Lessons Learned Through Commissioning and Analyzing Data From Transformer Differential Installations

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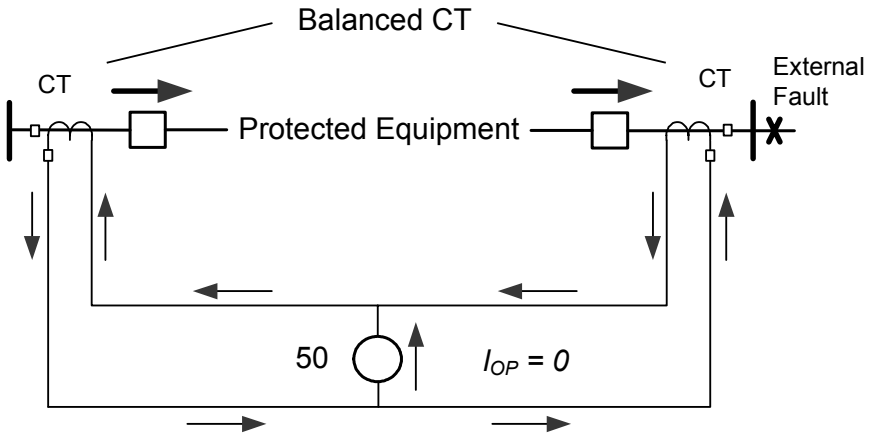
Differential Protection Principle



Differential Protection Challenges

- Transformer phase angle shift
  - ♦ Internal phase angle compensation
- Current magnitude mismatch
  - ♦ CTR and TAP settings
- No-load and under-load tap changes
  - ♦ Minimum sensitivity setting
- Unequal CT performance
  - ♦ Percentage-restraint or slope settings

Differential Protection Challenges

- Energizing inrush
  - ♦ Harmonic blocking or restraint
  - ♦ DC ratio blocking
  - ♦ Common or independent blocking
- Zero-sequence sources
  - ♦ Zero-sequence filtering
- Operating conditions that bypass CTs
  - ♦ Operating procedures and trip unlatch setting

Differential Protection Challenges

- Delta-connected CTs with traditional relays
  - ♦ Use wye-connected CTs with digital relays
- System phase rotation
  - ♦ Phase angle compensation setting
  - ♦ Impacts 3I2 calculation
- Phase-to-bushing connections
  - ♦ Impacts phase angle across transformer
- CT wiring
  - ♦ System phase should match relay phase

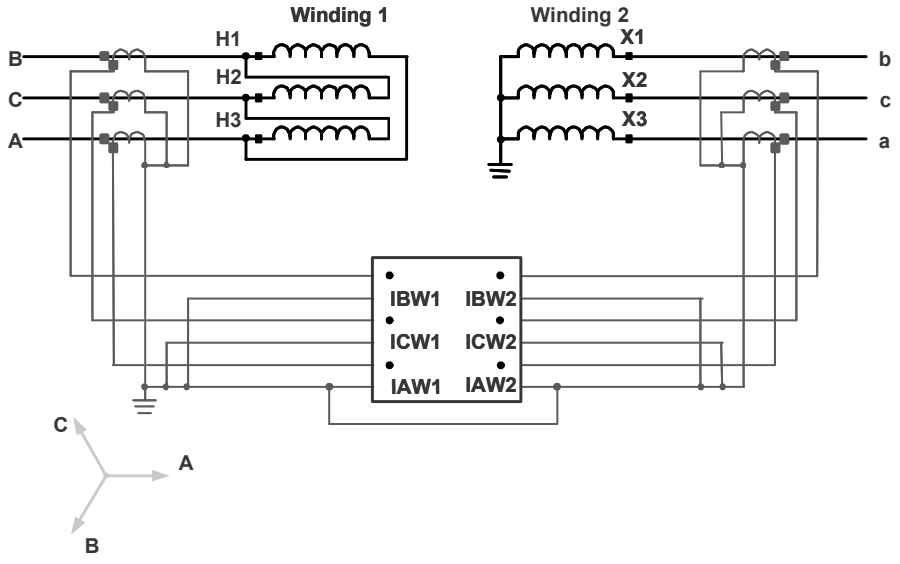
Differential Protection Challenges

- Mobile transformer installations
  - ♦ Settings account for wiring discrepancies
- Overexcitation
  - ♦ Volts/Hertz blocking or tripping
  - ♦ 5^{th} harmonic blocking or tripping
- Lack of sufficient load current
  - ♦ Primary injection tests or higher load
- 63 relay lacks dielectric strength
  - ♦ Use NO and NC contacts, debounce delay

