# Case study: Transformer Differential Incorrect Operation due to System Grounding

David Roh – University of Alberta, Edmonton, Canada

Lorne Clark – University of Alberta, Edmonton, Canada

JC Theron – GE Grid Solutions, Canada

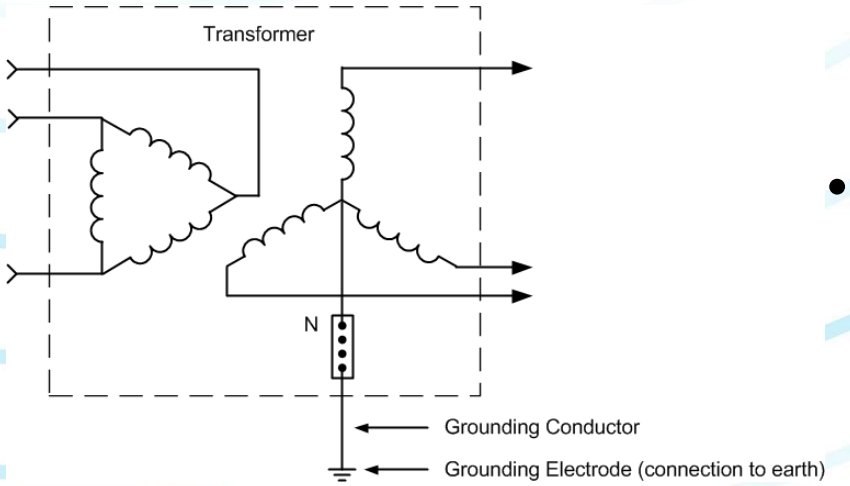
2019 Western Protective Relaying Conference

# Agenda

- Introduction
- History of LV Power System Grounding
- Multiple Sources with Solid Neutral Grounds
- Analysis of 13.8kV/600 V Transformer Differential Incorrect Operation
  - Introduction
  - Investigation
  - Analysis
- Securing Percentage-Differential Using Directionality Check & CT Saturation Detection
  - Directionality Check
  - CT Saturation Detection
- Conclusion

# Introduction

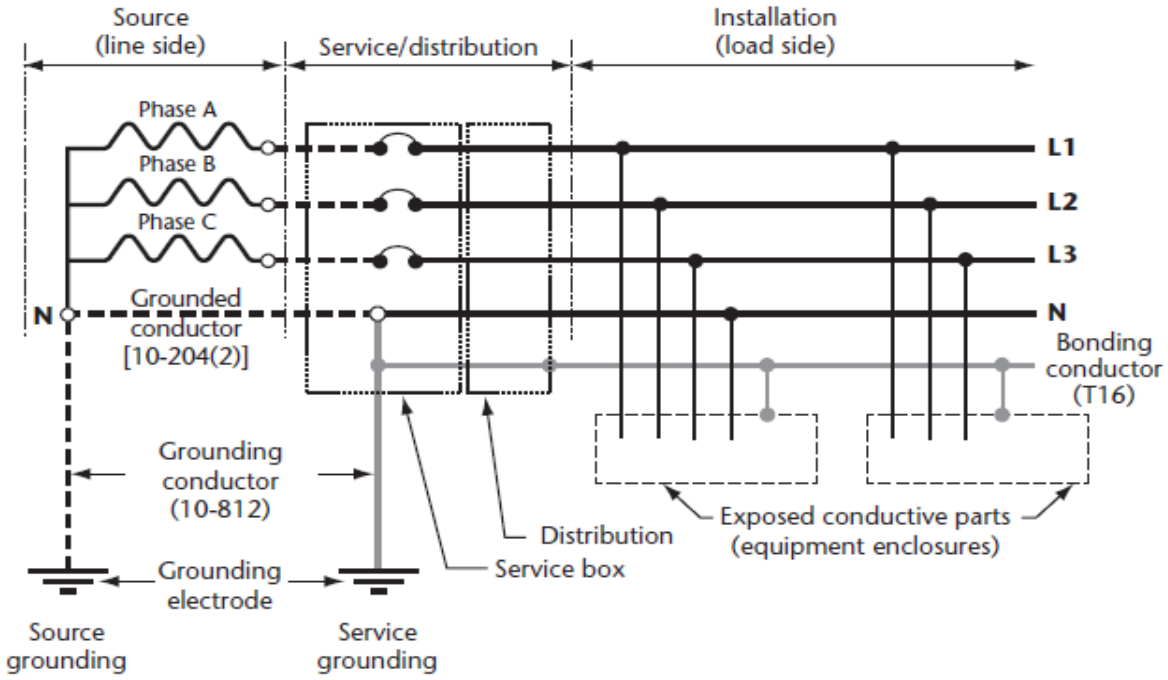
- Power system grounding: connection of three-phase AC power system to mass earth – normally via neutral, to accomplish:
- Provide reference to ground for AC power system
- Stabilize voltage during normal system operation
- Limit voltage rise on power system during abnormal system conditions eg. ground faults, surges, lightning, unintentional contact with higher voltage system or other abnormal system events
- Safeguard against undue voltage stress on power system primary component insulation, eg. cables, transformers, generators, motors




- Simple single ground of LV power system

# Introduction (2)

- All LV power system components must be electrically bounded and connected to ground:
- interconnection of conductive materials enclosing electrical conductors and equipment must establish an equipotential plane such that the possibility of a potential difference between the exposed non-current carrying metal parts is minimized
- LV Bonding System and its Connection to Ground




- Objective of equipment grounding and bonding
  - To provide adequate current-carrying capability in ground fault return path for duration of ground faults without any equipment risk, e.g. overheating and fire
  - To provide low-impedance path for ground fault current to facilitate operation of overcurrent protective devices, including its coordination time
  - To reduce risk of electric shock hazard to personnel

# Some Standards on LV Power System Grounding

- Numerous standards addressing grounding, bonding & protection requirements of LV power systems. Single or multiple source LV 3-phase power systems are:
- Canada: CSA C22.1-15
- Canadian Electric Code CEC Rule 10-206
- Canadian Electric Code CEC Rule 10-204
- Canadian Electric Code CEC Rule 14-102
- IEEE Green Book Std 142-1991
- IEEE Orange Book Std 446-1995
- USA National Electric Code NEC 230.95
- USA National Electric Code NEC 250.24
- USA National Electric Code NEC 250.30
- USA National Electric Code NEC 250.5
- USA National Electric Code NEC 250.21
- USA National Electric Code NEC 250.23
- USA National Electric Code NEC 250.26

# History of LV Power System Grounding

- 1890's: Ungrounded 3-phase delta
  - To power 3-phase squirrel-cage induction motors
  - Protect personnel from hazard during ground fault
- 1920's: 120/240V, 1-ph ("high-leg delta") and 208Y/120V, 3-ph
  - Solidly grounded
- 1940's: Corner-of-Delta grounding for 480V and 600V delta systems
  - Solidly grounded to prevent escalating system voltage to ground (5-6 times rated) during intermittent arcing ground faults in large LV systems from stray capacitance to ground
- Late 1950's: Solidly-grounded 4-wire, wye 600Y/347V and 480Y/277V systems
  - Fluorescent lighting produced much less heat than incandescent
  - At the time, fluorescent lighting required more than 120V operate
  - Service entrance ratings increased from 600A to 4000A
  - To meet increasing load density of buildings:
    - Utilities changed from delta to wye secondaries on power transformers

