GSU Transformer - Current Transformer Connections and Differential Relay Applications

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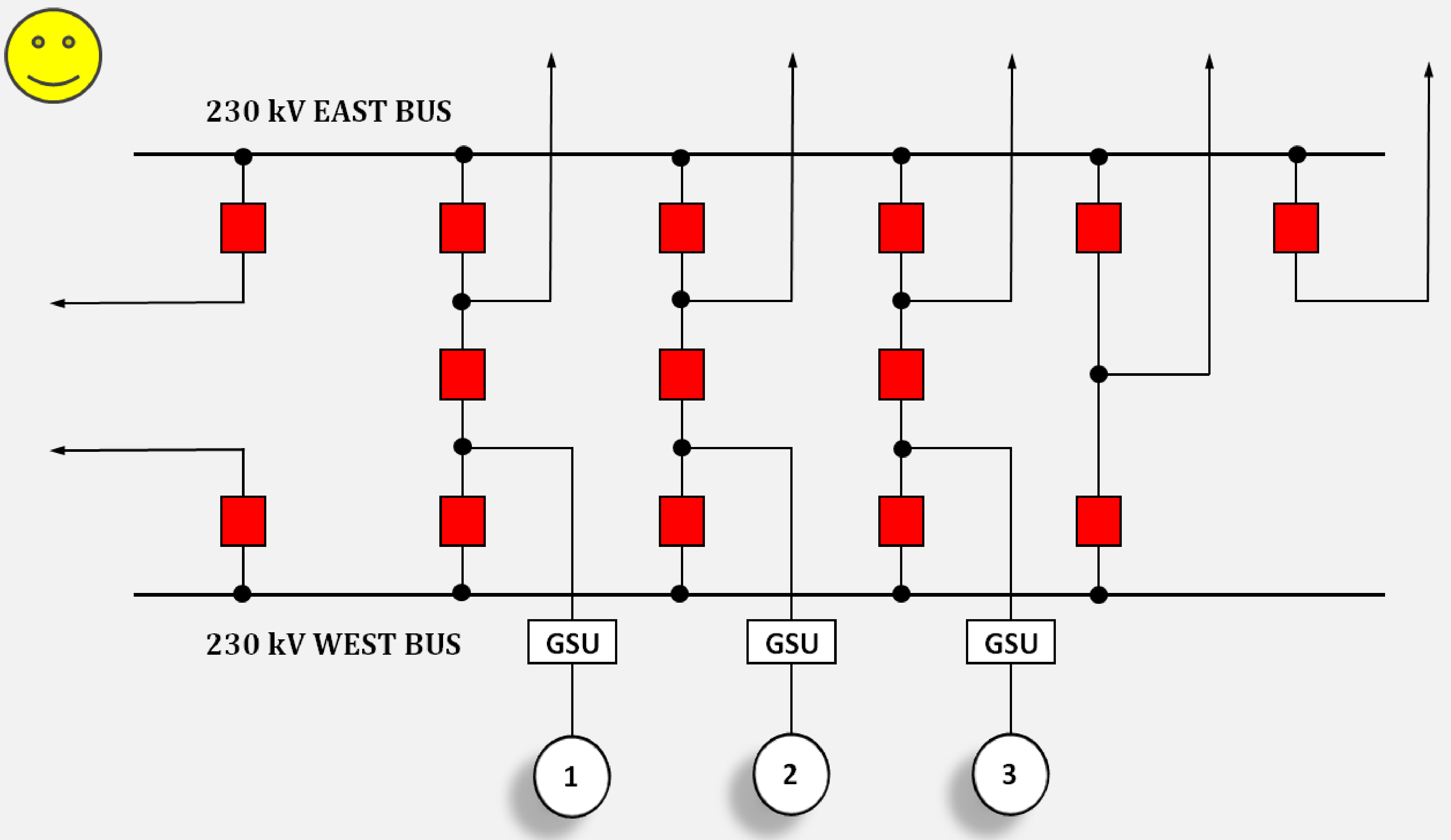
Subject Matter

- A Real-World Application
- 230 kV Switchyard – Generating Unit Connection
- Electromechanical Differential Relay for Overall Unit & GSU protection
- Relay & CT Connection Application - Vulnerability created for misoperation

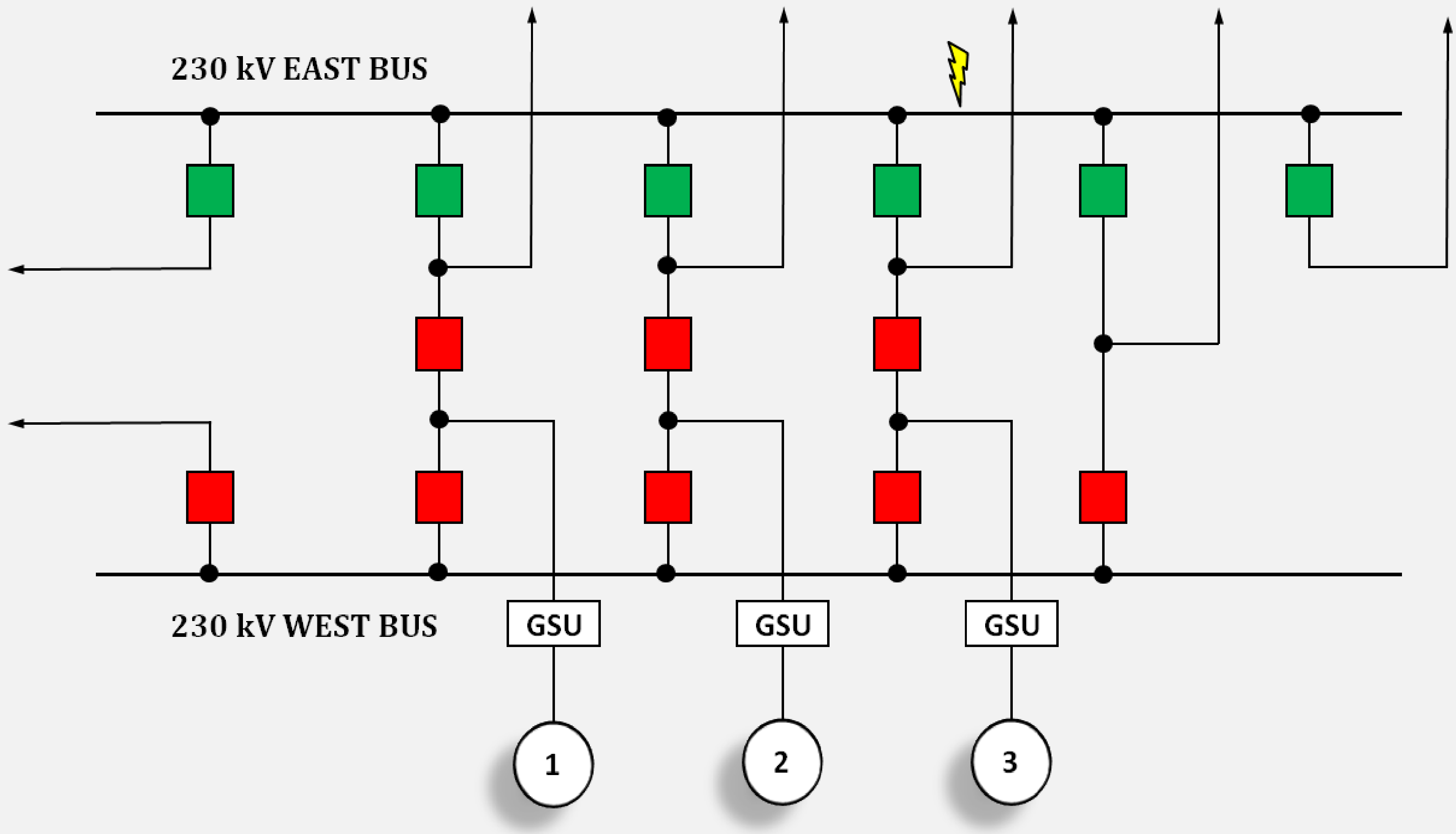
GENERATING STATION – 230 kV SWYD INITIAL CONDITIONS



