Effect of Transformer Connection and Construction on Single Phasing Detection

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Introduction

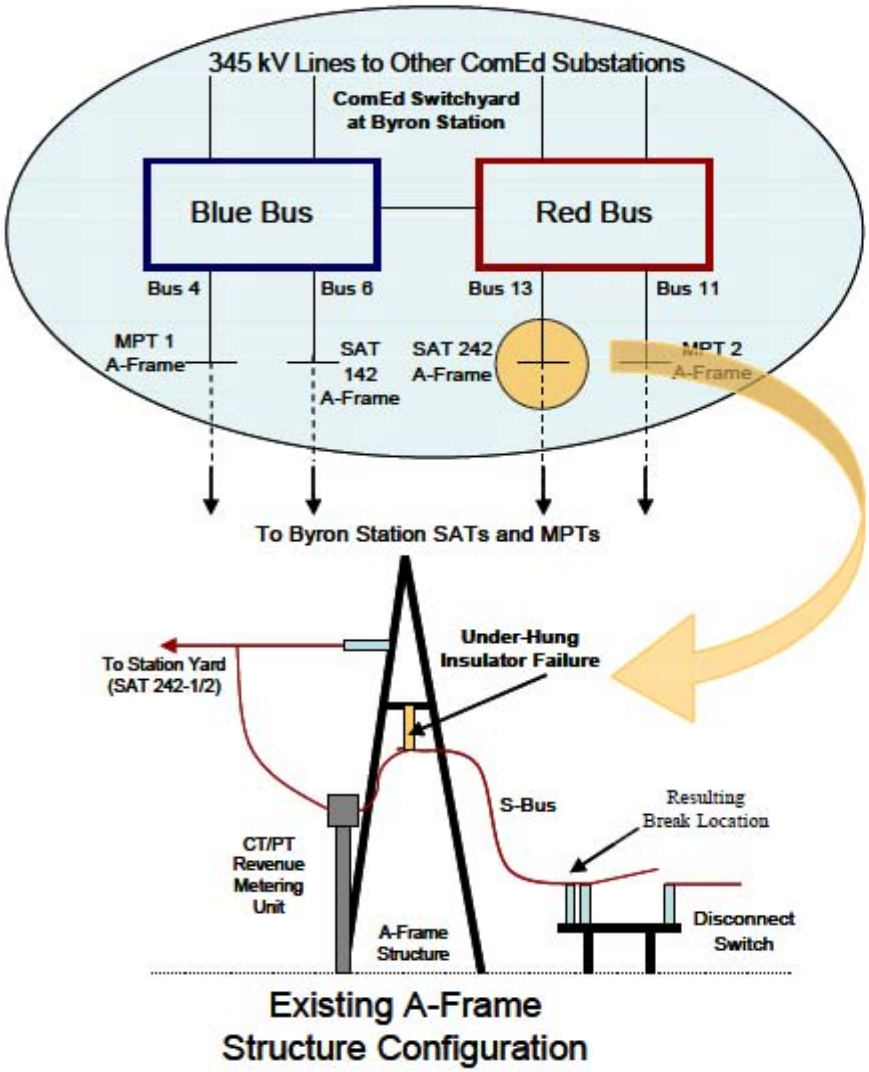
- **On January 30, 2012 Exelon's Byron Unit 2 experienced an event, resulting in a unit trip & loss of off site power.**

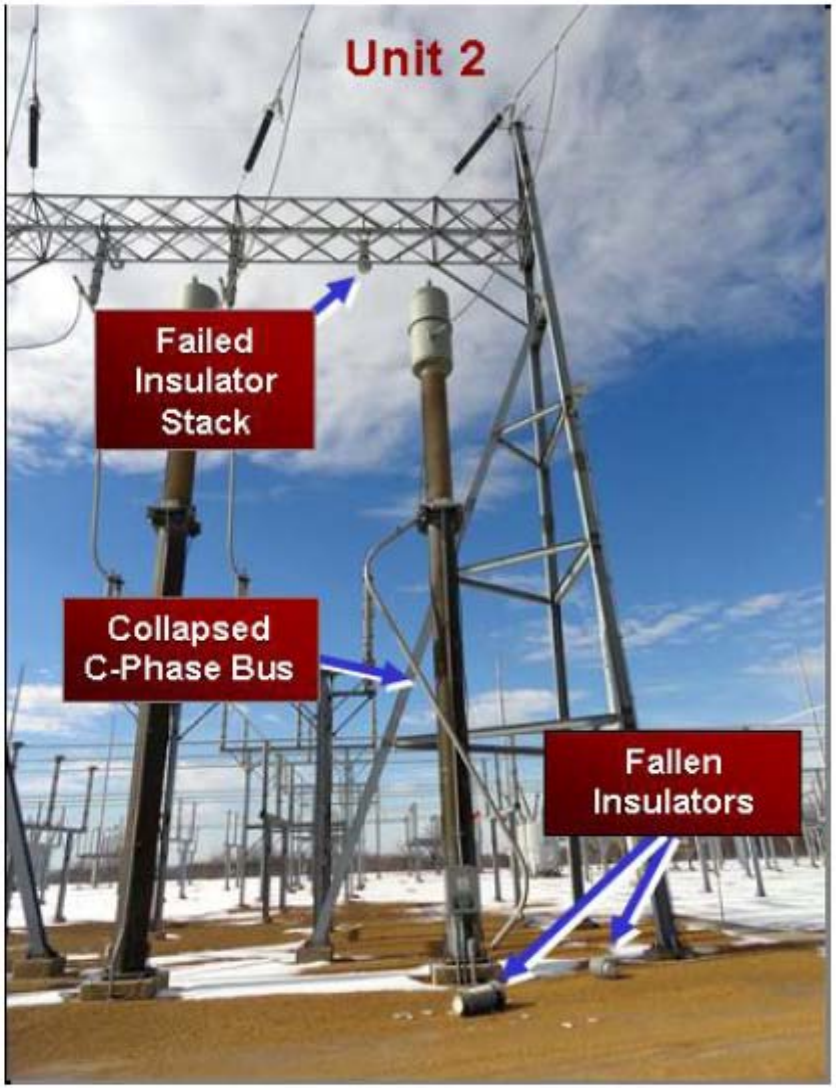
- **Event: Insulator failure on 345kV offsite power source caused phase "C" S Bus "break away" from the power line disconnect switch.**

Introduction

- As a result, both Unit 2 System Auxiliary Transformers (SATs) were single phased.
- Phase “C” of both SATs had a high Z ground
- Switchyard protective relaying is not designed to detect a single phasing event, did not operate
- SAT protection, including secondary Degraded Voltage Relay protection was not sensitive enough to detect the single phasing condition, did not operate