- Today, over 90% of LV power systems are solidly grounded 4-wire wye

# History of LV Power System Grounding (2)

- 1960's: Devastating electrical equipment burn-downs on solidly grounded 480Y/277V and 600Y/347V systems:
  - Fires, injuries, deaths
  - Even though affected equipments were protected in accordance with the CEC or NEC
- Caused by arcing ground faults that escalated into destructive three-phase arcing faults
- Fuses and thermal magnetic circuit breakers did not interrupt the three-phases fast enough to protect property and life.
- 1971 NEC added requirement for ground fault protection at service entrance. (from 2014 NEC)

**230.95 Ground-Fault Protection of Equipment.** Ground-fault protection of equipment shall be provided for solidly grounded wye electric services of more than 150 volts to ground but not exceeding 1000 volts phase-to-phase for each service disconnect rated 1000 amperes or more. The

- 1972 CEC added similar requirement (from 2012 CEC)

**14-102 Ground fault protection** (see Appendix B)

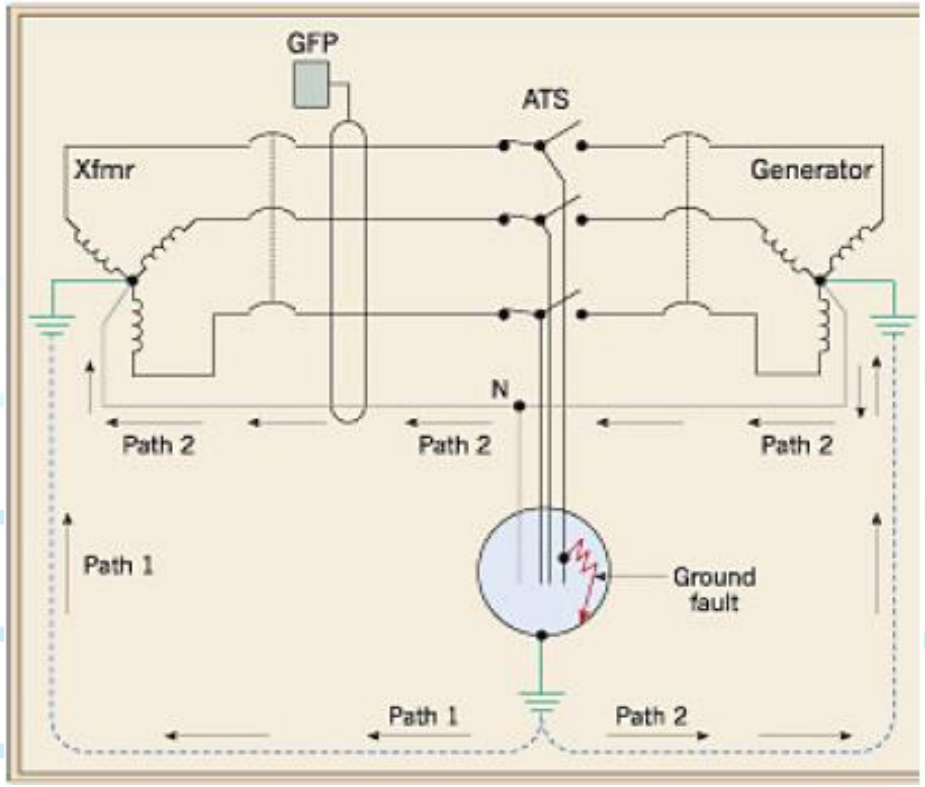
(1) Ground fault protection shall be provided to de-energize all normally ungrounded conductors of a faulted circuit that are downstream from the point or points marked with an asterisk in Diagram 3 in the event of

(a) for circuits of solidly grounded systems rated more than 150 volts-to-ground, less than 750 V phase-to-phase and 1000 A or more; and

(b) for circuits of solidly grounded systems rated 150 V or less to ground and 2000 A or more.

# Multiple Sources with Solid Neutral Grounds

- CEC and NEC rules require each source transformer of LV power system to have solidly grounded neutral (or neutral path)
- A generator connected to LV power system might meet requirements as a separately derived source and then its neutral must be solidly connected to that of the preferred source.
- Grounding of generator requirements not clear-cut and must be reviewed per NEC and/or CEC.



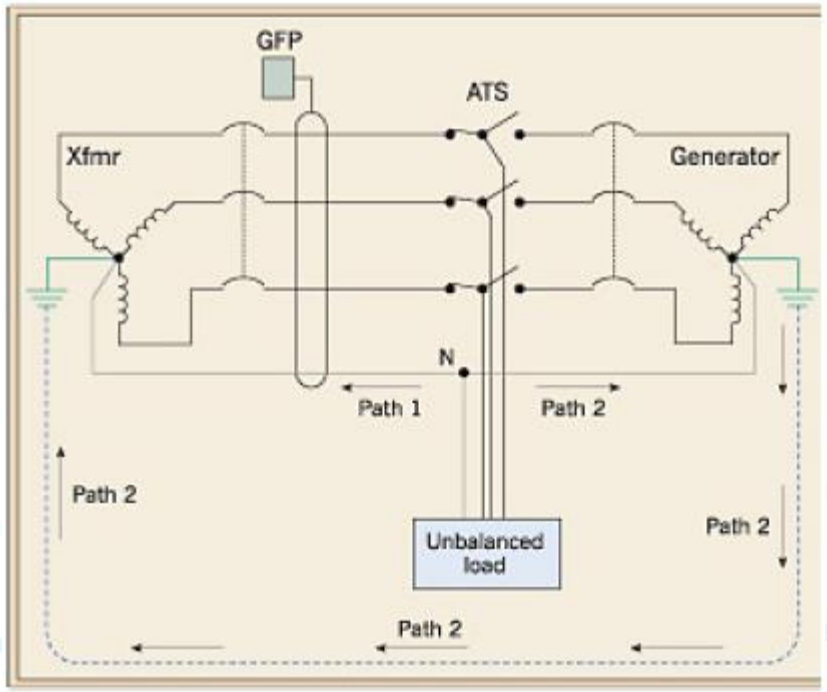

- Major problems arise if trfr and gen neutrals are grounded & tied together as per standard when using a 3-pole transfer switch or breaker:

1. Incomplete ground-fault sensing with separate solidly grounded transformer and generator. Two neutral currents paths, due to two separate grounds, will have each neutral circulating current for single-phase-to-ground faults

- Path 1 back to Trfr via grounded-wye
- Path 2 along grounded ntrl of gen, then via ntrl conductor to trfr. GFP sees only path 2, hence incomplete gnd fault current sensing

# Multiple Sources with Solid Neutral Grounds (2)

2. Nuisance tripping due to unbalanced load
   Again, the system will have two current paths due to an unbalanced load as below