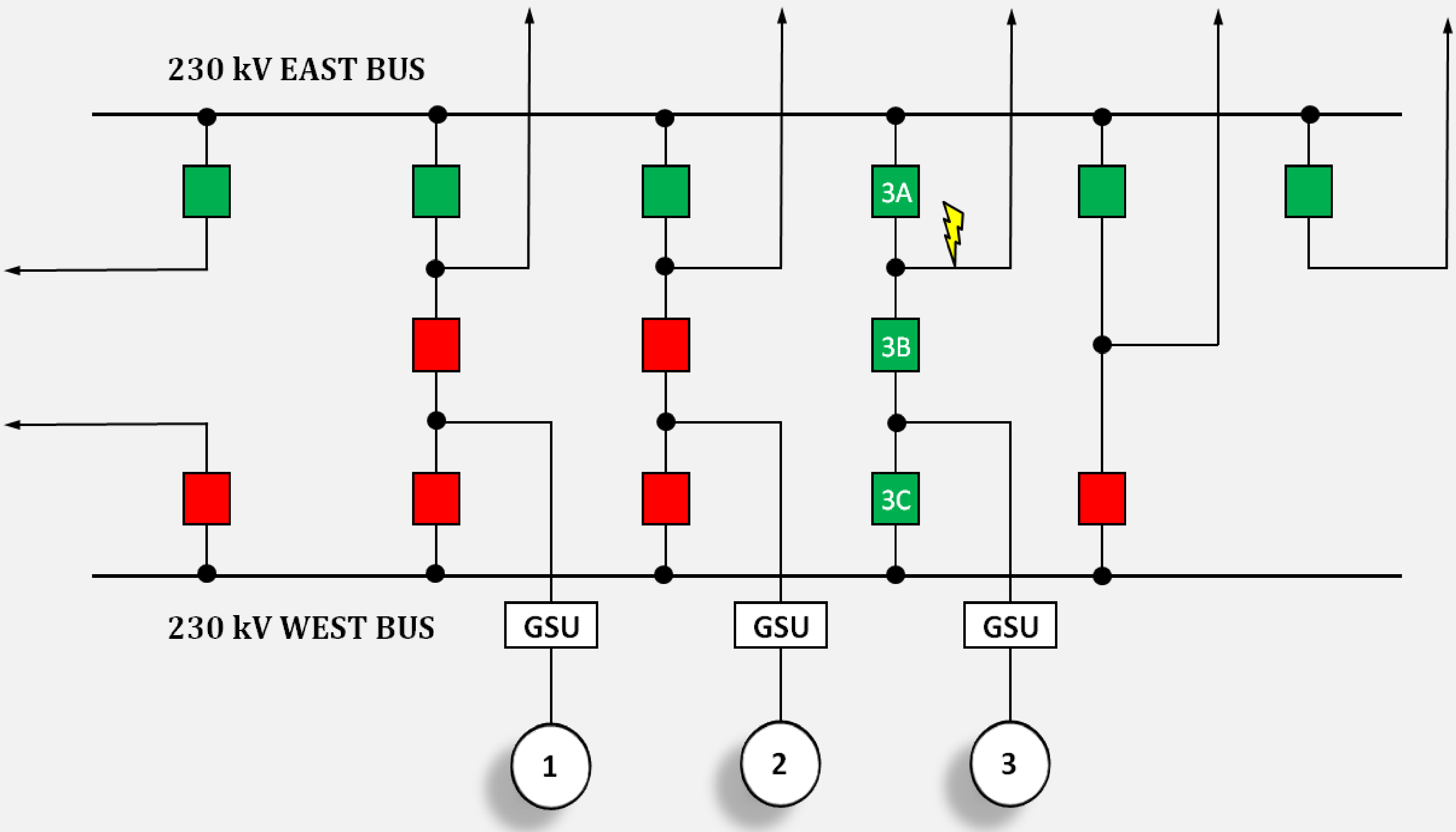
TWO 230 kV SWITCHYARD FAULTS

- Two back-to-back faults in the 230 kV switchyard: separated by three seconds.
- First Fault - a bus PT failure, L-G fault.
  - Cleared by the bus differential scheme.
  - The three generating units remained on-line.
- Second Fault - immediately outside U3 overall unit differential zone.
- The differential relay operated, tripping unit.

FIRST EVENT, L – G FAULT
POST EVENT BKR STATUS



LINE FAULT, A – B PHASE, 3 SECONDS LATER
UNIT 3, 87-OA TRIP



UNIT 3, OVERALL UNIT DIFFERENTIAL RELAY
“B” PHASE OPERATED

Trouble Shooting and Event Analysis Activities

1. Test relays – Ok – within acceptable tolerance
2. Saturation tests on the 230 kV breaker current transformers
3. Resistance measurements – CT and secondary circuit paths
4. Insulation resistance checks on CT and connecting circuits, checking for unintentional grounds or insulation failure.

