withstand a three-phase fault right at the terminals.
- The current magnitude produced during the out-of-phase close exceeded the three-phase fault current. The generator bracing was inspected to verify it was still intact.

Out-of-Phase Sync (OOPS)



The filtered current on C-phase rose as high in magnitude as 29,650 Amps.

1st Main Generator Protection Relay Sequence-of-Events

TIME STAMP	ELEMENT STATUS	Δt (cycles)	ACCUMULATED (cycles)	BREAKER STATUS
08:32:14.265	46DT, 46IT & 87#1 pickup	0	0	Closed
08:32:14.283	46DT, 46IT & 60FL pickup	1.08	1.08	Closed
08:32:14.301	46DT, 46IT & 81#4 pickup	1.08	2.16	Closed
08:32:14.310	21#2, 46DT, 46IT & 46IT & pickup	0.54	2.70	Closed
	81#4 dropout			Closed
08:32:14.397	46IT & 46IT & pickup	5.22	7.92	Closed
08:32:14.401	46DT, 46IT & 50BF pickup	0.24	8.16	Closed
08:32:14.424	27#1, 46DT, 46IT & 50BF pickup	1.38	9.54	Closed
08:32:14.438	27#1, 46DT, 46IT, 50BF & 64S pickup	0.84	10.38	Closed
08:32:14.442	27#1, 46DT, 46IT, 50BF, 64S & 87#1 pickup	0.24	10.62	Closed
08:32:14.461	27#1, 46DT, 46IT, 50BF, 59N#1, 59N#2, 64S & 87#1 pickup	1.14	11.76	Closed
08:32:14.465	27#1, 46DT, 46IT, 50BF, 64S, 81#4 & 87#1 pickup	0.24	12	Open
	59N#1 & 59N#2 dropout			
08:32:14.479	46DT, 46IT, 50BF, 64S & 81#4 pickup	0.84	12.84	Open
	87#1 trip			
08:32:14.506	46DT, 46IT, 50BF, 64S & 81#4 pickup	1.62 cycles	14.46	Open
	87#1 trip			
08:32:14.524	46DT,46IT & 64S pickup	1.08	15.54	Open
08:32:14.528	46DT,46IT, 64S & 81#4 pickup	0.24	15.78	Open
08:32:14.565	46DT, 46IT & 81#4 pickup	2.22	18	Open
	64S trip			

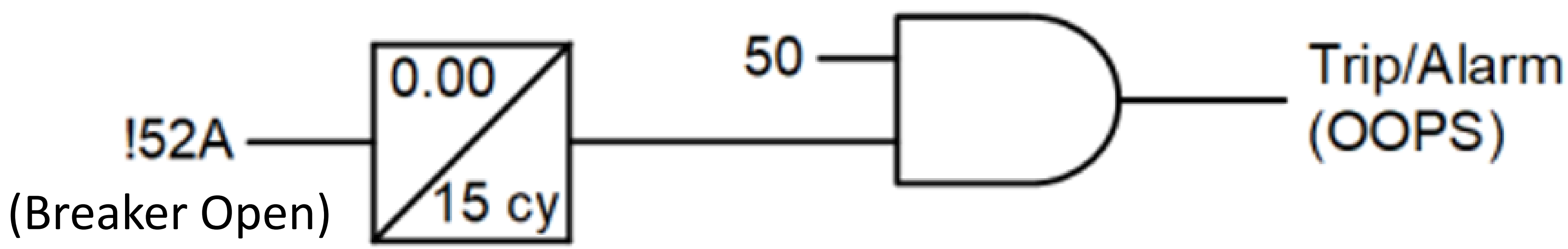
OUT-OF-PHASE SYNC (OOPS) PROTECTION

- An out-of-phase synchronization (OOPS) event results in a torque transient on the generator and prime mover.
- It exposes the generator, generator step-up (GSU) transformer, and system elements to a current transient that puts high mechanical and thermal stresses on windings and other conductors.
- These transients can be significant and result in through current magnitude equivalent to a three-phase fault located at the terminals of the generator.
- Since damage due to mechanical stresses tends to be cumulative in nature, it is important to detect these occurrences and clear the condition as quickly as possible.