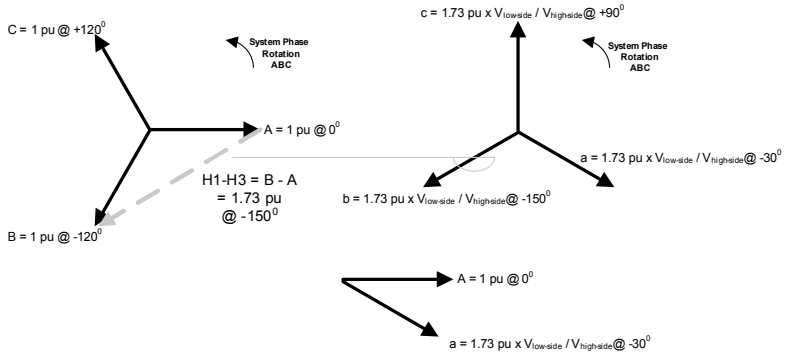
Differential Protection Challenges

- Low current magnitude faults
  - ♦ Restricted earth fault or ground differential
  - ♦ Sudden pressure relays
  - ♦ Gas-accumulator relays
- Through-fault damage
  - ♦ Backup overcurrent protection
  - ♦ Monitor accumulated damage
- Overloads
  - ♦ Thermal model and monitor

Example Differential Installation



Transformer Phase Angle Shift



Relay Phase Angle Compensation

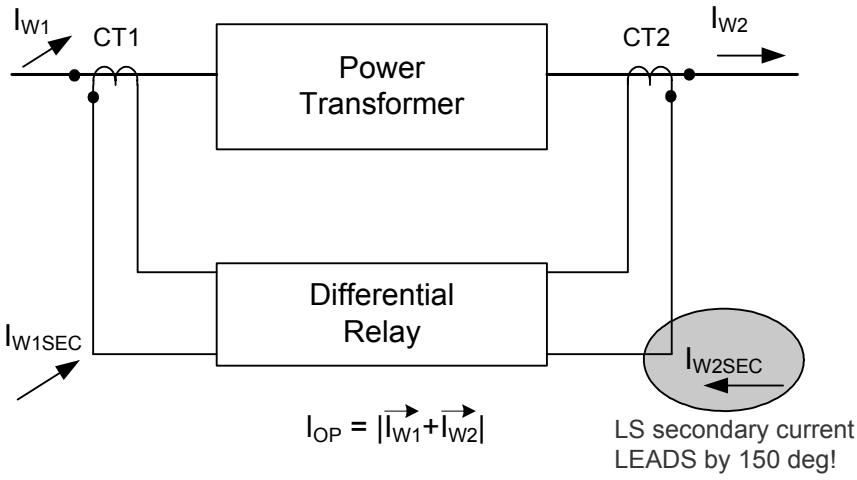
$$\begin{bmatrix} IAWnC \\ IBWnC \\ ICWnC \end{bmatrix} = [CTC\ (m)] \cdot \begin{bmatrix} IAWn \\ IBWn \\ ICWn \end{bmatrix}$$

- [CTC(m)] = 3 X 3 matrix, where m = 0 - 12
  - m = 0: Identity matrix (no changes)
  - m ≠ 0: Remove I0; rotate angles m x 30 degrees CCW for ABC rotation (CW for ACB)

$$[CTC(1)] = \frac{1}{\sqrt{3}} \bullet \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix}$$