Along with the field tests, additional activities:

5. Confirm tap setting calculations
6. Model the AC components of the protection system, and dynamically simulate the fault

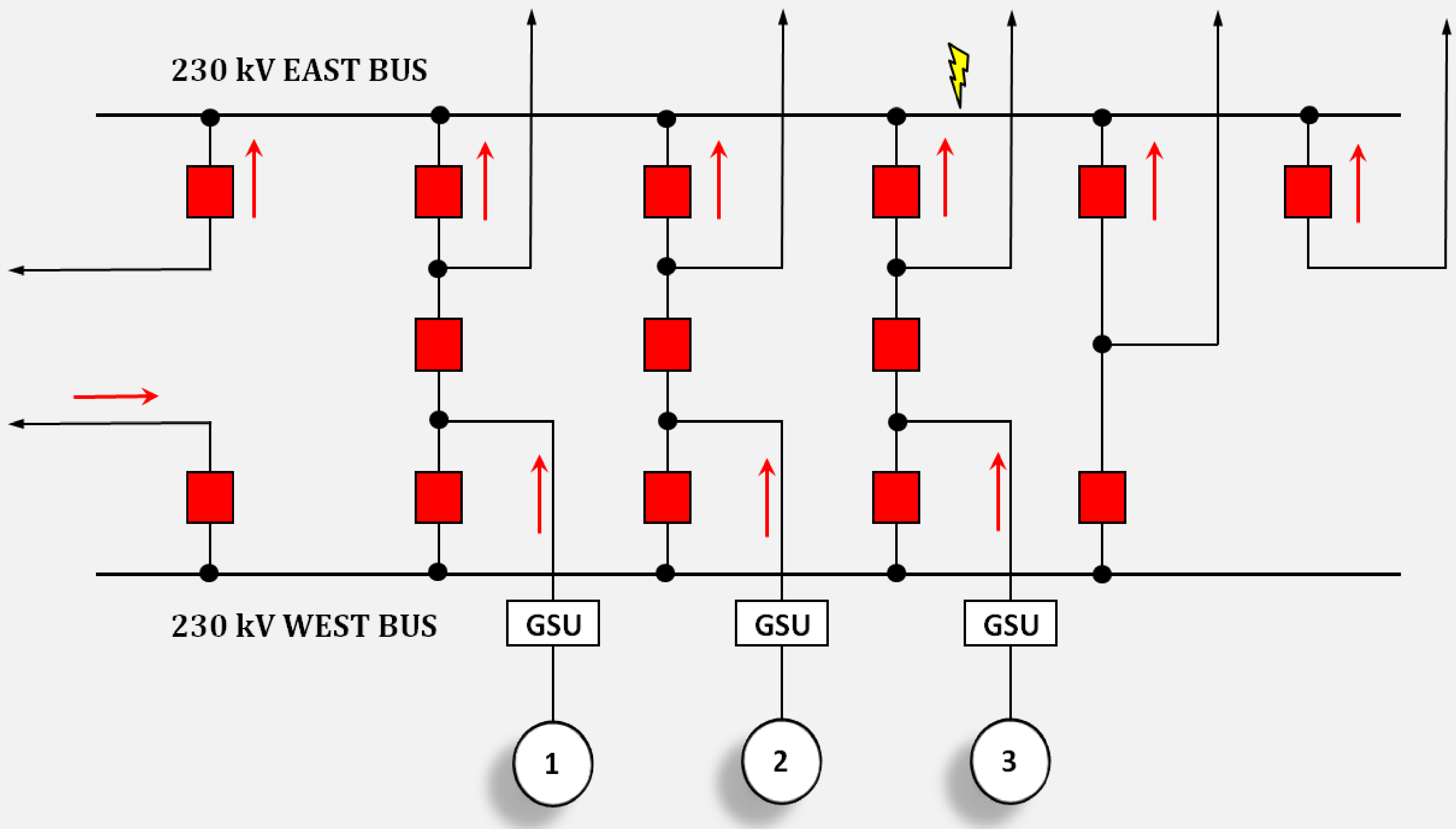
RESULT – *NO SMOKING GUN*

Analysis to Determine Probable Cause:

1. Additional examination of relay event records
2. Records for the 230kV 3B breaker provided the following:
   - Validate the fault currents and phase relationships
   - Determine RMS fault currents levels through the breaker: slightly above 30kA (see Figure 3)
3. By calculation, estimated generator contributions to fault: approximately 1150A through the 3B breaker
4. Approximate 3C breaker fault currents: 3B breaker currents minus the Unit 3 generator contributions.