- Path 1 will be directly to neutral of the solidly grounded wye of the transformer
- Path 2 is generator neutral current, circulating back to transformer wye via grounding of generator metallic enclosure, conduit, fittings etc.
  Path 2 current would have same effect on GFP as ground-fault current, hence, unbalanced load would have same effect as ground fault on transformer GFP, without any faults on the system

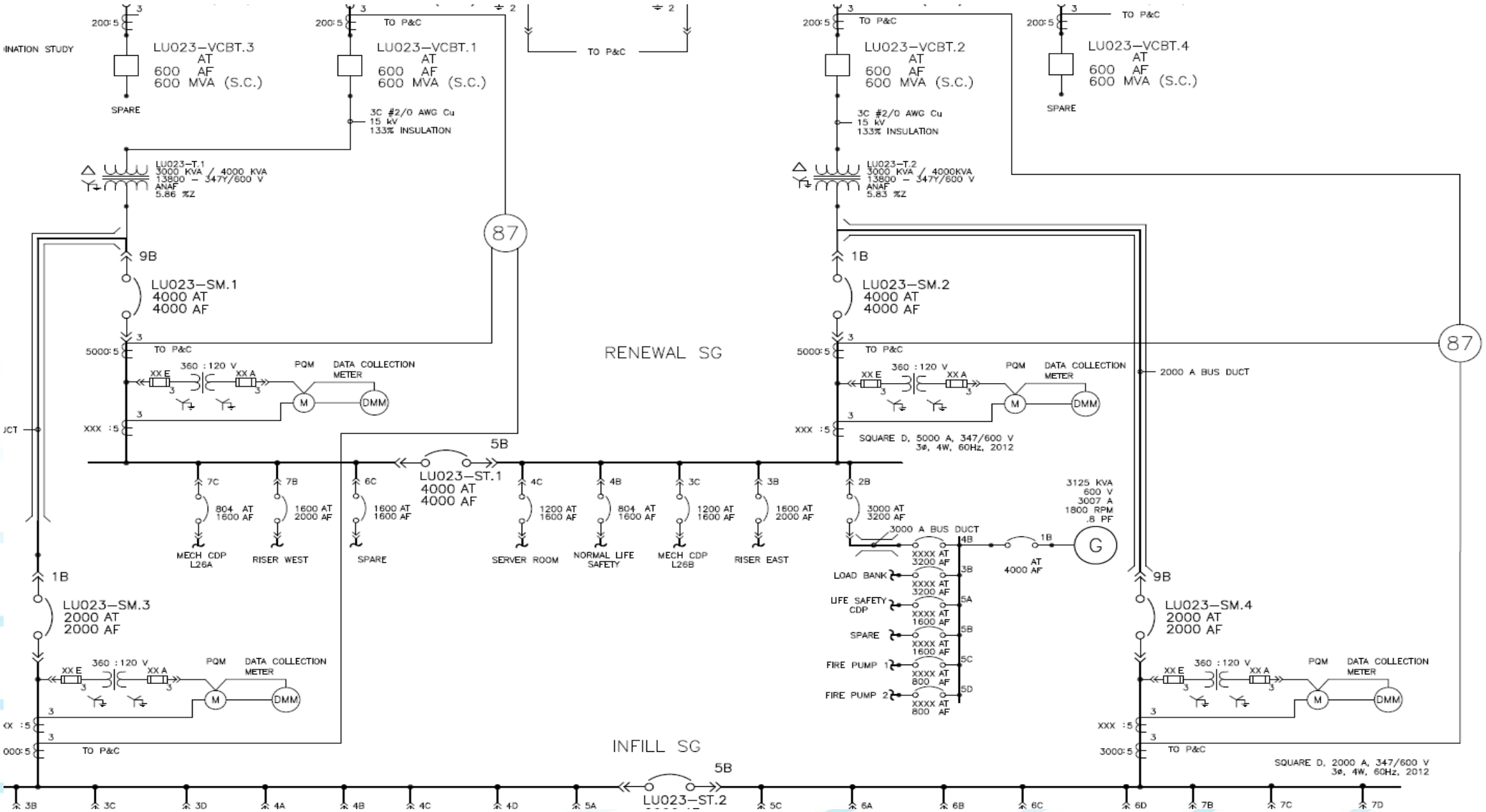
3. Unbalanced currents due to generator paralleled with utility supply
   Generator and transformer voltage supplies are different (different wounding and pitch) and causes circulating currents

- Solutions: Use 4-pole transfer switch by opening neutral; Install impedance between gen neutral

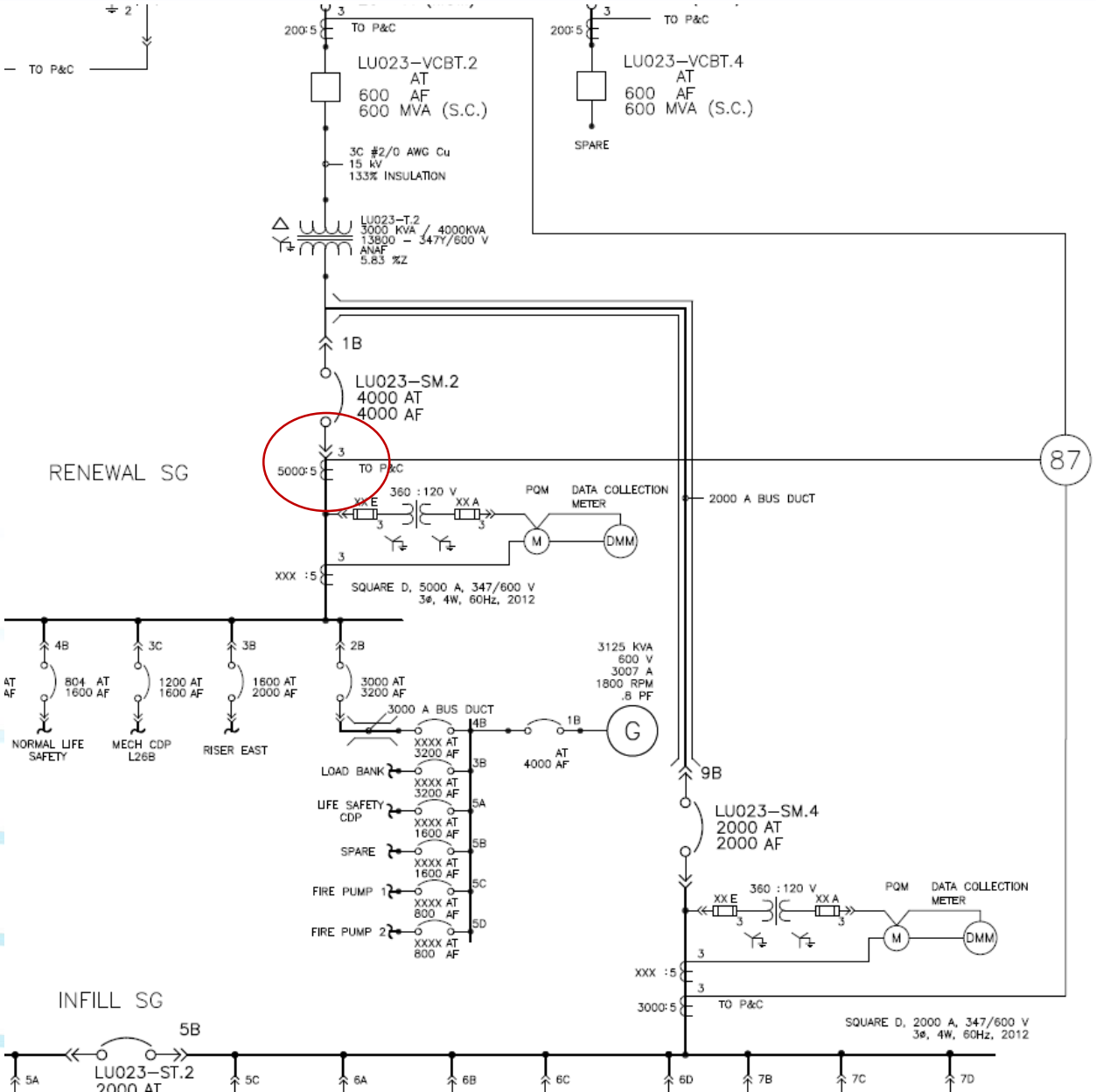
- Transformer differential protection also impacted by this circulating current