  - m = 12: Remove I0; no angle compensation

Secondary Currents for Power Flow

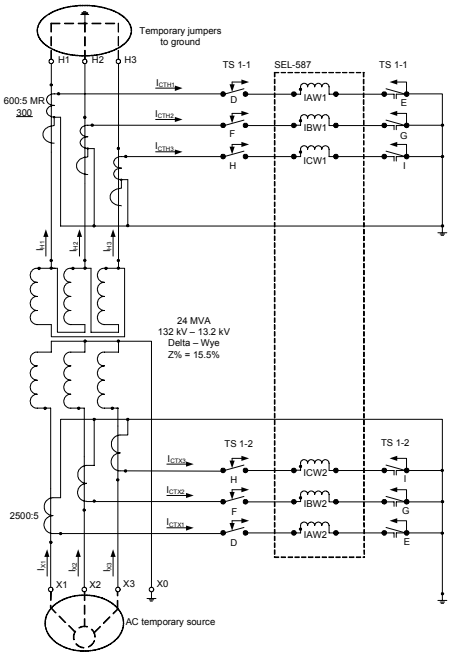


Ready to Go Into Service?

```
=>MET SEC

                                                Date: 03/10/99    Time: 16:10:16.927

                    Phase Currents                                Sequence Currents

Wdg1              IAW1       IBW1       ICW1          3I1W1      3I2W1      IRW1
I (A,sec)         0.37       0.33       0.35           1.05       0.04      0.02
Angle (deg)       0.00    -121.21     121.68           0.17     -16.28     35.89

Wdg2              IAW2       IBW2       ICW2          3I1W2      3I2W2      IRW2
I (A,sec)         0.29       0.29       0.37           0.94       0.14      0.19
Angle (deg)    -150.66      72.14     -17.73        -150.88     178.37      7.01

Wdg3              IAW3       IBW3       ICW3          3I1W3      3I2W3      IRW3
I (A,sec)         0.82       0.83       0.92           2.47       0.03      0.01
Angle (deg)    130.55      11.22    -109.91         130.62     -57.32     62.45

Wdg4              IAW4       IBW4       ICW4          3I1W4      3I2W4      IRW4
I (A,sec)         0.00       0.00       0.00           0.01       0.00      0.01
Angle (deg)    -72.55     107.45      17.45        -117.55      62.45     62.45
```

Commissioning

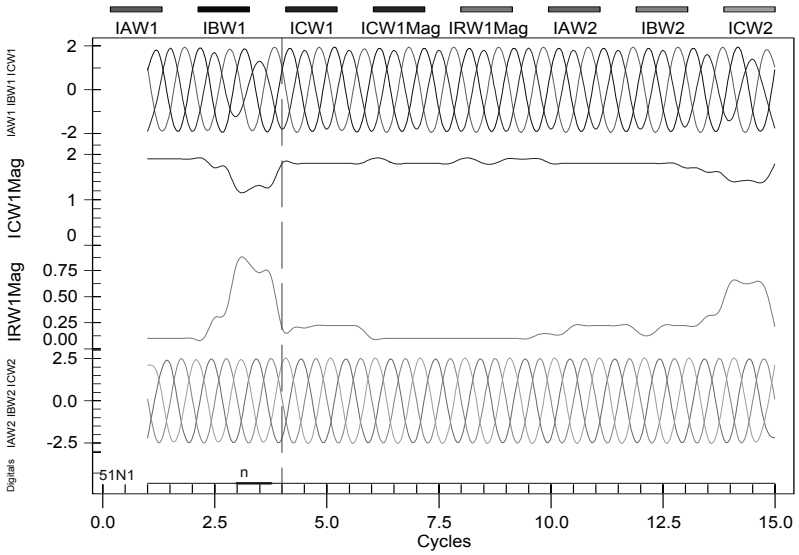
- I_{SEC} > 250 mA ?
- Phase sequence OK?
- Phase angle and polarity OK?
- Current magnitude OK?
- 3I2 = 3I0 = 0
- IOP_X / IRT_X < 10%



Event Analysis Procedure

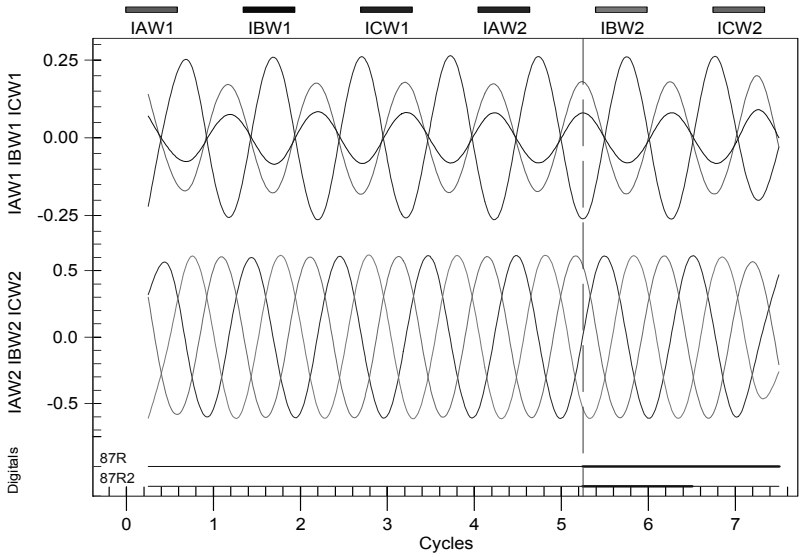
1. Understand expected operation for given conditions
2. Collect all relevant information
3. Gather available analysis tools
4. Compare actual event to expectations
5. Resolve all differences; find root cause!
6. Test proposed solutions
7. Document findings