OOPS Protection Scheme Logic

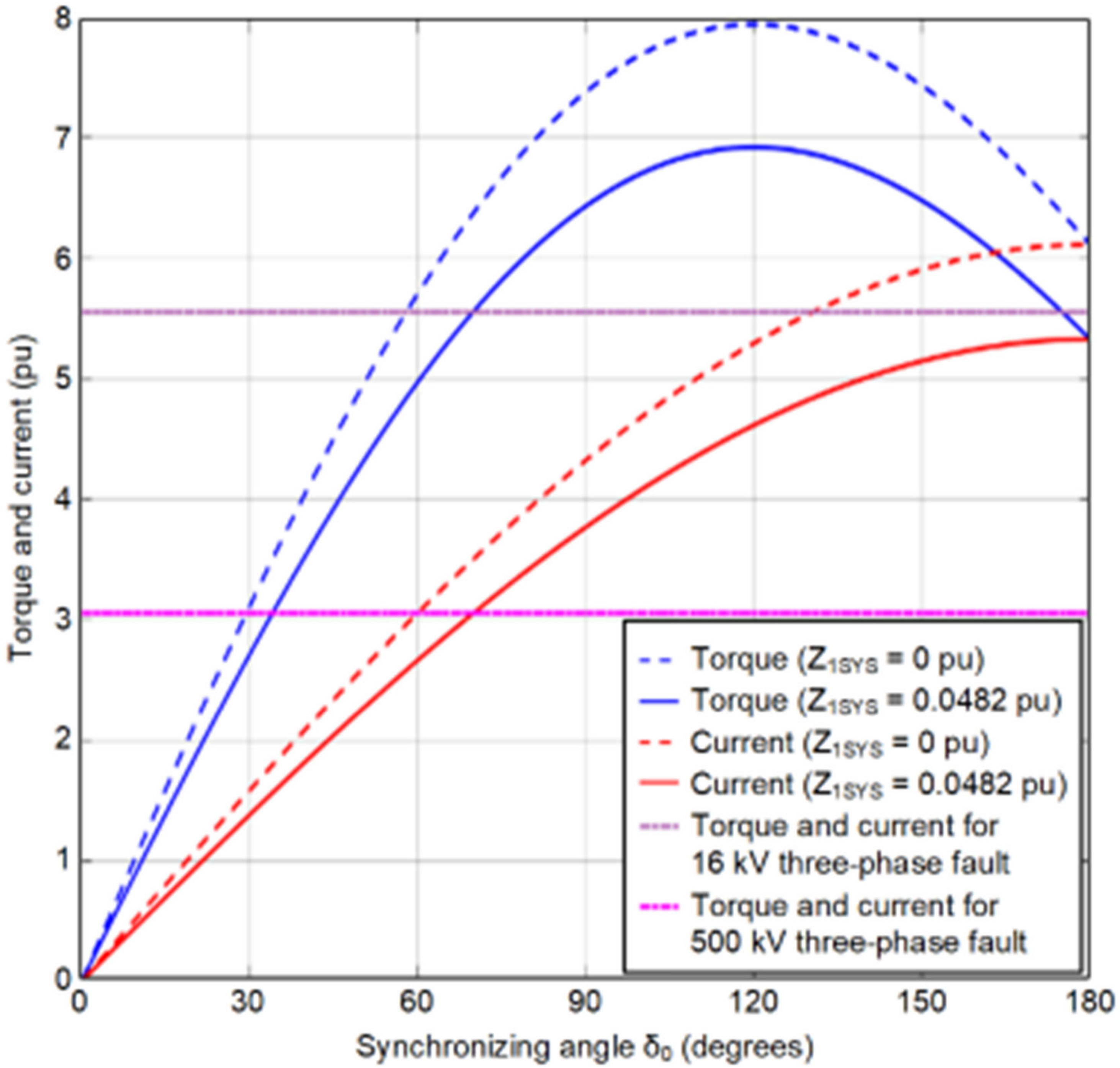
- The scheme requirements for an OOPS event are not onerous, and, in the interest of accurate targeting, a dedicated scheme is warranted.
- Traditional generator protection cannot typically detect OOPS events.
- Generally, most elements that might be responsive to the high currents during an OOPS event are time delayed, and high-speed differential elements are blind to this event.
- The inadvertent energization element is typically disarmed by the presence of voltage, thus disabling the element during an OOPS event.
- Furthermore, an OOPS event can continue to occur every time a generator is synchronized until the underlying cause is addressed.

OOPS Protection Scheme Logic



- The 50 element should not be enabled while the machine is online due to the inability to coordinate the element with other protective systems.
- An OOPS event results in high current magnitude at the instant of breaker closure.
- Use a 52A status signal, in conjunction with a timer set for a 15-cycle dropout delay, to disable the overcurrent element after the breaker closes.
- There is no additional time delay provided and the element should trip instantly.
- This scheme also detects and trips high-speed for the slow breaker close OOPS scenario.

OOPS Protection Scheme Logic



- Consider the plot, for a 60 degrees OOPS, which plots both current and torque as a function of the synchronizing angle, there is 5 per unit torque applied to the shaft.
- Therefore, it pertinent to inspect the machine.
- The OOPS protection scheme trips the 86 lockout and shuts down the unit.
- The root cause that led to the OOPS must be determined and properly prior to another attempt to sync the machine.

CONCLUSION

- The protective relays operated properly as verified by the detailed analysis. An important lesson learned is that any time a protection trip occurs the oscillography should be reviewed first prior to attempting to re-energize any load.
- It was shown how to program numerical multi-function generator protective relays to trip for these out-of-phase events.
- **No attempt should be made to close a breaker again until all pertinent data collected from the relays is examined; that is, oscillography, sequence-of-events report, etc.**

ACKNOWLEDGEMENTS

The author wishes to acknowledge Jason Young of SEL, Inc. for his significant contribution to analyzing these events.