Byron Generating Station Unit 2 Switchyard





Background
Byron Auxiliary Power System

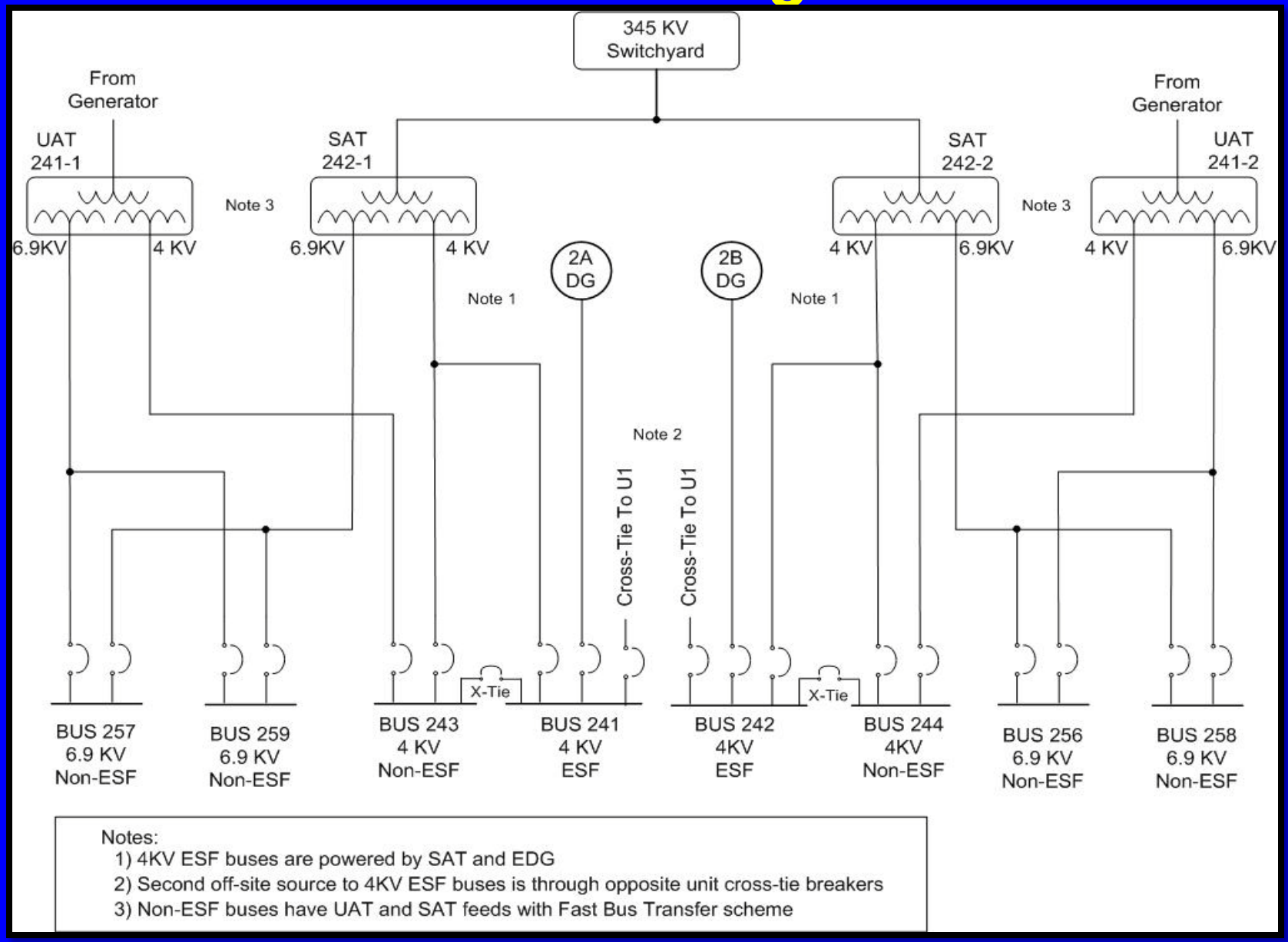
- Each Unit has two SATs
  - 142-1/142-2 for Unit 1
  - 242-1/242-2 for Unit 2

- Each SAT
  - Has 3-windings
  - Is Wye/wye-wye connected
  - Step down 345 kV/6.9 kV – 4.16 kV
  - Is a 3 legged core form transformer

Background
Byron Auxiliary Power System

- SAT 345kV primary winding is solidly grounded
- Secondary's are resistance grounded
  - 4.16 kV winding
    - supplies one division of Engineered Safety Features, ESF buses (safety bus) and one Non-ESF
  - 6.9 kV winding
    - supplies two Non-ESF buses

Byron Unit 2 Auxiliary Power System One Line Diagram

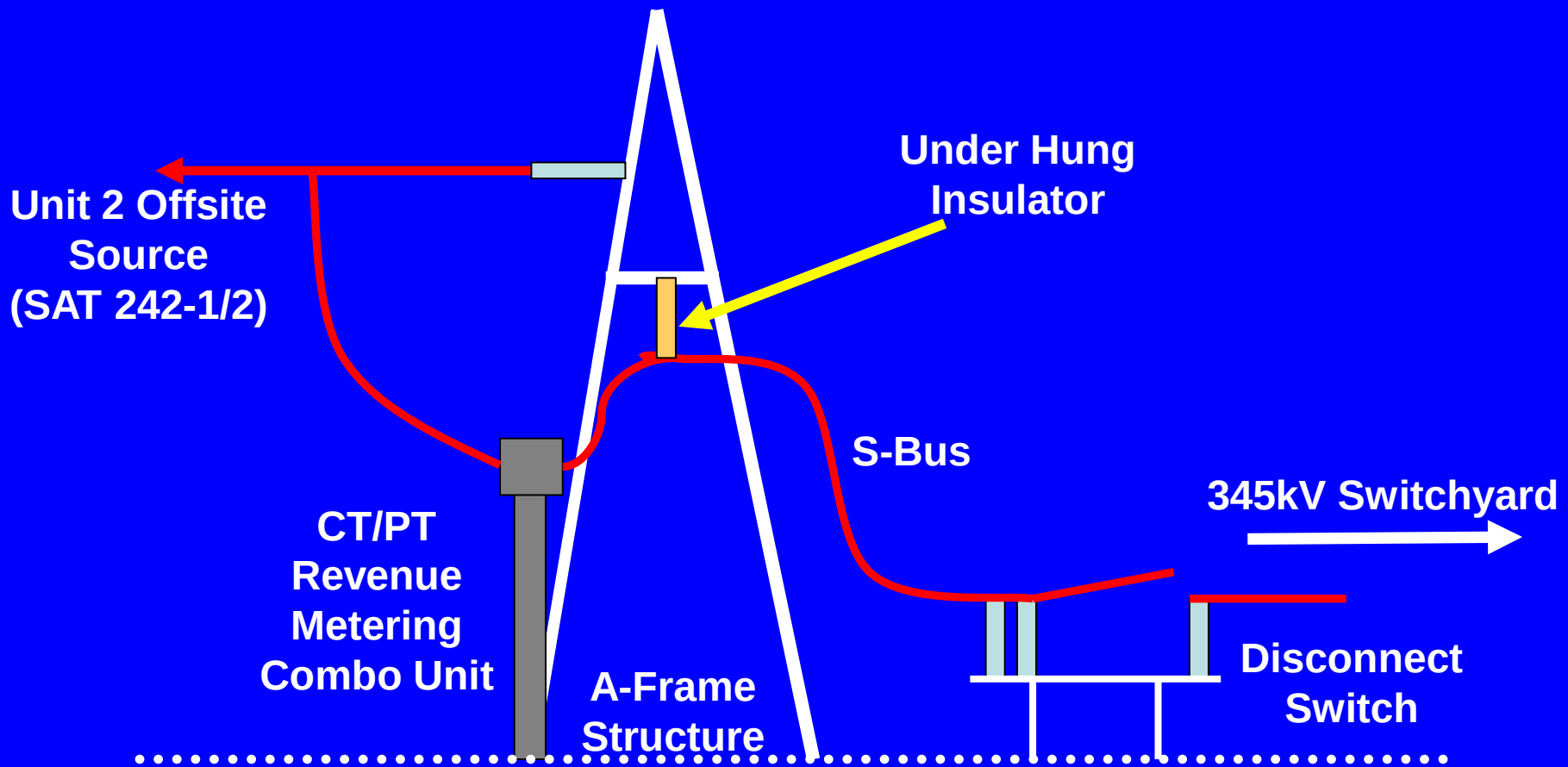


Notes:
1) 4KV ESF buses are powered by SAT and EDG
2) Second off-site source to 4KV ESF buses is through opposite unit cross-tie breakers
3) Non-ESF buses have UAT and SAT feeds with Fast Bus Transfer scheme