Intermittent Changes Indicate Arcing



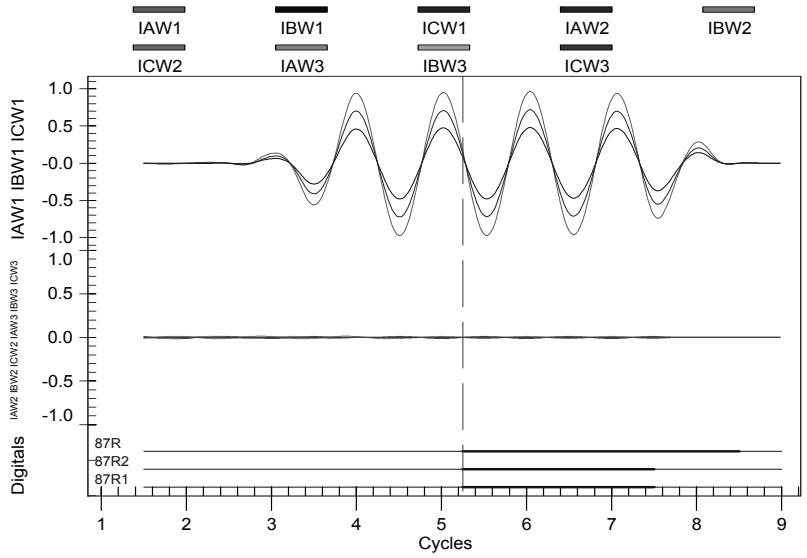
Section VI

Continuous Problem Indicates Short



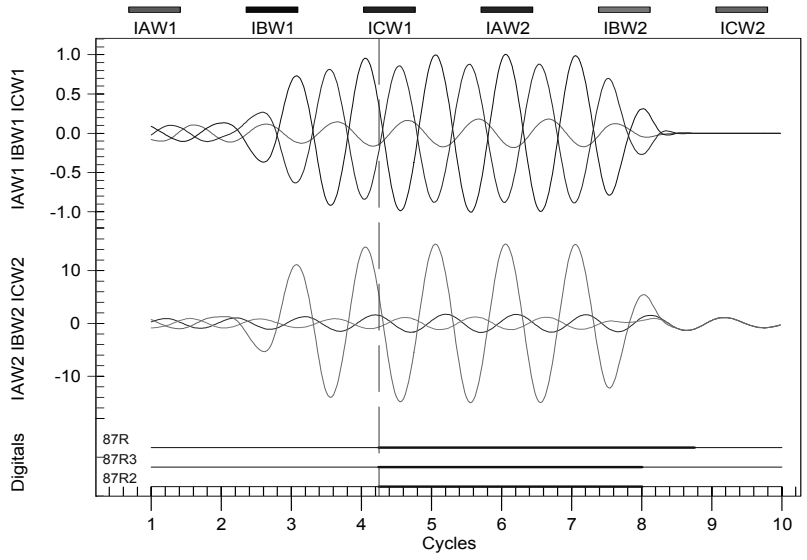
Section VII

Continuous Problem Indicates Short



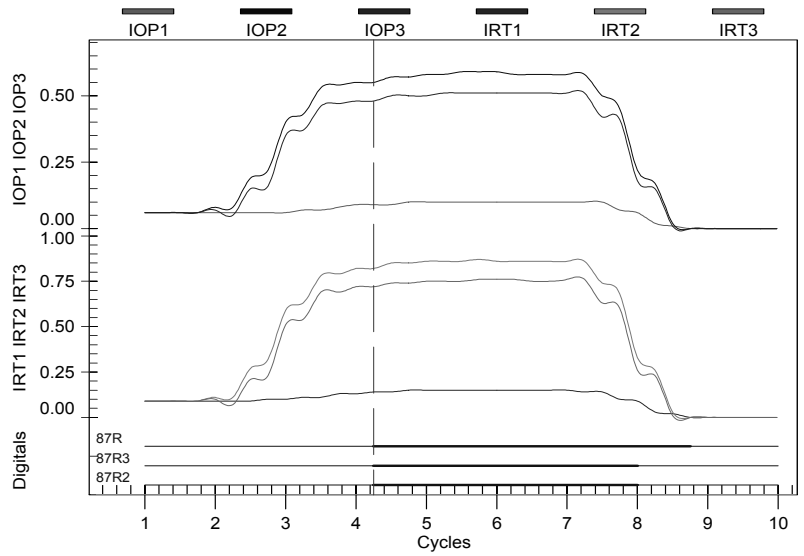
Section VII

Phase-to-Ground Fault on Wye Side