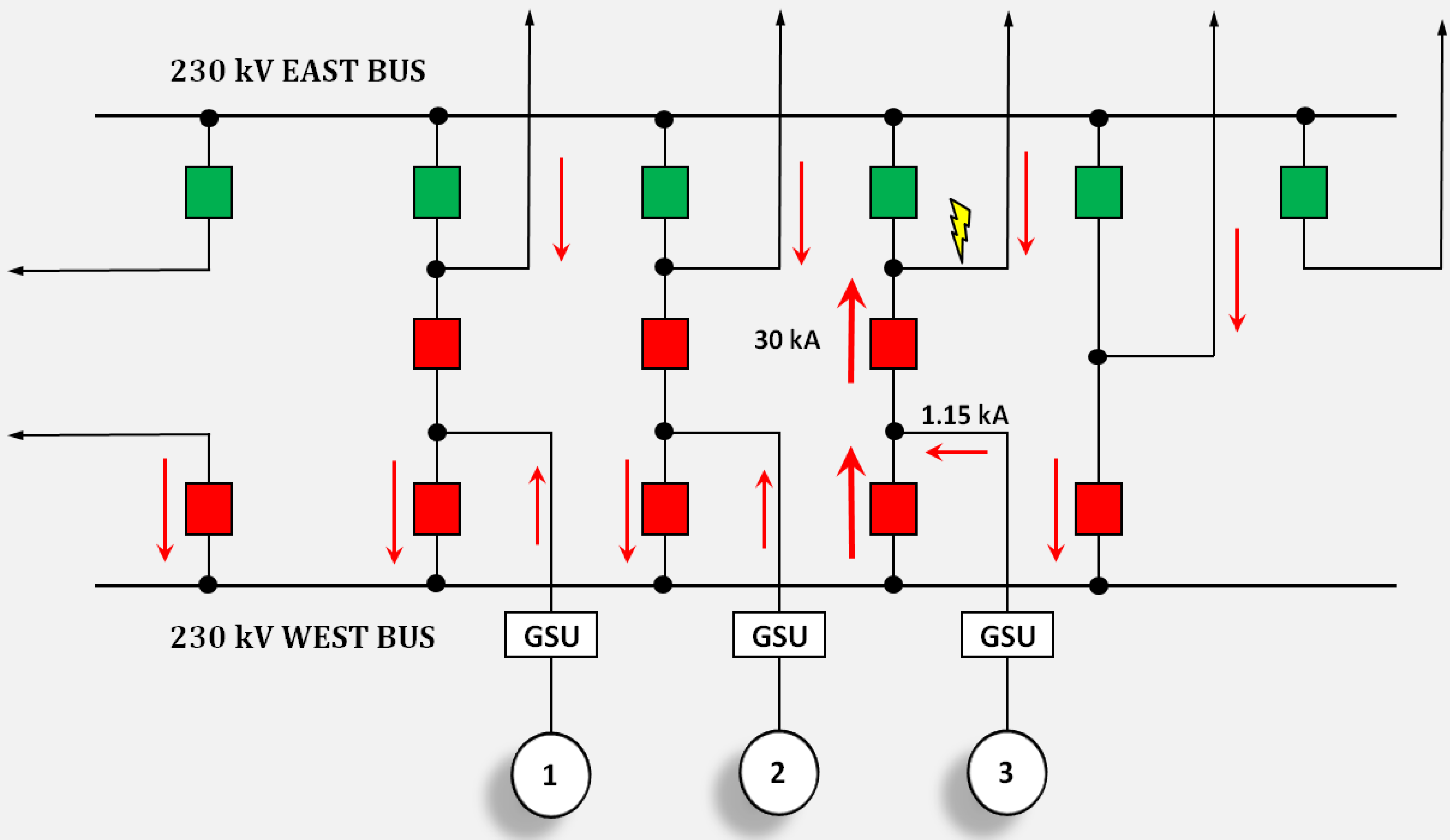
FIRST FAULT - CURRENT PATHS

MULTIPLE FAULT PATHS = LESS CURRENT PER ELEMENT



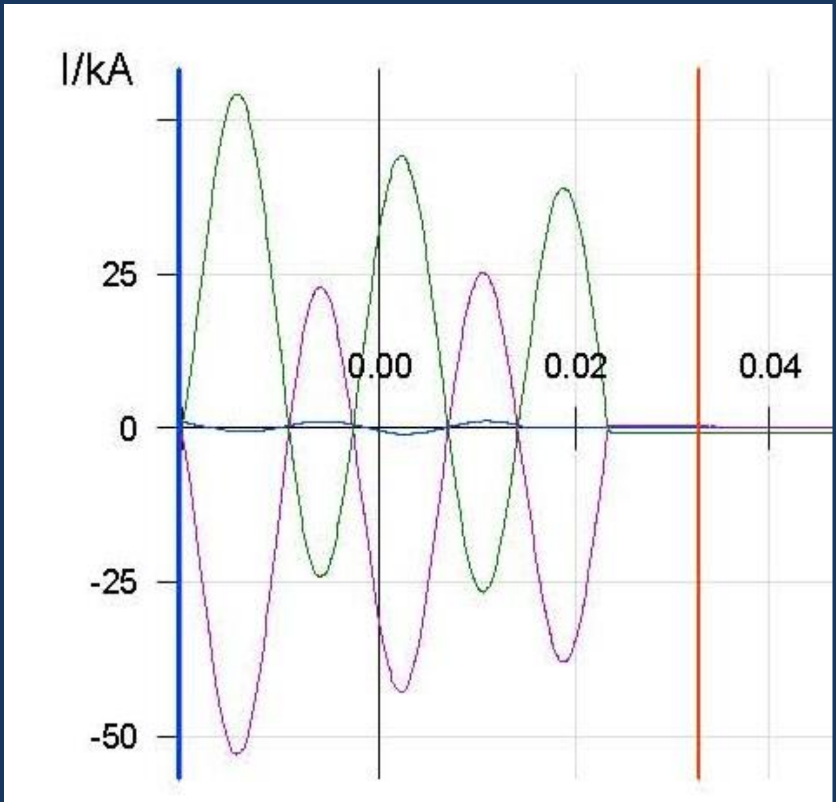
SECOND FAULT – FEWER SOURCE PATHS

FAULT CURRENT IS ACCUMULATED TO HIGHER CONCENTRATION

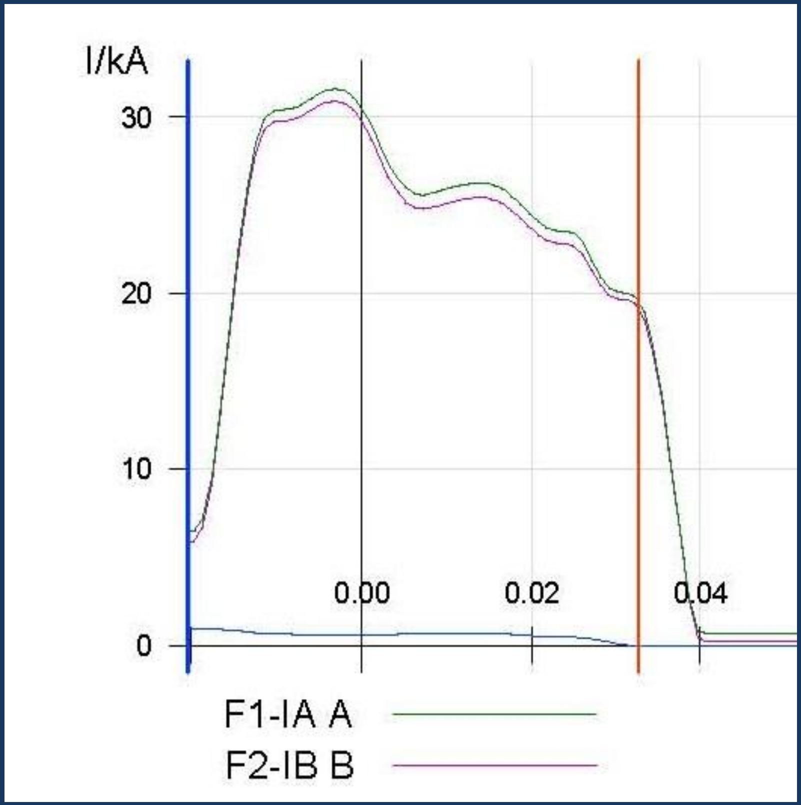


230kV 3B BREAKER
EVENT RECORDS

CURRENT OSCILLOGRAPHY



RMS CURRENTS

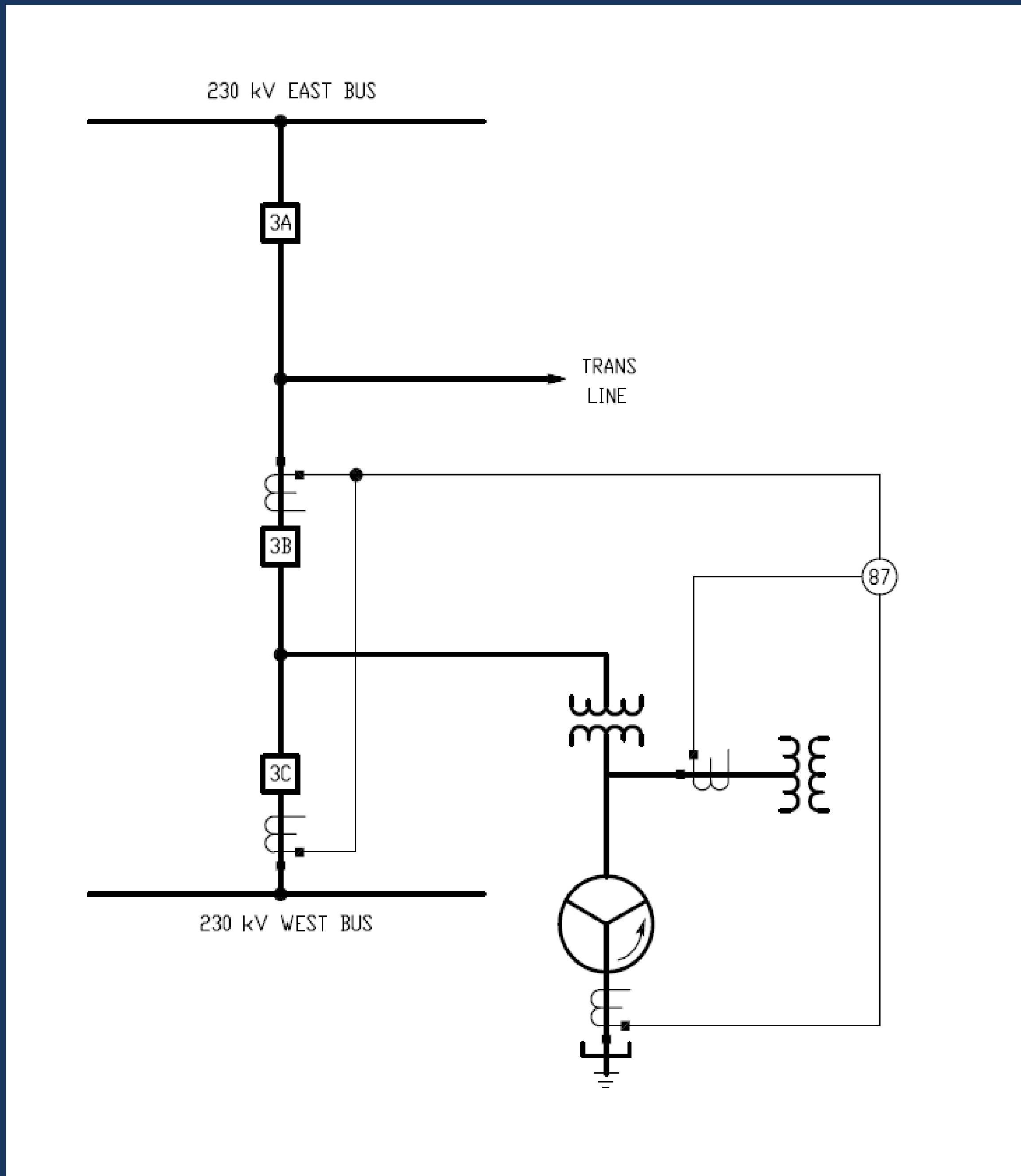


ELECTROMECHANICAL DIFFERENTIAL RELAYS APPLICATION