# Analysis of 13.8kV/600V Trfr Diff Incorrect Operation

- Introduction



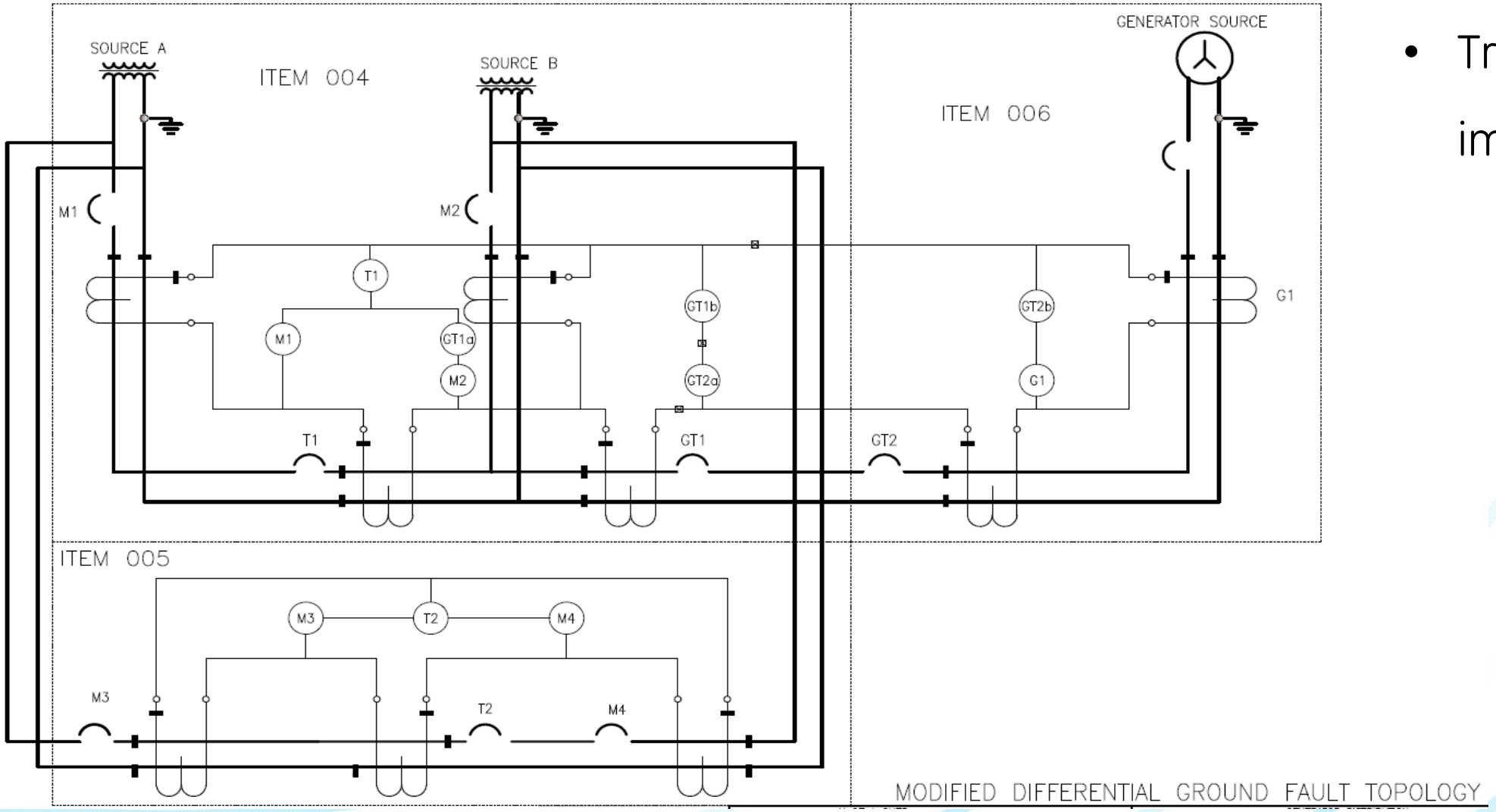
# Introduction




- Trf T2 differential connections
- System:
  - Two 3MVA 13.8/0.6kV Delta/Wye solid gnd
  - Differential 3-winding
  - One 3.125MVA 2.5MW 600V solid gnd 2-pole pair emergency supply diesel gen
  - Synchronized during test runs
  - Critical loads on bus Renewal SG