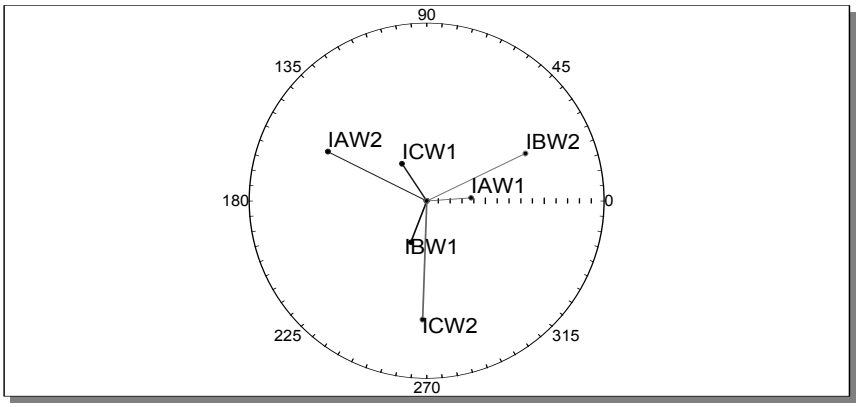
Section VIII

IOP in Prefault Indicates Error



Section VIII

Prefault Power In ≠ Power Out Indicates Incorrect CT Tap

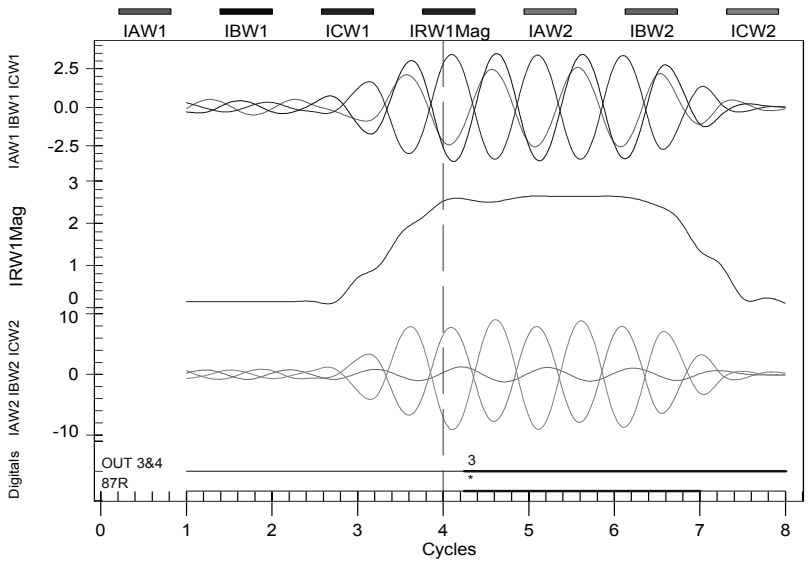


$$PowerIn = \sqrt{3} \bullet 0.1A \bullet 40 \bullet 115\ kV = 796\ kVA$$

$$PowerOut = \sqrt{3} \bullet 0.9A \bullet 80 \bullet 12.47\ kV = 1.6\ MVA$$