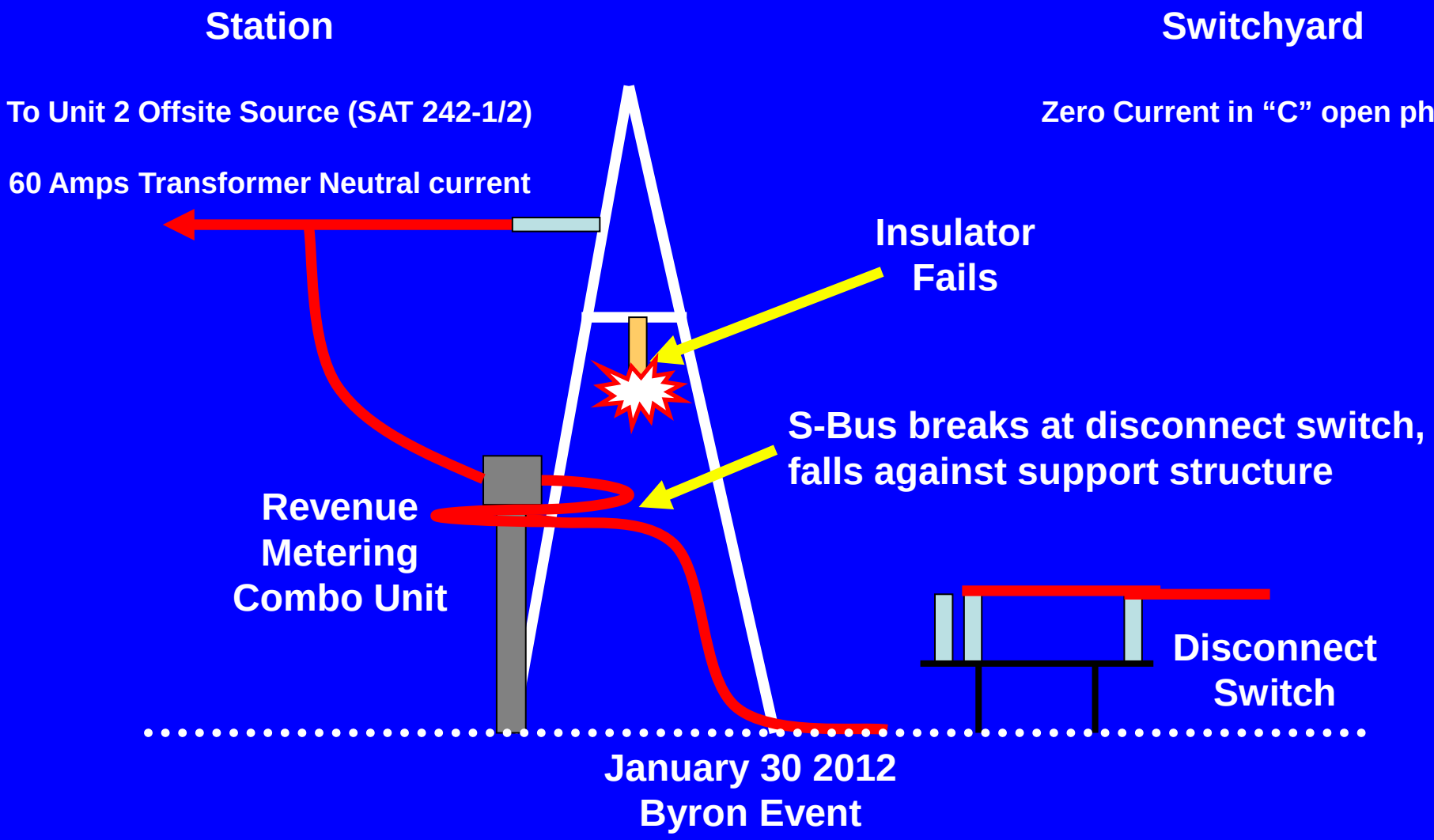
Background
Byron Auxiliary Power System

- SAT high side for a given unit connects to a common 345kV switchyard bus section
- Connection to SATs
  - from the 345kV bus
  - through a solid pipe “S-Bus”
  - through flexible connections
  - into the revenue metering “combo units”
  - to a common bus for both SATs

Byron Auxiliary Power Transformer Connection



Byron Unit 2 Post Failure



Byron Unit 2 Switchyard “C” Phase Failure

Root Cause

- Manufacturing defect; porcelain was not fully fired in the kiln. Forensic Evaluation
  - Failure caused by service propagation of a manufacturing material defect that covered approximately 40% of the fracture cross-section.
  - Defect was characterized as poorly vitrified porcelain containing a high density of porosity and micro-cracks.
  - No evidence the internal porcelain defect was open to external surface of the insulator until the final fracture
  - No evidence external cracking or a projectile impact preceded the failure

Bus Insulator Fracture

Root Cause

- The insulator failure
  - Ohio Brass under hung four stack insulator manufactured in 1977
  - Byron had experienced failures of these insulators in the past
    - The previous failures were on rotating switches
      - Failure mode believed to be related to the torque on the porcelain during switch operation
      - All switches in this application had been replaced

Byron Auxiliary Power System

- On a loss of SATs, non-safety buses fast-transfer to Unit Aux TXs (UATs) and safety buses load onto the emergency diesels
- Second source of offsite power is opposite unit SAT through operator (manual) action

The Event

- On January 30, 2012, 345kV switchyard “C” phase insulator fails leading to loss of “C” phase power to both Unit 2 SATs
- Resulting voltage imbalance cascades to the station buses through the SAT
- Reactor trips on RCP bus under voltage (2 out of 4 logic) fed from SAT .
- Motor driven and diesel driven Auxiliary Feedwater (AF) pumps receive signal to start on RCP bus under voltage
  - Diesel driven AF pump starts successfully.
  - Motor driven AF Pump does not accelerate (was powered from SAT)

The Event

- Essential Service Water, Component Cooling, and Condensate Booster pumps trip on overcurrent.
- The degraded voltage relay scheme actuates and alarms following the 10 second time delay; however, the alarm clears in approximately 2 seconds
- Additional loads continue to trip on overcurrent
- Small loads trip due to TOL relays
- Approximately 30 seconds after the Reactor Trip, the Reverse Power Main Generator Trip occurs as expected