# Introduction

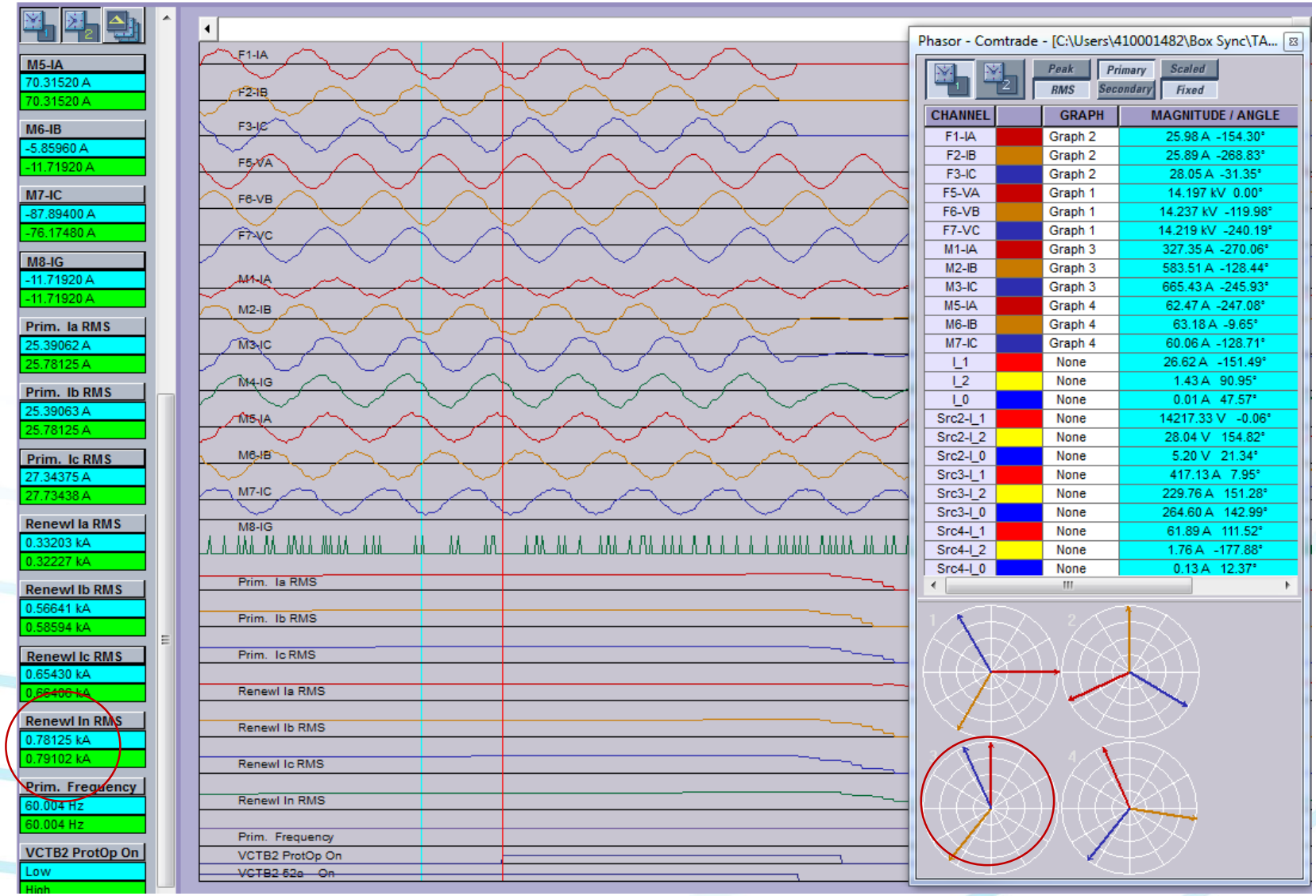
- Utility Transformers and Generator with Modified Ground Fault Topology




- Trf differential impacts?

# Introduction

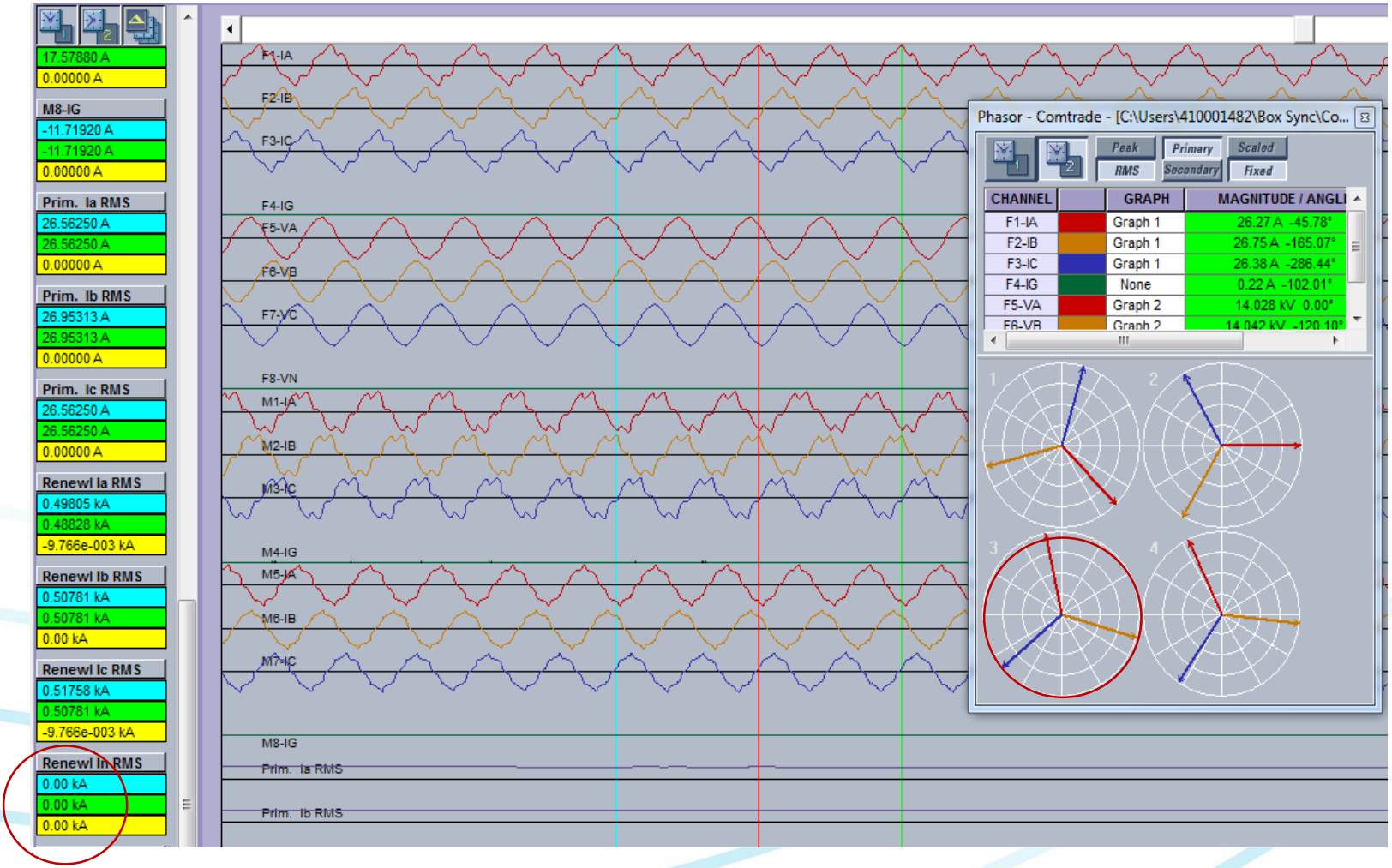
- Transformer T2 had undesired differential trip during generator test run




- Trfr diff installed 2011
- Low load currents; some harmonics (Renewal wdng)
- Renewal bus and gen loads not known
- Clearly no fault on system
- Renewal C-phase winding appears to be inverted??
- Large neutral current in Renewal winding

# Introduction

- Transformer T2 current with generator offline




- Renewal C-phase winding phase rotation is correct
- No neutral current in Renewal winding

# Investigation

- IED operating characteristic:

**TRANSFORMER SETTINGS AND CTs**

| Nomber of Windings: | 3 | | | | | |
|---|---|---|---|---|---|---|
| | W1 | W2 | W3 | | | |
| Rated(MVA) | 3 | 3 | 3 | 0 | 0 | 0 |
| Nom. (kV) | 13.8 | 0.6 | 0.6 | | | |
| Connection | DELTA | WYE | WYE | | | |
| Grounding | NO | YES | YES | | | |
| Angle WRT | 0 | -30 | -30 | | | |
| CT primary | 200 | 5000 | 3000 | | | |
| CT sec. tap | 5 | 5 | 5 | | | |
| Inom. Prim. | 125.5 | 2886.8 | 2886.8 | | | |
| Inom.Sec. | 3.138 | 2.887 | 4.811 | | | |
| *Rotations* | ABC | *Select Magnitude Ref. Winding:* | | | | auto |

**DIFF / RSTR CHARACTERISTIC**

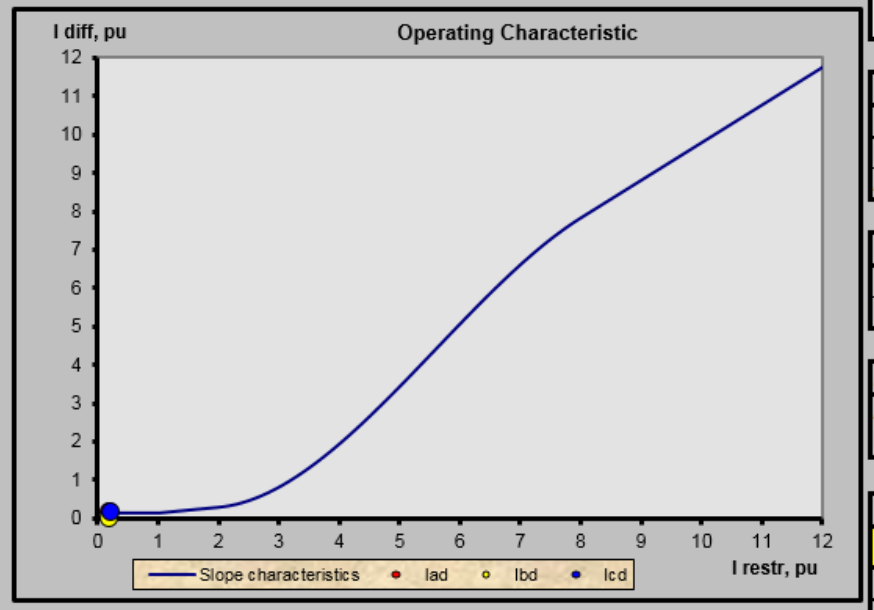
| DIFFERENTIAL- RESTRAINT GRAPH | | | |
|---|---|---|---|
| Diff. min. PKP | 0.15 | Slope1 | 15.0 |
| Kneepoint 1 | 2.00 | | |
| Kneepoint 2 | 8.00 | Slope2 | 98.0 |

| Pre-calculated graph points | | | |
|---|---|---|---|
| Id/Ir, (%) | Ph A | Ph B | Ph C |
| | 15.0 | 15.0 | 15.0 |

>>Pre-calculated ratio of the point from the characteristic, corresponding to the same restraint as per the actual Id/Ir ratio. The trip occurs, when the actual Id/Ir ratio,(%) is bigger than the pre-calculated Id/Ir ratio, (%)

**TEST CURRENTS**

| | IA | IB | IC |
|---|---|---|---|
| W1 | | | |
| Magnitude | 0.65 | 0.65 | 0.70 |
| Angle | -153.7 | -268.5 | -31.1 |
| W2 | | | |
| Magnitude | 0.33 | 0.58 | 0.66 |
| Angle | -269.9 | -127.9 | -245.8 |
| W3 | | | |
| Magnitude | 0.10 | 0.11 | 0.10 |
| Angle | -246.8 | -9.7 | -128.7 |
| | | | |
| | 0.00 | 0.00 | 0.00 |
| | -180.0 | -300.0 | -60.0 |
| | | | |
| | 0.00 | 0.00 | 0.00 |
| | -180.0 | -300.0 | -60.0 |
| | | | |
| | 0.00 | 0.00 | 0.00 |
| | 0.0 | 0.0 | 0.0 |




**ACTUAL VALUES**

| Magnitude Ref. Winding #: | 3 |
|---|---|

| DIFFERENTIAL CURRENTS | | | |
|---|---|---|---|
| | Iad | Ibd | Icd |
| Magnitude | 0.15 | 0.00 | 0.15 |
| Angle | -210.9 | -227.3 | -31.2 |

| RESTRAINT CURRENTS | | | |
|---|---|---|---|
| | Iar | Ibr | Icr |
| Magnitude | 0.20 | 0.20 | 0.21 |

| Actual Differential/Restraint Ratio | | | |
|---|---|---|---|
| Actual | ph A % | ph B % | ph C % |
| Id/Ir ratio | 74.4 | 1.5 | 70.3 |

| DIFF. OPERATION | | |
|---|---|---|
| TRIP | | |
| Ia | Ib | Ic |
| No trip | No trip | Trip |

- Currents well in load region
- C-phase diff operated
- CT saturation not suspected

# Investigation

- Comparing transformer T2 currents with and without gen running: (Renewal bus loads were different between two events)

| Sequence Components | Generator Running | | Generator Not Running | |
|---|---|---|---|---|
| | Prim 13.8kV | Renewl 600kV | Prim 13.8kV | Renewl 600V |
| I1 | 26.51A∠-151.1° | 416.87A∠8.3° | 26.46A∠-45.8° | 497.20A∠101.8° |
| I2 | 1.37A∠87.9° | 230.37A∠151.5° | 0.3A∠114.4° | 11.06A∠-69.8° |
| I0 | 0.02A∠59.4° | 263.06A∠143.1° | 0.14A∠-97.7° | 0.98A∠-162.1° |

- Renewal winding currents with and without gen running:

| Phase | Generator Running | Generator Not Running |
|---|---|---|
| | RMS Currents | RMS Currents |
| Ia | 322A | 498A |
| Ib | 586A | 508A |
| Ic | 664A | 508A |
| In | 791A | 0A |

- High neutral currents due to neutral circulating current from the generator to the utility transformer T2 neutral (Increases as generator load increases)