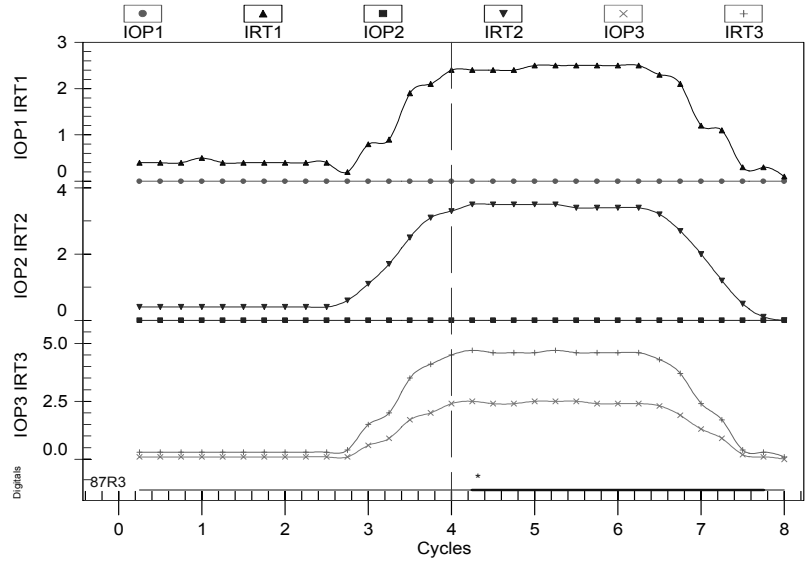
Section VIII

Phase-to-Phase Fault on Wye Side



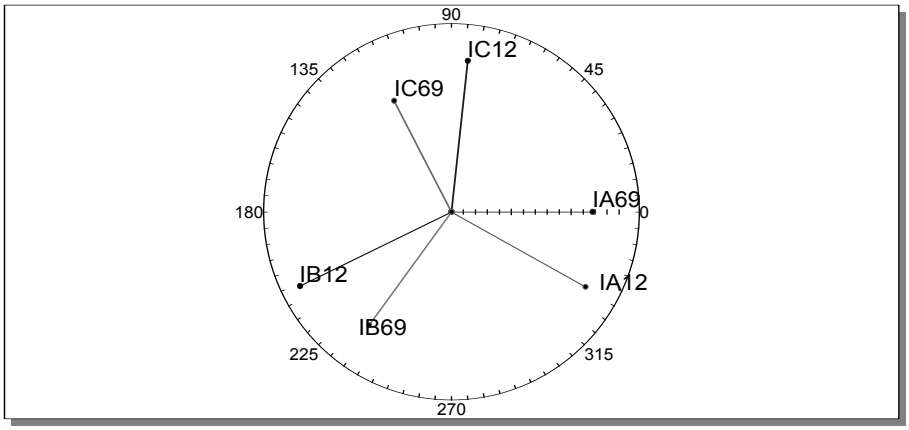
Section IX

IOP ≠ 0 in Only One Element



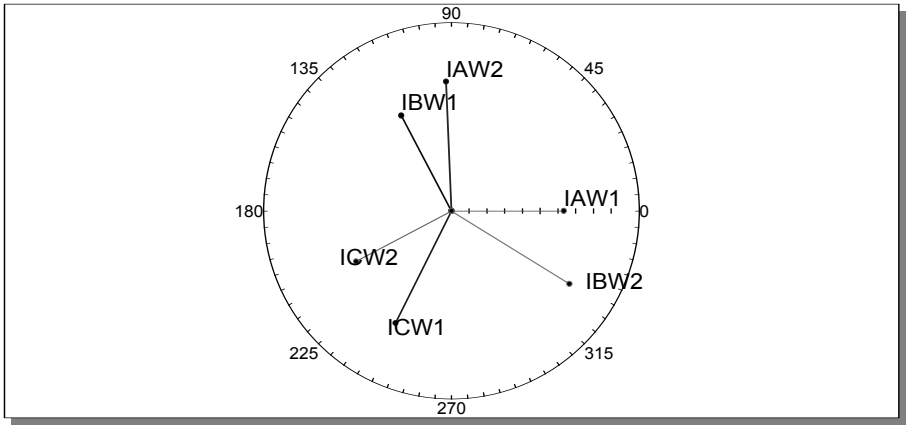
Section IX

Incorrect Phase Angle Indicates Incorrect CT Polarity



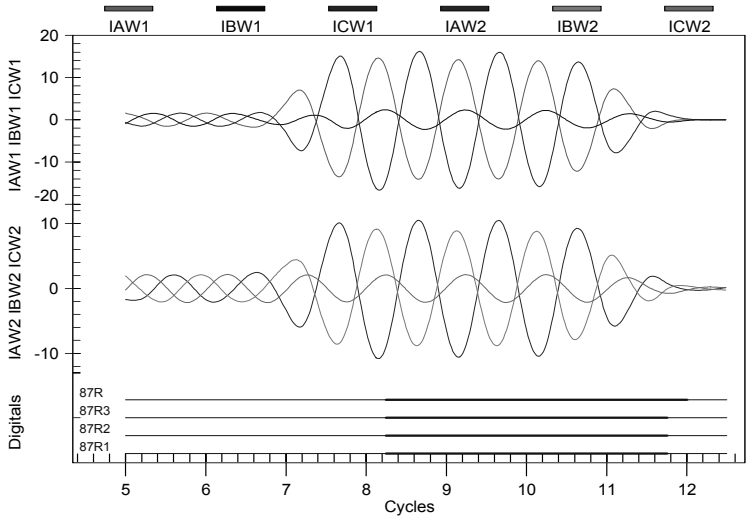