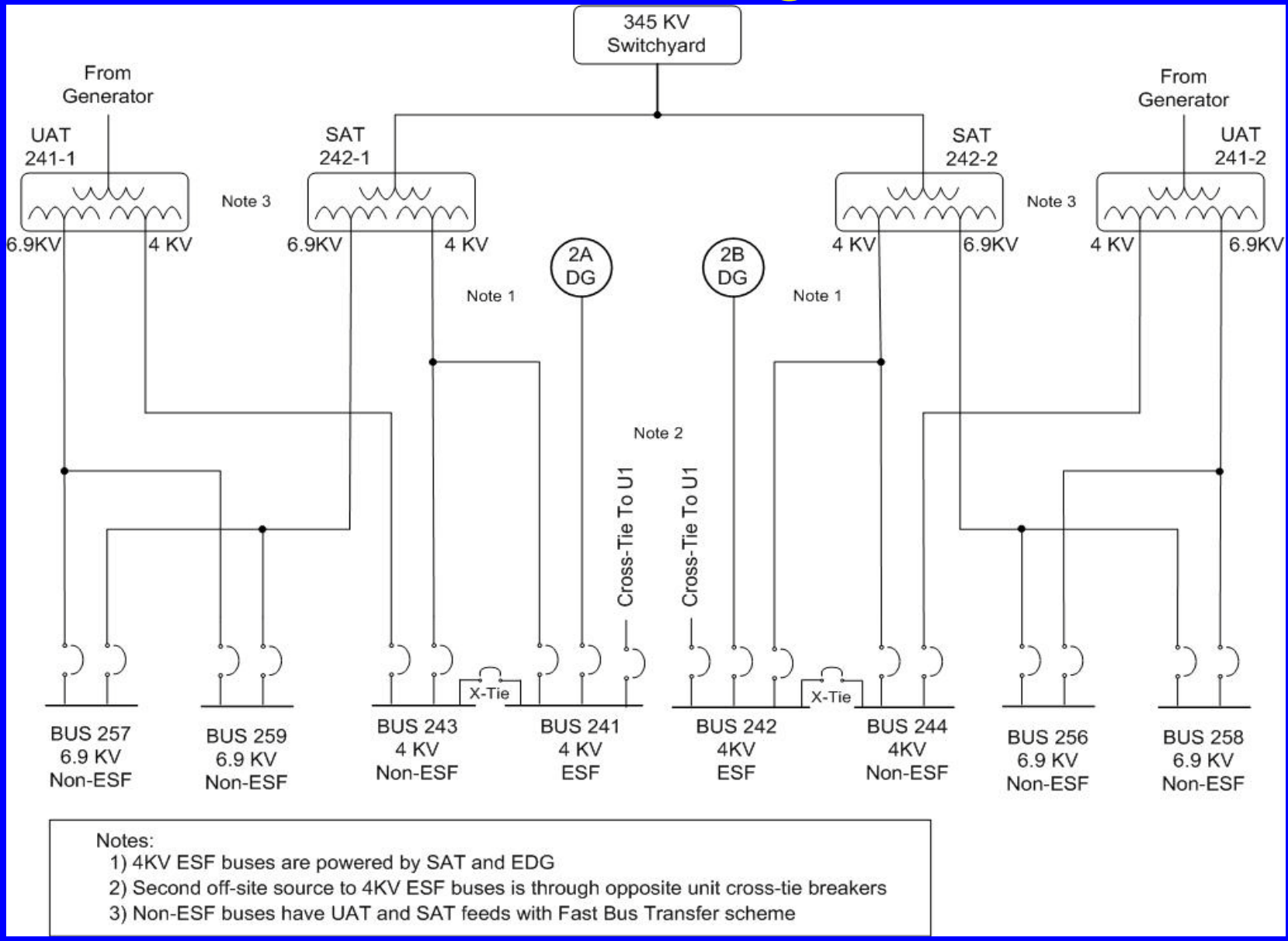
The Event

- Fast bus transfer occurs from UAT to SAT
- The remaining 2 RCPs trip following transfer
- Operators recognize the voltage imbalance 8 minutes into the event and manually open SAT feeds to all buses
- Emergency Diesel Generators (EDGs) automatically start and re-energize the safety buses
- An Unusual Event is declared

The Event

- 4KV non safety related buses are subsequently re-energized from the 4kV safety buses to provide EDG power to select non-1E loads
- The switchyard insulator is repaired next day, off site power is restored.
- Unusual Event is terminated

Byron Unit 2 Auxiliary Power System One Line Diagram



Notes:
1) 4KV ESF buses are powered by SAT and EDG
2) Second off-site source to 4KV ESF buses is through opposite unit cross-tie breakers
3) Non-ESF buses have UAT and SAT feeds with Fast Bus Transfer scheme

Event
Design and Licensing Basis

- Event revealed a design vulnerability not detected by the existing protective relay schemes
  - Switchyard protective relaying is not designed to detect this open phase event
  - Existing SAT protection was not sensitive enough to detect the open phase condition
  - Detection down to the level of this type of failure is beyond the requirements of GDC 17 or BTP PSB-1
- A Loss-of-Coolant-Accident (LOCA) coincident with this switchyard event is considered to be beyond the existing design and licensing basis of the plant

Event Design Vulnerability

- The degraded grid voltage relay scheme on the 4.16kV safety bus is not designed to actuate for voltage unbalance created by an open phase between offsite grid and SAT

- Degraded grid voltage relays on the 4.16kV safety bus provide isolation from the offsite grid and the automatic start and loading of the emergency onsite diesel gens

Degraded Voltage Relay Scheme Description

- The Degraded Voltage Relay (DVR) protection scheme consists of two under voltage relays on each 4kv ESF buses (AB, BC)
- Two separate time delays are provided:
  - A 10 second delay = sustained degraded voltage condition = alarm in Cont Room
  - A 5 minute delay to allow for restoration of voltage through operator action
  - After delay, 4kv ESF buses separate from offsite power, switch to respective EDG. If a Safety Injection actuation signal is received during 5 minute delay, the 4kv ESF buses will immediately be separated from the offsite power source

Wye-G/Wye-G Transformer Bank 3-legged Core Form Analysis

- **Note for this analysis:**
  - **(a) no flux passes through air**
  - **(b) ΦA + ΦB = -ΦC**
  - **(c) the flux in the A or B legs is defined by the A and B voltages**