Primary Contributing Factors to 87 Relay Operation

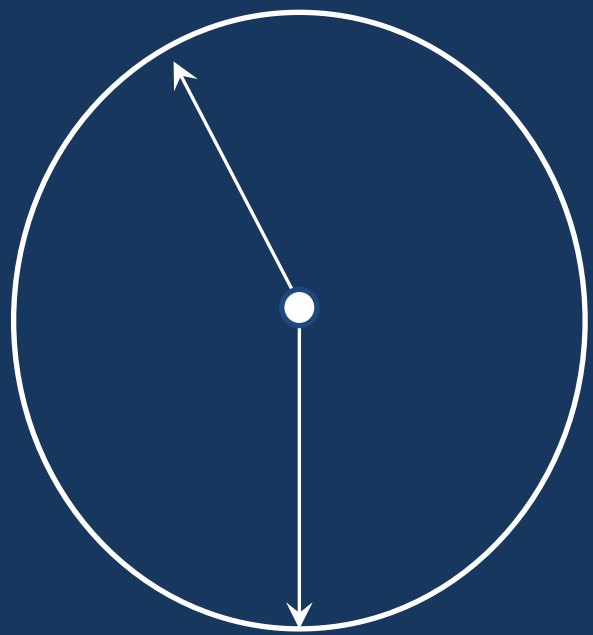
1. Limitation of three winding inputs
   - If using more than three sources, need parallel CT connections to a single winding input
   - Vulnerability is created with HV source CT inputs
2. Transformer phase shift: compensated with external CT circuit connections
   - Wye connected transformer windings → delta connected CTs.