# Investigation

- Percentage-differential and transformer settings

| PARAMETER | CT F1 | CT M1 | CT M5 |
|---|---|---|---|
| Phase CT Primary | 200 A | 5000 A | 3000 A |
| Phase CT Secondary | 5 A | 5 A | 5 A |
| Ground CT Primary | 200 A | 5000 A | 3000 A |
| Ground CT Secondary | 5 A | 5 A | 5 A |

| PARAMETER | WINDING 1 | WINDING 2 | WINDING 3 |
|---|---|---|---|
| Source | Prim. (SRC 1) | Renewl (SRC 2) | Infill (SRC 3) |
| Rated MVA | 3.000 MVA | 3.000 MVA | 3.000 MVA |
| Nominal Phs-phs Voltage | 13.800 kV | 0.600 kV | 0.600 kV |
| Connection | Delta | Wye | Wye |
| Grounding | Not within zone | Within zone | Within zone |
| Angle Wrt Winding 1 | 0.0 deg | -30.0 deg | -30.0 deg |
| Resistance | 10.0000 ohms | 10.0000 ohms | 10.0000 ohms |

| SETTING | PARAMETER |
|---|---|
| Operating Characteristc Graph | View |
| Function | Enabled |
| Pickup | 0.150 pu |
| Slope 1 | 15 % |
| Break 1 | 2.000 pu |
| Break 2 | 8.000 pu |
| Slope 2 | 98 % |
| Inrush Inhibit Function | Trad. 2nd |
| Inrush Inhibit Mode | Average |
| Inrush Inhibit Level | 20.0 % fo |
| Overexcitation Inhibit Function | Disabled |
| Overexcitation Inhibit Level | 10.0 % fo |
| Block | OFF |
| Target | Latched |
| Events | Enabled |

- Settings consistent for transformer and connections
- Question: Was the transformer differential operation correct??

# Analysis

- Based on settings, diff should remove zero sequence current, however did operate
- Calculation of differential current:
- Rated current and CT margin: based on $I_{rated}[w] = \frac{P_{rated}[w]}{\sqrt{3} \times V_{nom}[w]}$ and $I_{margin} = \frac{CT\ primary[w]}{I_{rated}[w]}$

| Winding | Rated Current | CT Margin |
|---|---|---|
| Primary | 125.51A | 1.59 |
| Renewal | 2886.71A | 1.73 |
| Infill | 2886.71A | 1.04 |

Closest to 1 is Infill winding. Setting is Auto hence Infill is reference winding

- Magnitude compensation factors: based on $M[w] = \frac{I_{primary}[w] \times V_{nom}[w]}{I_{primary}[w_{ref}] \times V_{nom}[w_{ref}]}$

| Winding | Compensation Factor |
|---|---|
| Primary | 1.53 |
| Renewal | 1.67 |
| Infill | 1 |

# Analysis

- Phase and zero-sequence compensation equations :

Delta

| $\Phi_{comp}[w]$ | Grounding[w] = "Not within zone" |
|---|---|
| 0° | $I_A^P[w] = I_A[w]$<br>$I_B^P[w] = I_B[w]$<br>$I_C^P[w] = I_C[w]$ |

Wye

| | |
|---|---|
| 330° lag | $I_A^P[w] = \frac{1}{\sqrt{3}} I_A[w] - \frac{1}{\sqrt{3}} I_B[w]$<br>$I_B^P[w] = \frac{1}{\sqrt{3}} I_B[w] - \frac{1}{\sqrt{3}} I_C[w]$<br>$I_C^P[w] = \frac{1}{\sqrt{3}} I_C[w] - \frac{1}{\sqrt{3}} I_A[w]$ |

- Magnitude, phase angle and zero-sequence compensation equations

$I_A^C[w] = M[w] \times I_A^P[w]$

$I_B^C[w] = M[w] \times I_B^P[w]$

$I_C^C[w] = M[w] \times I_C^P[w]$

- Secondary currents of each winding captured at differential operation:

| Winding | $I_A^C$ | $I_B^C$ | $I_C^C$ |
|---|---|---|---|
| Primary | 0.65A∠-153.7° | 0.65A∠-268.5° | 0.7A∠-31.1° |
| Renewal | 0.33A∠-269.9° | 0.58A∠-127.9° | 0.66A∠-245.8° |
| Infill | 0.1A∠-246.8° | 0.11A∠-9.7° | 0.1A∠-128.7° |

- Compensated currents for each winding:

| Winding | $I_A^C$ | $I_B^C$ | $I_C^C$ |
|---|---|---|---|
| Primary | 0.99A∠-153.7° | 0.99A∠-269.9° | 1.07A∠-31.1° |
| Renewal | 0.83A∠-299.7° | 1.02A∠-94.7° | 0.37A∠-45.1° |
| Infill | 0.1A∠-36.7° | 0.1A∠-6.2° | 0.099A∠-277.7° |

# Analysis

- Differential and restraining currents:

Differential based on:

IdA = IAC[1] + IAC[2] + IAC[3]

IdB = IBC[1] + IBC[2] + IBC[3]

IdC = ICC[1] + ICC[2] + ICC[3]

Restraining currents based on:

IrA = max |IAC[1]|, |IAC[2]|, |IAC[3]|

IrB = max |IBC[1]|, |IBC[2]|, |IBC[3]|

IrC = max |ICC[1]|, |ICC[2]|, |ICC[3]|

- Differential and restraint currents in A:

| | $I_A$ | $I_B$ | $I_C$ |
|---|---|---|---|
| Differential | 0.741A.∠-210.9° | 0.035A.∠-227.3° | 0.754A.∠-31.2° |
| Restraint | 0.99A | 0.99A | 1.07A |

- Differential and restraint currents in p.u.:

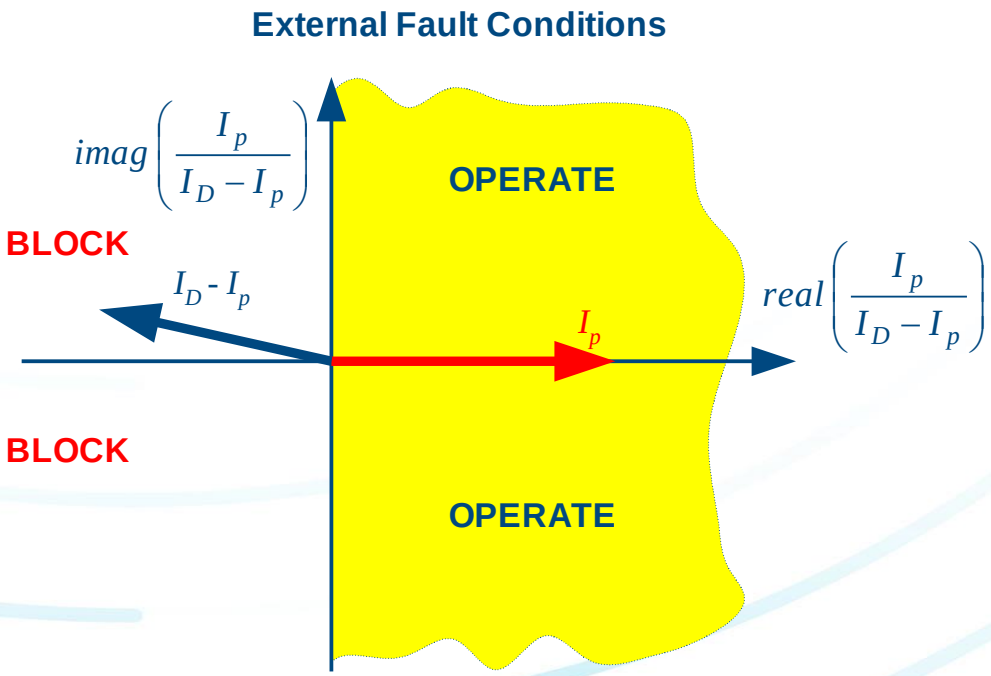
| | $I_A$ | $I_B$ | $I_C$ |
|---|---|---|---|
| Differential | 0.148p.u.∠-210.9° | 0.007p.u.∠-227.3° | 0.151p.u.∠-31.2° |
| Restraint | 0.20p.u. | 0.20p.u. | 0.21p.u. |
| Trip/No-trip | No-trip | No-trip | Trip |