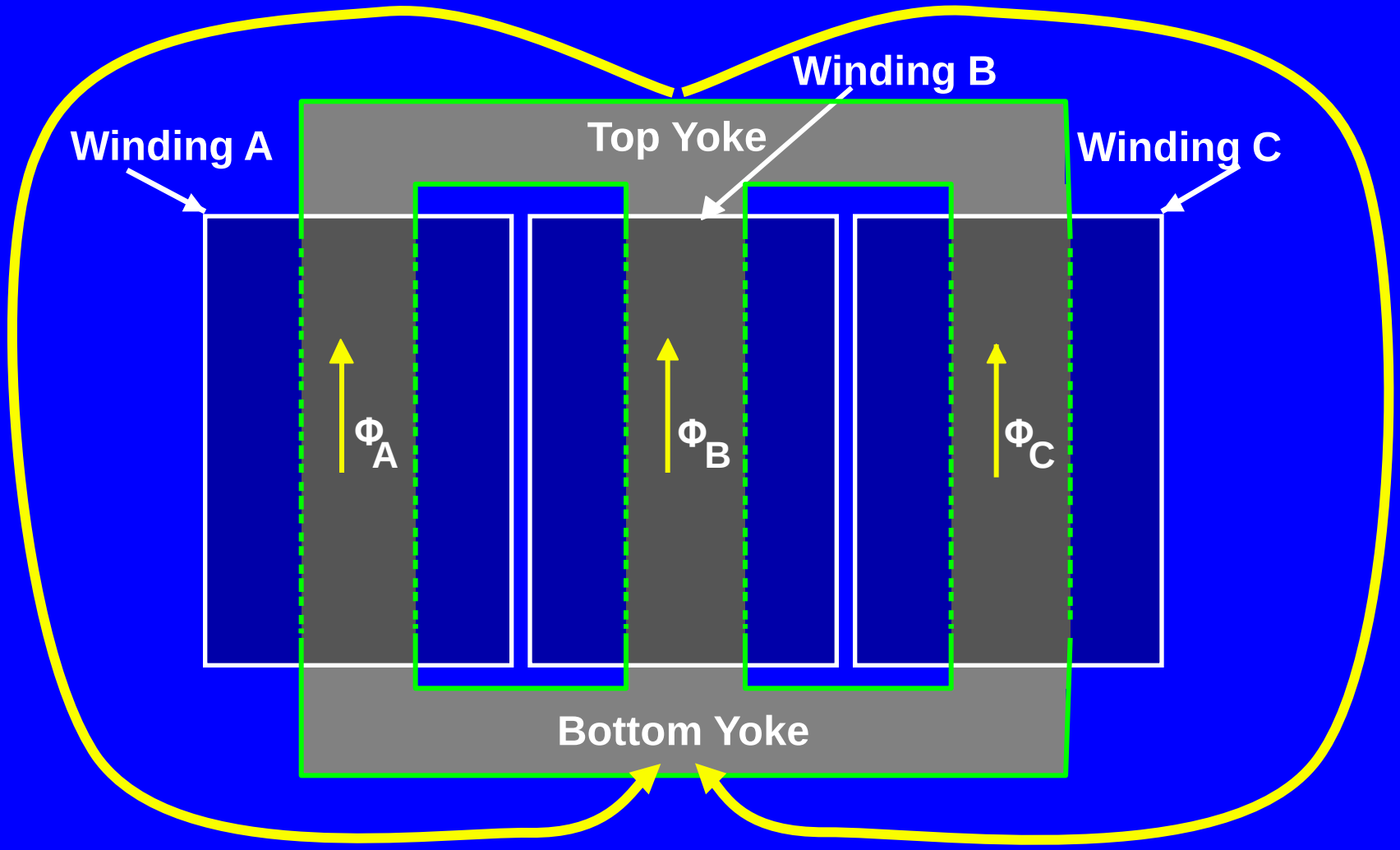
Wye-G/Wye-G Transformer Bank 3-legged Core Form Analysis

When primary phase C is disconnected:

- **Phase A leg flux is proportional to 120 ∠0°**
- **Phase B leg flux is proportional at 120 ∠-120°**
- **Phase C leg flux is initially unknown**

- **Ideally, sum of the fluxes must equal zero in a three legged core:**
  - **Flux A + Flux B + Flux C = 0 or:**
  - **Flux C = - (Flux A + Flux B) = - (120 ∠0° + 120 ∠-120°) = - (120 ∠-60°) = 120 ∠120°, replicating the missing voltage and angle**