OVERALL UNIT DIFFERENTIAL CONNECTION FOR ELECTROMECHANICAL RELAYS

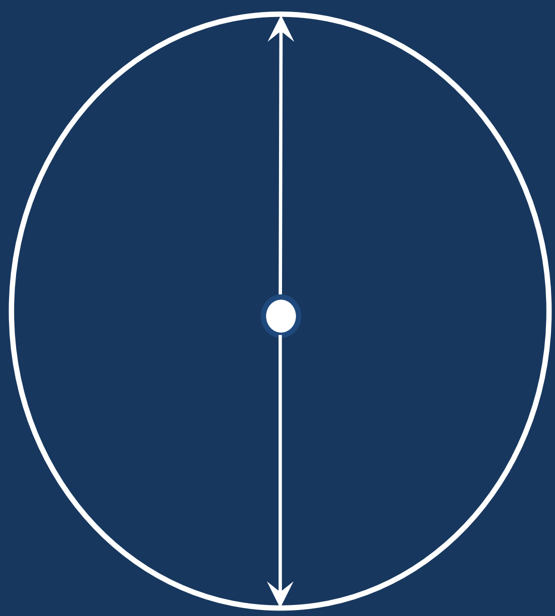


DIFFERENTIAL CURRENTS TO A Y-Δ TRANSFORMER

Uncompensated Current Phasors

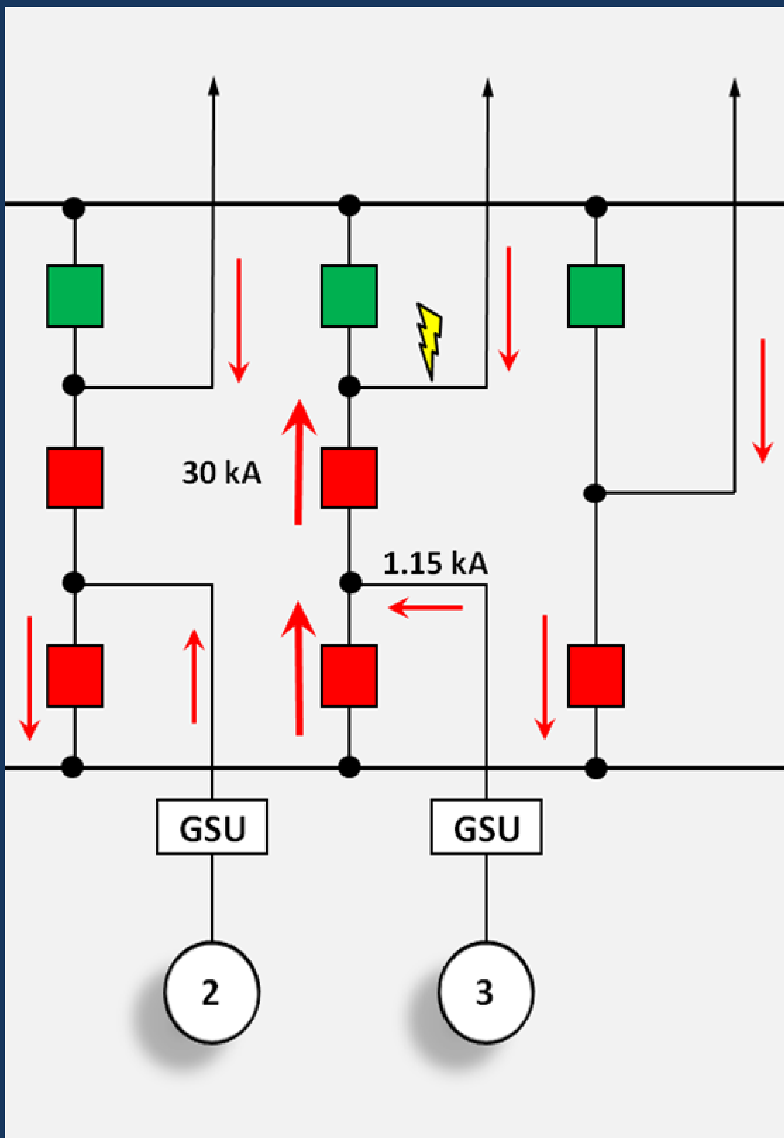


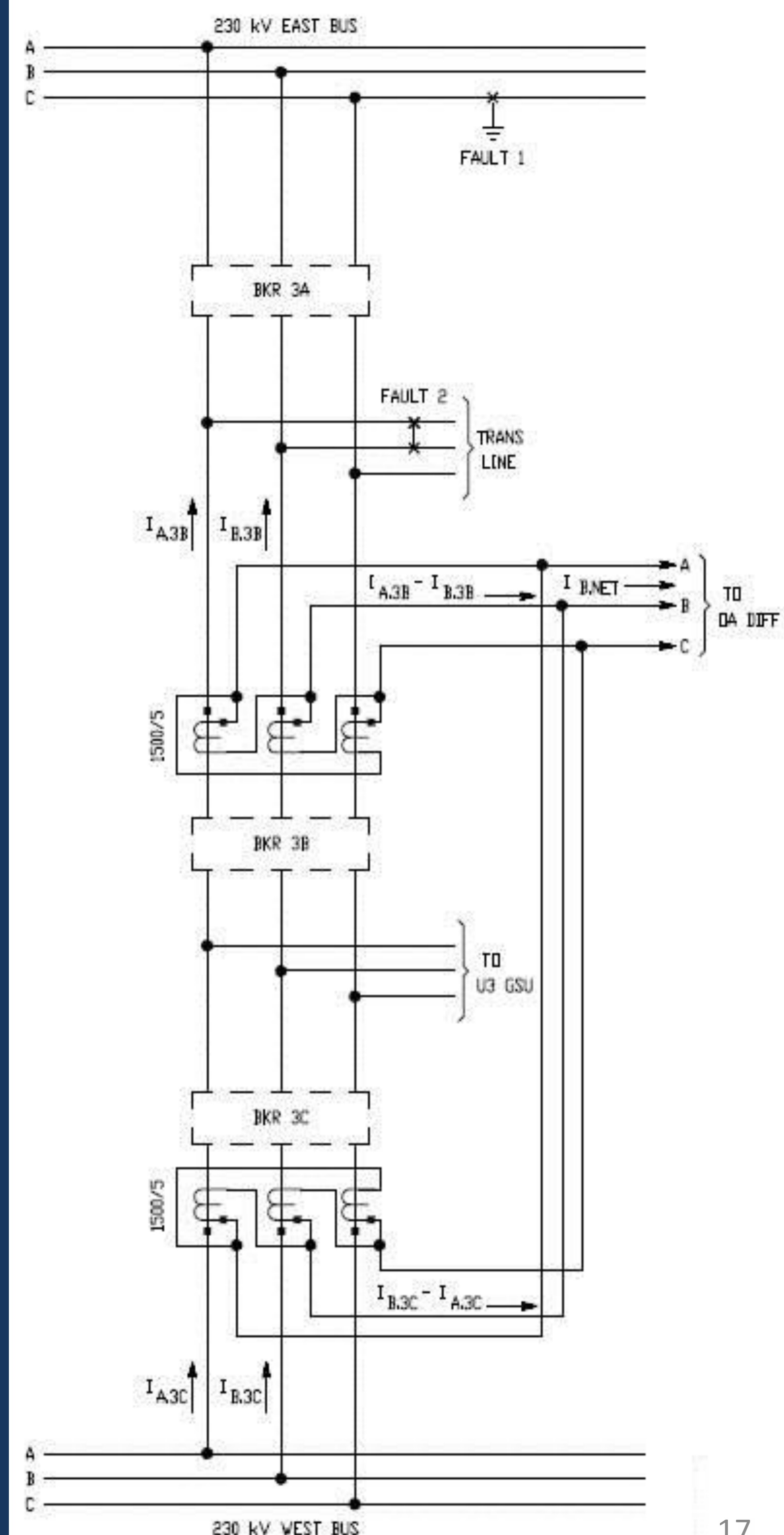
Compensated Current Phasors



Connection Diagram

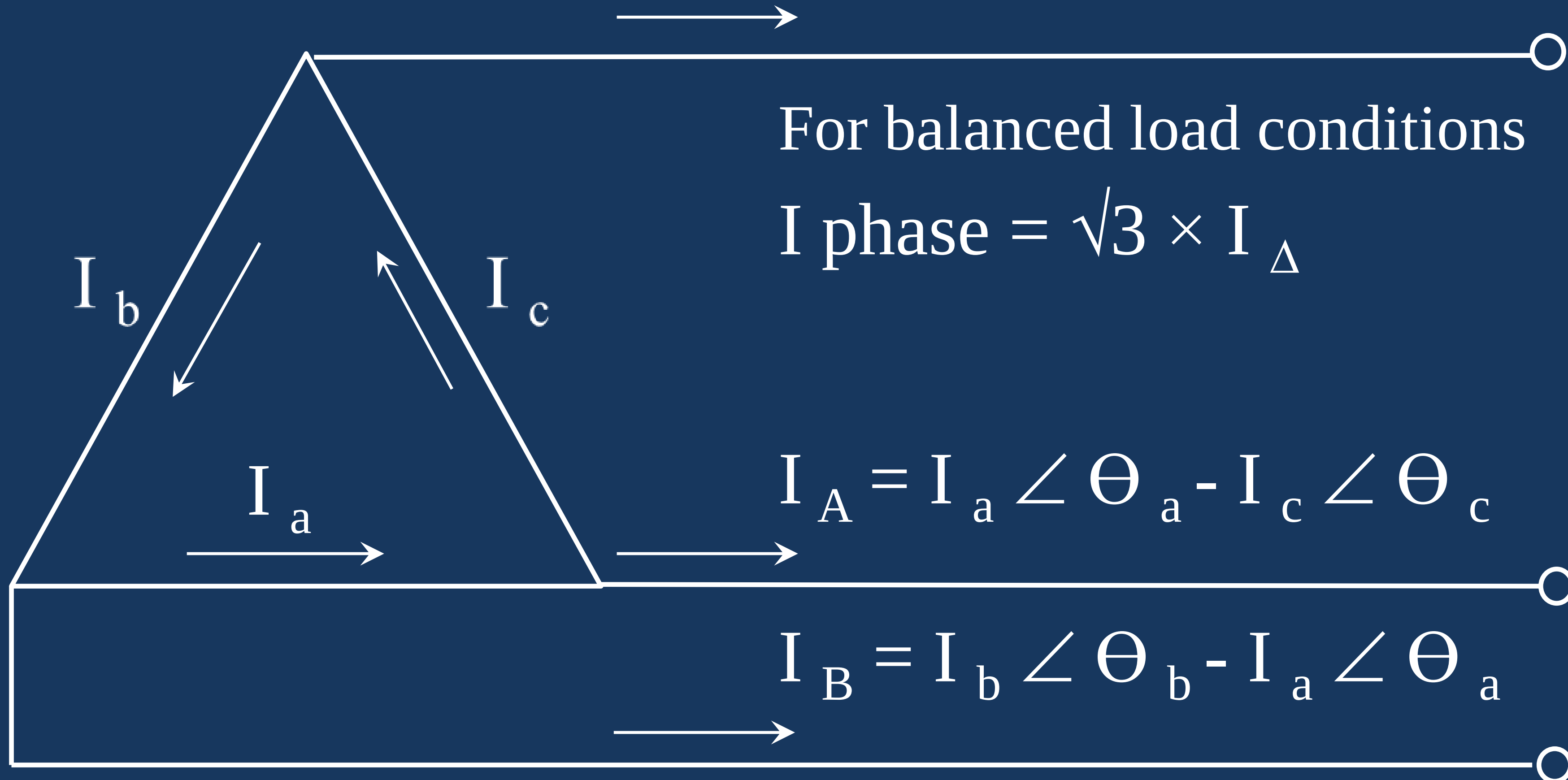
Parallel Connection of CTs on HV Circuits to a Single Winding Input





PHASOR CURRENTS FOR DELTA CONNECTED CTs

$$I_C = I_c \angle \Theta_c - I_b \angle \Theta_b$$



For balanced load conditions

$$I\ \text{phase} = \sqrt{3} \times I_{\Delta}$$

$$I_A = I_a \angle \Theta_a - I_c \angle \Theta_c$$

$$I_B = I_b \angle \Theta_b - I_a \angle \Theta_a$$

Misoperation Risk of Paralleling Two High Voltage Current Transformers

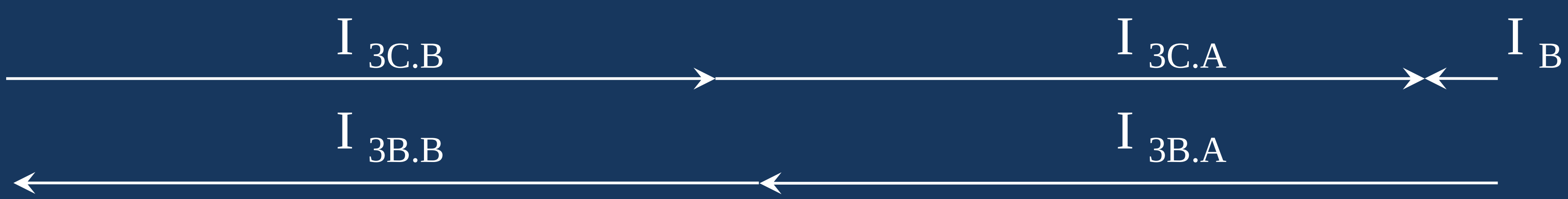
1. Risk is for Through Faults, Outside the 87 Zone of Protection
2. Individual Primary and Secondary currents are high
3. CTs typically Delta Connected for E-M relays; relay inputs are vector sum of two currents.
4. Net currents are very low for through faults; relay input is the vector sum of four CT secondary currents.
5. Small CT ratio errors, within tolerance, can have a significant impact on relay current inputs

Two High Voltage Current Transformers Connected in Parallel

CURRENT TO EACH 87 RELAY IS THE VECTOR SUM OF FOUR PHASORS: $I_{B} = I_{3C.B} \angle \Theta_{B} - I_{3C.A} \angle \Theta_{A} - I_{3B.B} \angle \Theta_{B} + I_{3B.A} \angle \Theta_{A}$

LINE - LINE FAULT: PRIMARY PHASE CURRENTS, 180^{O} OUT OF PHASE.

$$I_{B} = (I_{3C.B} \angle 0) - (I_{3C.A} \angle 180) - (I_{3B.B} \angle 180) + (I_{3B.A} \angle 0)$$