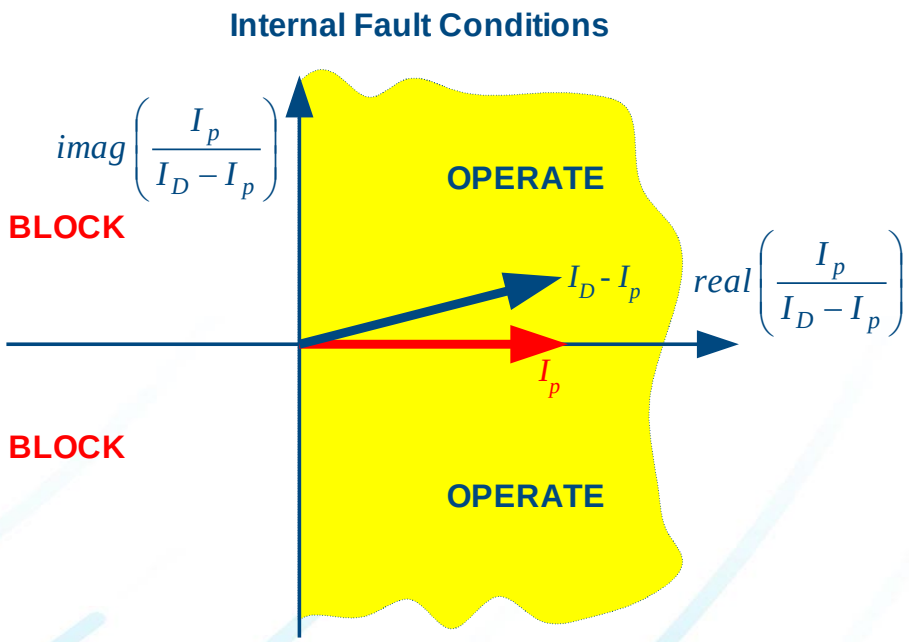
Differential in C-phase just above differential/restraint characteristic (minimum setting is 0.15p.u.) and operates. A-phase just below where B-phase has very little differential current

- Analysis confirms correct differential operation

# Securing Percentage Differential With Dir Check

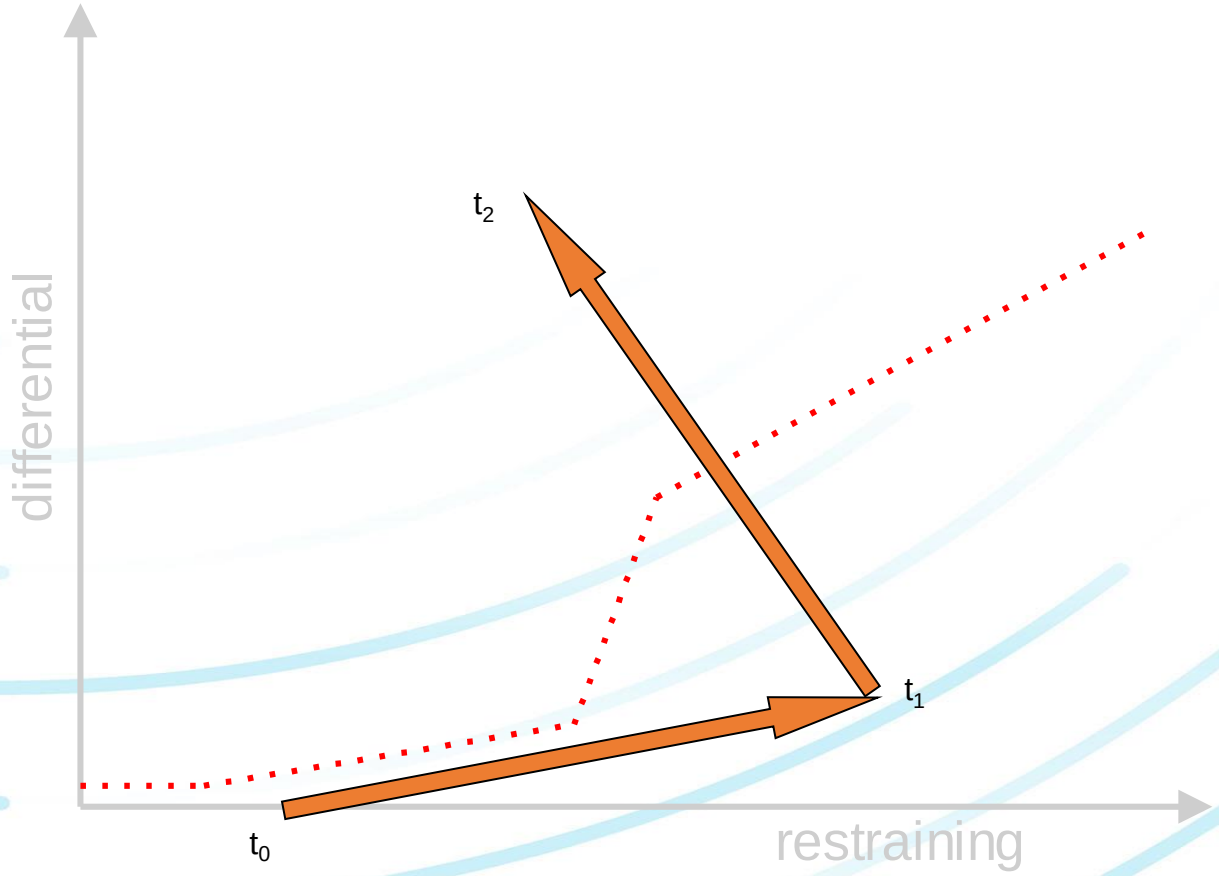
- Directionality Check of Current Phase Angles: (No Voltages Used)



# Securing Percentage Differential With CT Saturation

- CTs provide typically 2-4 ms unsaturated current
- Fault starts at $t_0$, CT starts to saturate at $t_1$, fully saturated at $t_2$



# Conclusions

- LV power system neutral currents can be significantly impacted by two grounds from dissimilar sources eg. utility transformer and standby generator
- In this particular case due to synchronization of solidly grounded backup diesel generator, not intended to be synchronized continuously, connected to utility transformer solidly grounded wye-winding neutral
- Ground fault protection scheme did not operate since a Modified Differential Ground Fault scheme is deployed, which is adapted for scenarios like this
- Impact of neutral circulating current on transformer differential must be considered
- Differential was enhanced with added security (CT saturation detection and Directionality check) which would mitigate this operation
- Presence of the neutral circulating current and reducing it is being reviewed

# Thank You

# Questions?