Three-Legged Core-Type Transformer Magnetic Paths

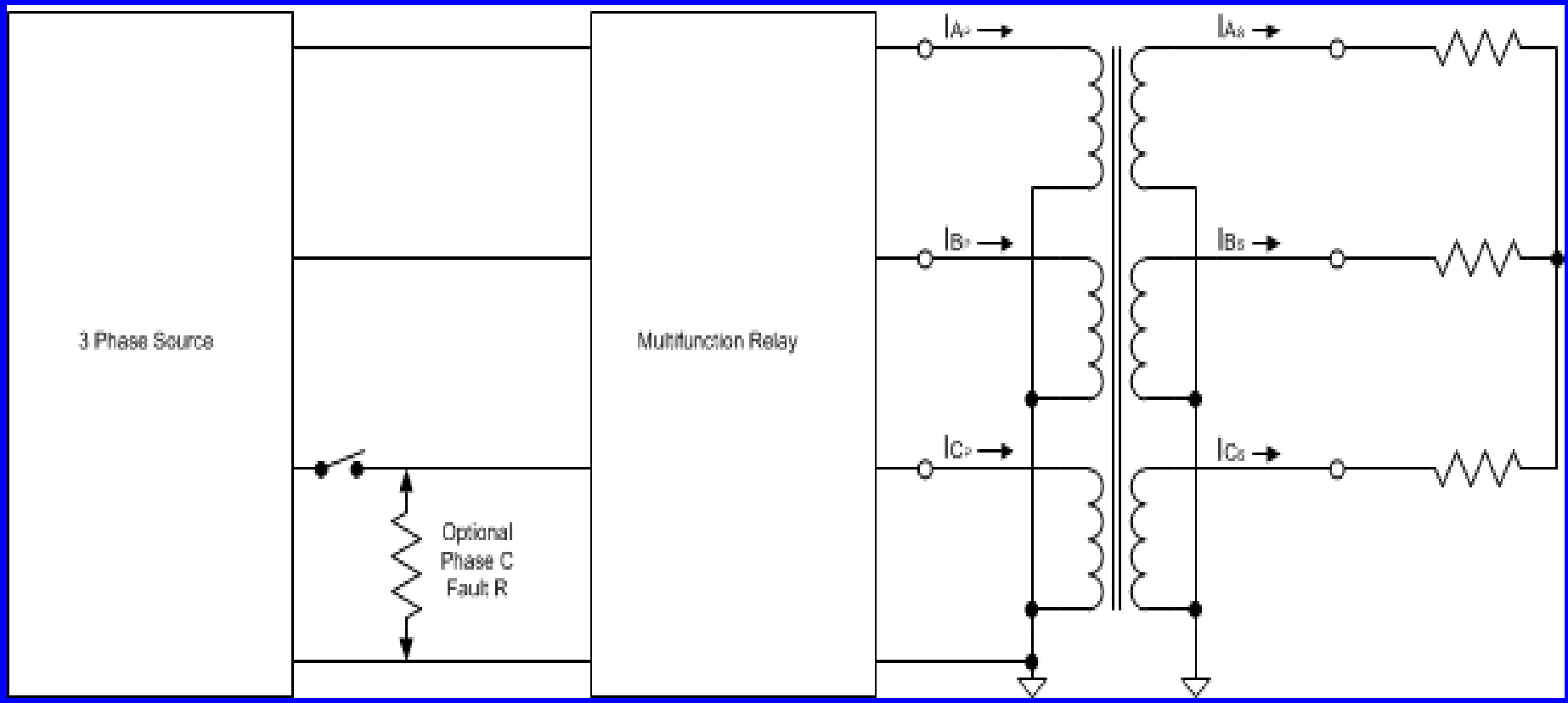


Wye-G/Wye-G Transformer Bank Analysis

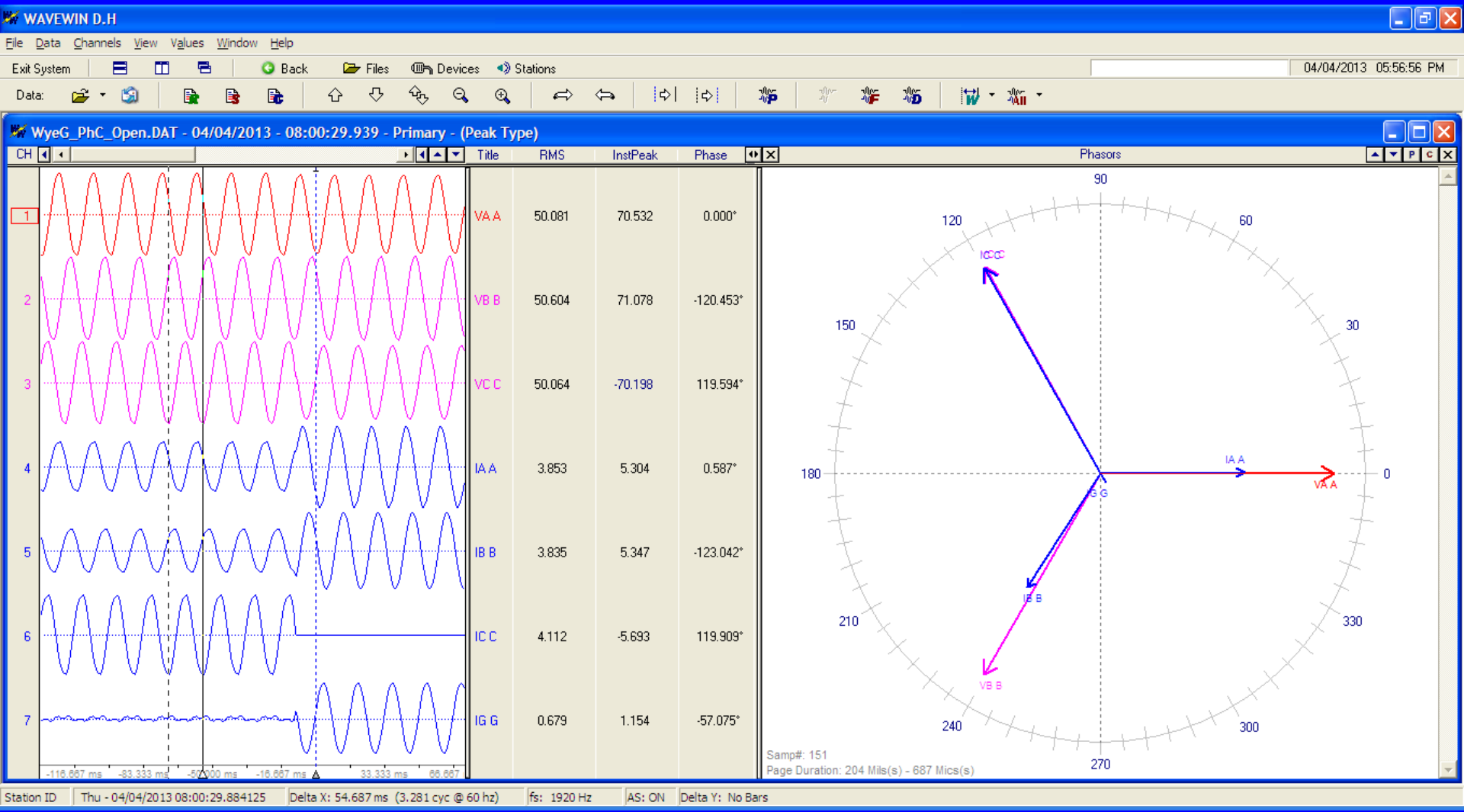
- Open phase on the 345kV primary A, B, or C phases results in unpredictable change of the low side voltage depending on load & high z ground

- Different flux patterns are the result of having closed or open zero sequence current paths depending on the ground connection of the primary (high voltage) winding

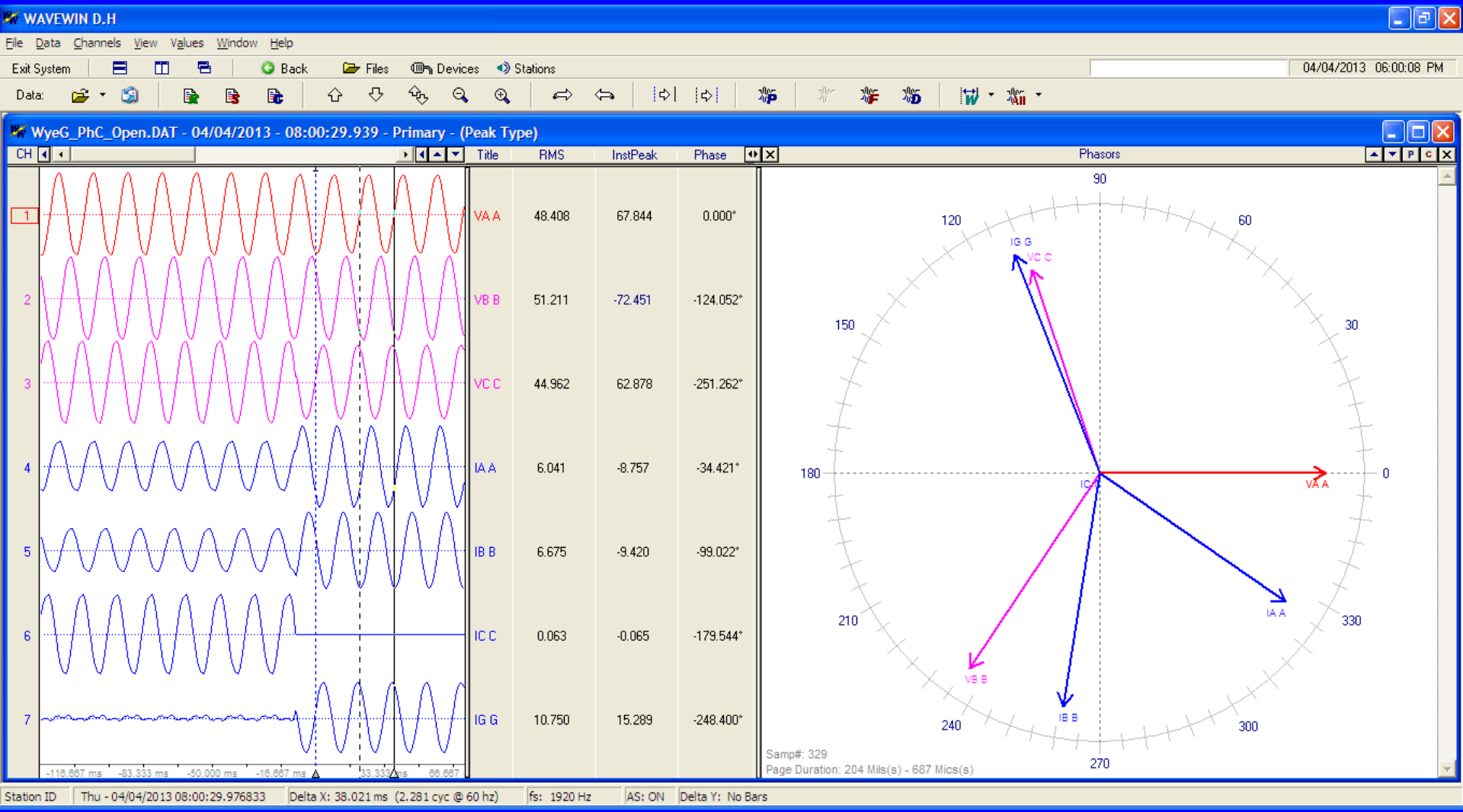
Test Connection for Open Phase with Ground Simulation