<u>RESTRAINT CURRENT IS A SMALL PERCENTAGE OF CT OUTPUT</u>

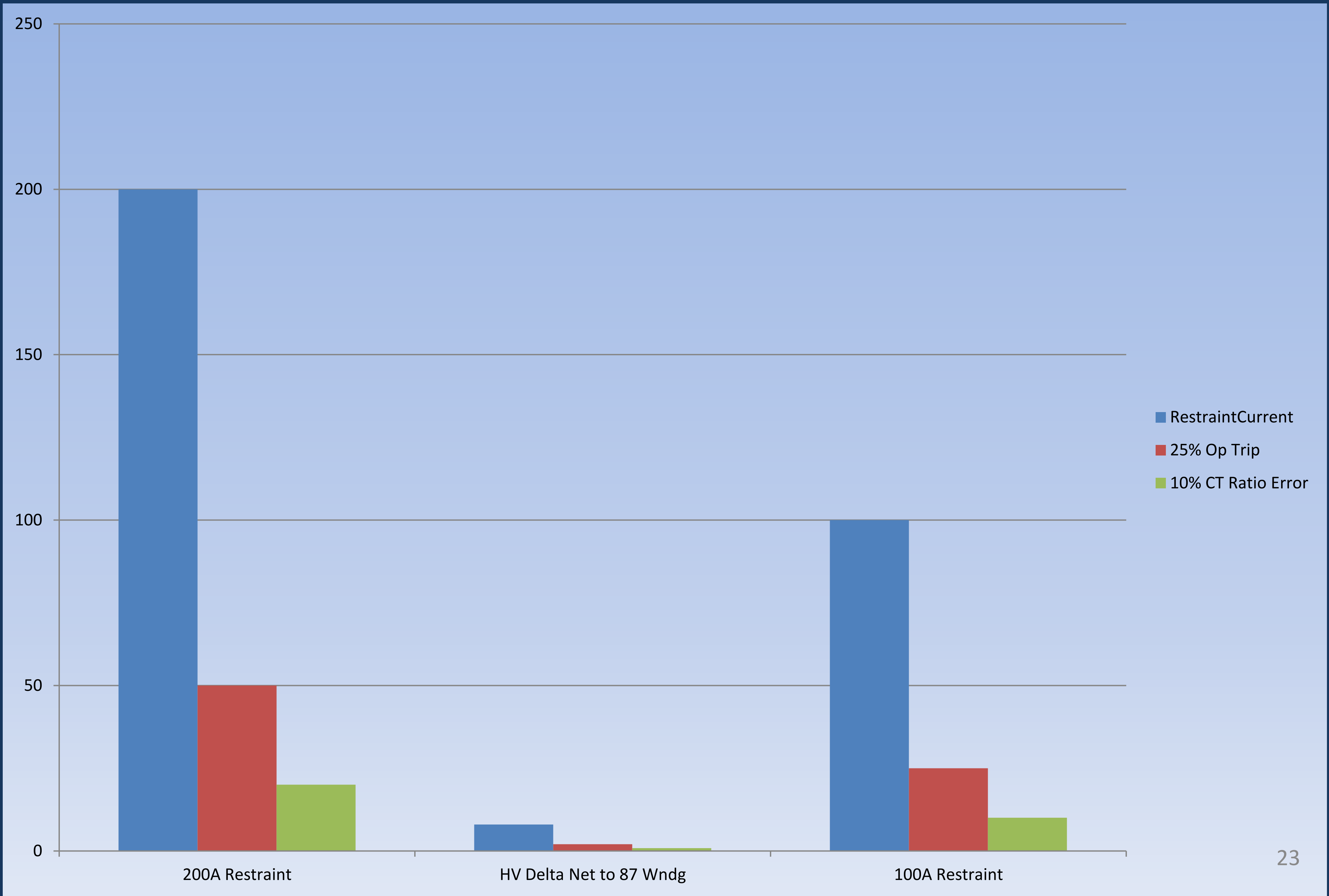
ANALYSIS OF SECOND FAULT

1. Fault is outside U3 Zone of Protection.
2. Fault currents flow through Breakers 3B and 3C.
3. Breaker 3B phase current > 30kA.
4. Unit 3 Generator HV fault contribution is 1.15 kA fault current (4% of 30kA).
5. The vector sum of four high-magnitude currents ($I_{A.3B}$, $I_{B.3B}$, $I_{A.3C}$, and $I_{B.3C}$). The sum must equate to 1.15 kA (Unit 3 generator contribution).
6. On percentage restraint differential relay applications, high restrain current $\rightarrow$ high operating current to trip.
7. From the input perspective of differential relay restraint coils, this was a low-level fault.
8. The low restraint currents to relay grossly misrepresent the high currents flowing in CTs.

ANALYSIS OF SECOND FAULT

- Delta connected CTs outputs from 3B breaker: B phase current is 57 × times the relay tap setting (200A ÷ 3.5A)
- Subtract the currents from the 3C breaker & Net relay restraint currents are miniscule to fault currents.
- With no error in CT performance, the net combined CT outputs are only 2.3 × times the relay tap (8.0A ÷ 3.5A).
- Using rounded numbers of estimated fault current, 30kA through Breaker 3B with 1500/5A CT is 20 × tap.
- IEEE C57.13-2008, CT ratio error tolerance is 10%
- At 20 times rated current, a ratio error difference as low as 2% can create sufficient differential operating current to reach the relay trip threshold.

Graphical Representation of Restraint & Operating Current For Relative Comparison the CT Ratio Error



CORRECTIVE ACTION OPTIONS

NEW INSTALLATIONS

Vulnerability avoided with proper design and installation practices with two primary features:

1. Select a relay with sufficient winding inputs.
   – Each HV breaker CT connects to a separate input.
   – The relay recognizes individual inputs as restraint currents.
   – The operating current threshold increases for out of zone of faults; provides security against false operation.
2. Connect the current transformers in wye.
   – Avoid need for external compensated delta connected CTs
   – Lowers the current levels in the secondary circuits.
   – Avoid two × secondary phase currents, as possible with delta connected CTs
   – Ability to record and meter the individual phase currents

UPGRADE OR RETROFIT

The best technical solution: replacement and re-design, using same features of a new installation.

These included the following characteristics:

- Remove and replace the electromechanical relays with microprocessor based.
- Re-design of the CT circuits to change the delta secondary to a wye.
- If two high voltage breakers are used with parallel connections to a single relay winding input, separate the circuits into two independent relay winding inputs.

WHEN ECONOMICS DON'T JUSTIFY COMPLETE RE-DESIGN
OPTIONS FOR CAREFUL CONSIDERATION

- Determine the through fault current levels and understand the impact of CT ratio tolerance on protection
- Use a relay with programmable logic.
  - Consider a delay for percentage restraint differential elements under through fault current levels.
  - Use normal high speed time for current levels above through-fault
  - Use complementary rapid pressure rise or sudden pressure activation for high speed protection for internal transformer faults.
- Where justifiable, increase the minimum differential operating pickup and raise the slope of the percentage differential characteristic.
- Install backup instantaneous overcurrent protection on the high voltage breaker circuits. Use typical transformer instantaneous settings for backup protection of the high voltage section of differential zone.

VULNERABILITY IN NEW INSTALLATIONS

Bidding projects for design and installation in the absence of detailed requirements or design guidance:

- Natural competitive pressures: cut every possible cost.
- Very inexpensive differential relays with limited winding inputs are available.
- Very creative designs are available to parallel multiple CT inputs into a common winding input.
- Paralleling two HV breaker CTs into a single relay winding input fundamentally creates the same vulnerability as shown in the electromechanical relay application.
  - Relay is unable to distinguish faults currents outside the relay zone of protection
  - Unable to apply the most favorable security features of differential relays.

CONCLUSION

1. Without recorded oscillography of CT currents into the electromechanical differential relays, there was no absolute, definitive evidence to demonstrate the cause of the differential relay operation.
2. Due to the standard 10% ratio error of CTs at 20 × the tap, it is reasonable to attribute the relay misoperation to differential currents created by CT performance within accepted tolerance.
3. The delta connection of current transformers contributed to the high magnitude in portions of secondary circuits.
4. The vector summation of four high level current magnitudes produces the net result: one relatively small current.
5. With acceptable CT ratio tolerance of 10% at a current level of 20 × the tap, it is reasonable to conclude that small differences in the CT performance created sufficient differential current to trip.
6. Plan for contingencies: A major contributing factor was the first fault, which set up vulnerabilities revealed by the second fault.
7. The key to overcoming the flaw: good planning & design, use the available features of microprocessor relays, and don't cut corners.