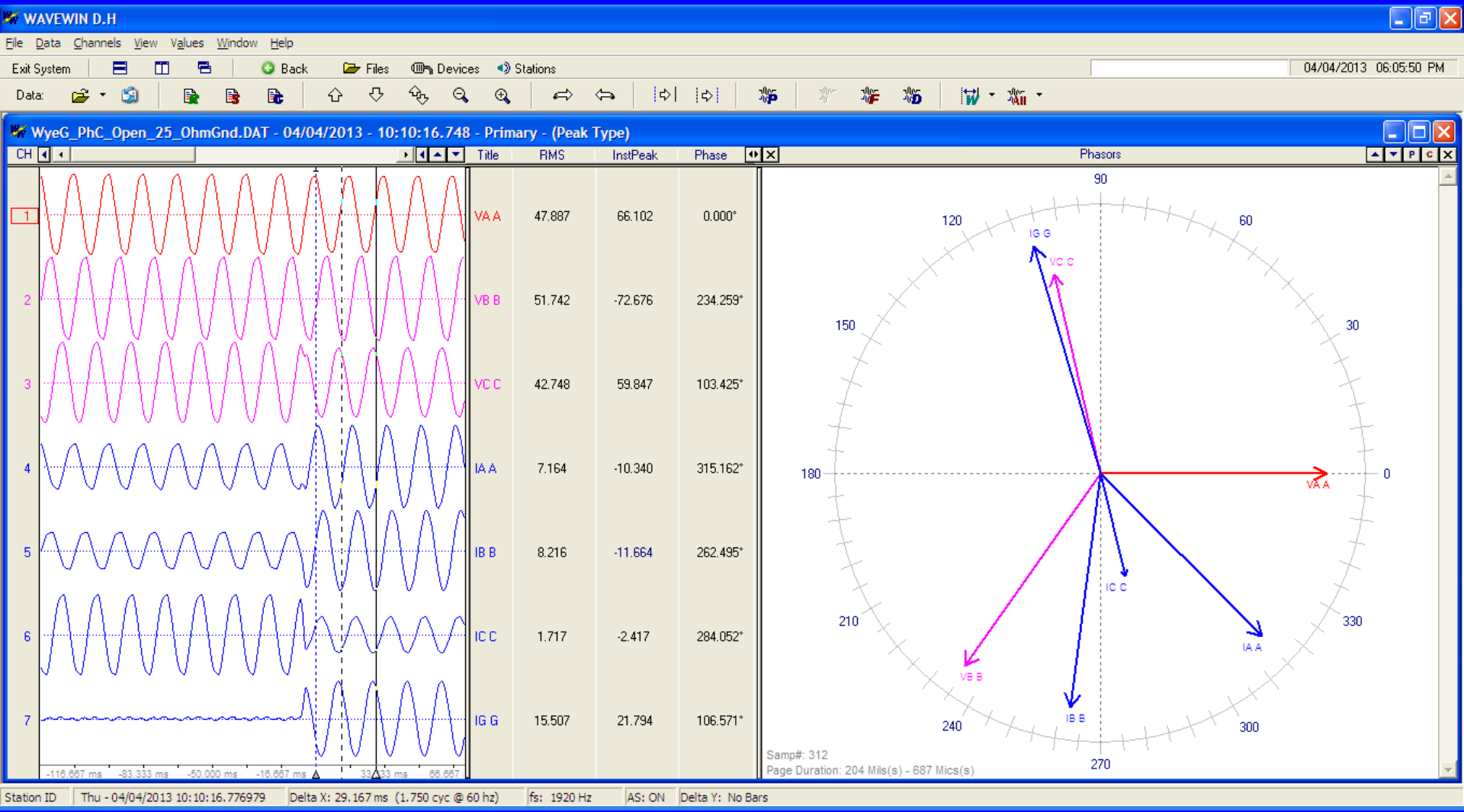
Test TX, Normal 3-Phase Connection



Test TX, “C” Open



Test TX, “C” Phase Open with 20 ohm Ground on “C” Phase



Existing Protection Schemes

- The degraded voltage scheme is not sensitive enough to detect this condition.
  - For wye/wye-wye connected transformers with a three legged core, the inter-phase flux coupling keeps the secondary voltage on the open phase close to the normal value.
    - For the units without a buried delta, the zero sequence flux path is through the tank which acts as a high impedance delta.

New Protection Scheme

- Installing a microprocessor based relay solution using current detection and also using symmetrical component currents supervising the trip output to provide security.
  - Monitors primary side (high voltage side) current.
  - Not dependent on the voltage
  - Proof of concept testing has been successfully completed
  - This scheme is being implemented at Byron using existing CTs.

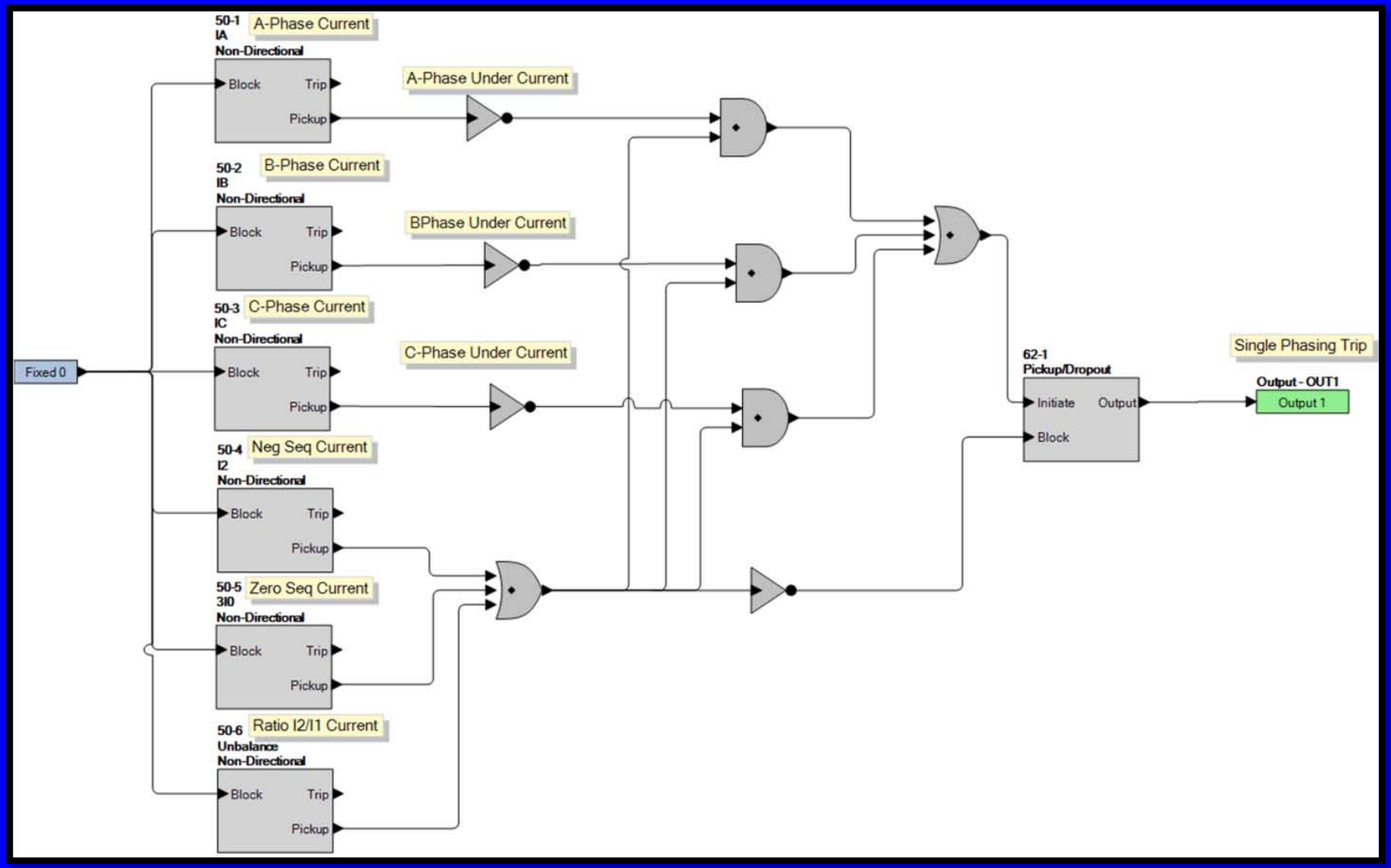
New Protection Scheme (Cont'd)

- Exelon performed extensive EMTP studies to assure both dependability as well as security under different conditions
  - Normal system unbalance,
  - Downstream faults on the LV side
  - Coordination with upstream protective devices (line relaying)
  - Transients on the system

EMTP Studies

- Exelon modeled more than 200 scenarios (see link Appendix A at end of paper).
- Analyzed scenarios included the following:
  - Unbalance in the grid: The unbalance can cause both negative and zero sequence voltages in the source voltage.
  - Variations in the grid voltage: Both maximum and minimum grid voltages were considered.
  - Faults on the transmission line: The relay must coordinate with back up line relaying.
  - Faults in the plant auxiliary system.
  - Transformer Energization.
  - Unequal loading of the two SATs.
  - Light and heavy loading on the auxiliary buses.
  - Motor starting and bus transfer scenarios.

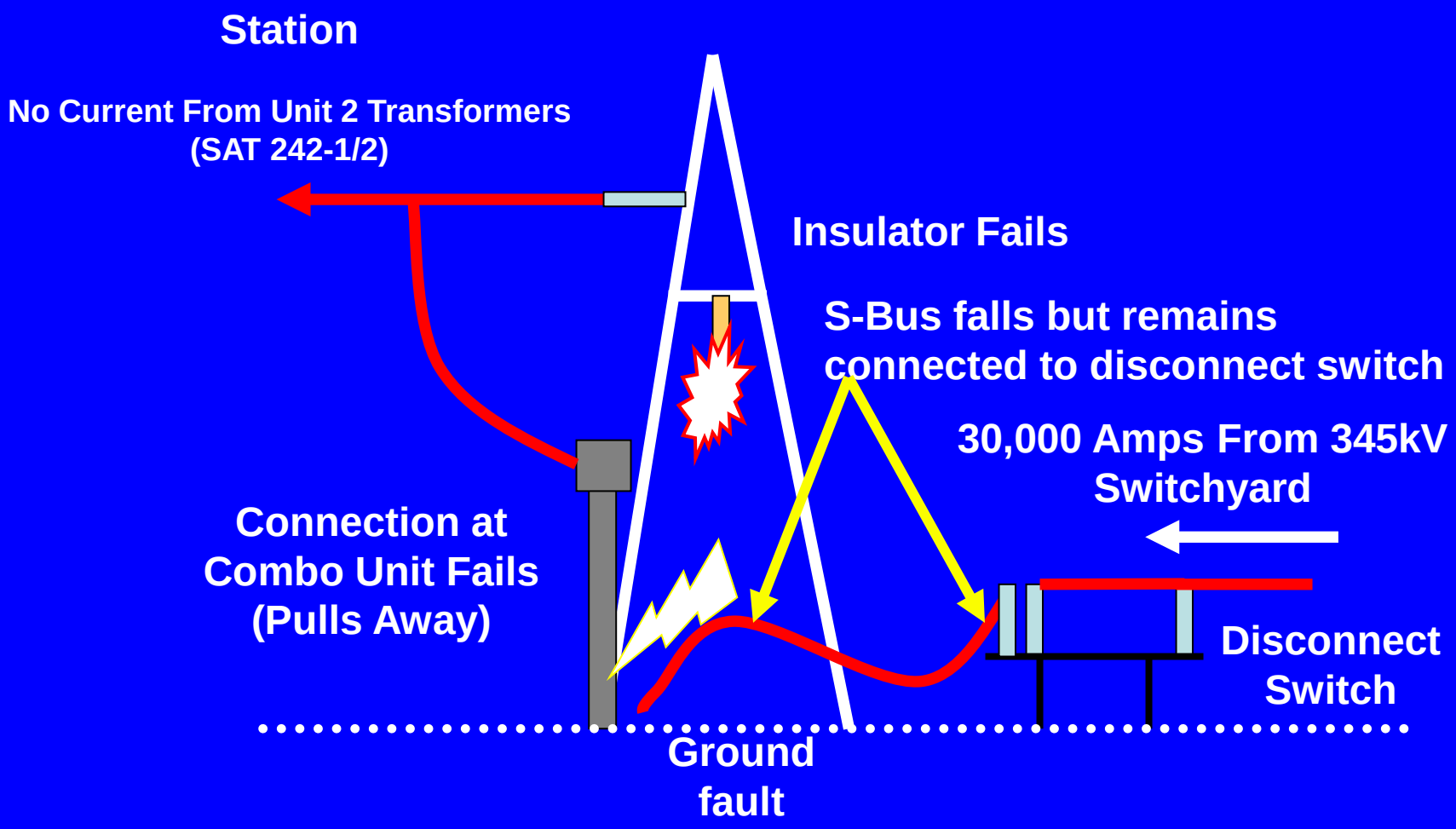
Example using CTs from the High Side of the Transformer and a Microprocessor-Based Relay



Byron Unit 1 Event 02/28/2012

- On February 28, 2012 Byron Unit 1 experienced a similar failure when the A-phase under hung insulator separated
- A-phase connection still connected to disconnect switch
- Connection to revenue metering combo unit pulls out
- Source to SATs open to switchyard
- A-phase to switchyard grounded
- 30kA phase to ground fault
  - Fault cleared in 3 cycles
  - Ground fault, phase overcurrent and differential relays actuated.
  - Non-safety buses transferred to UAT
  - EDGs started, re-energized safety loads

Byron Unit 1 Post Failure



Conclusions

- The open phase or open phase grounded may be difficult to detect.
  - Transformer design may hold the voltage on the degraded phase high, independent of the actual current in the winding.
  - Transformer loading may render schemes insensitive to this fault condition.
    - Trip settings high enough to support maximum expected load compared to a much lower normal load.

Conclusions

- Current only schemes will detect the condition but are subject to false tripping.
  - Many transients have similar symptoms as the open phase or open phase grounded.
- A Microprocessor based relay solution using current detection AND symmetrical component current supervision for the trip output, provide security and dependability.

Questions?