Section X

Unequal Phase Sequences Indicate Rolled CT Secondary Wires



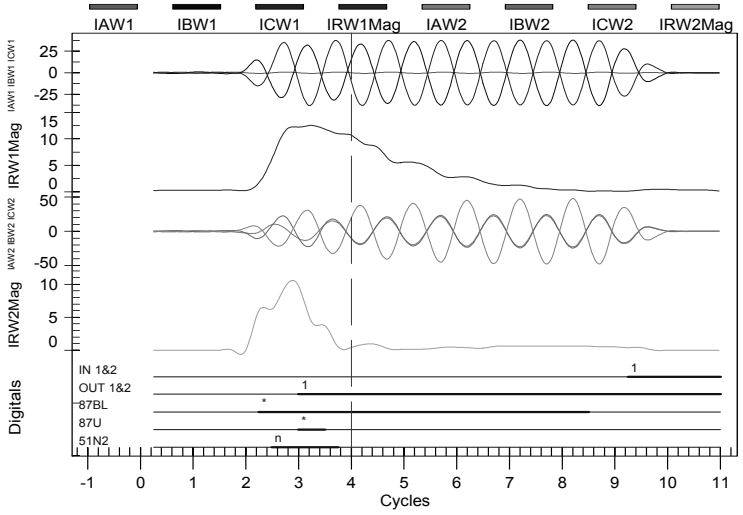
Section XI

Missing Neutral Creates Unexpected Results Only During Unbalances



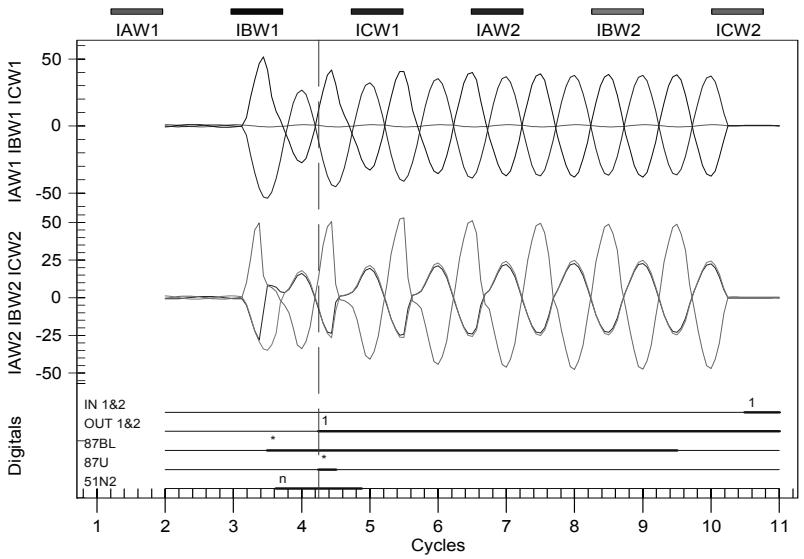
Section XII

Unexpected and Decreasing 60 Hz 3I0 Indicates CT Saturation



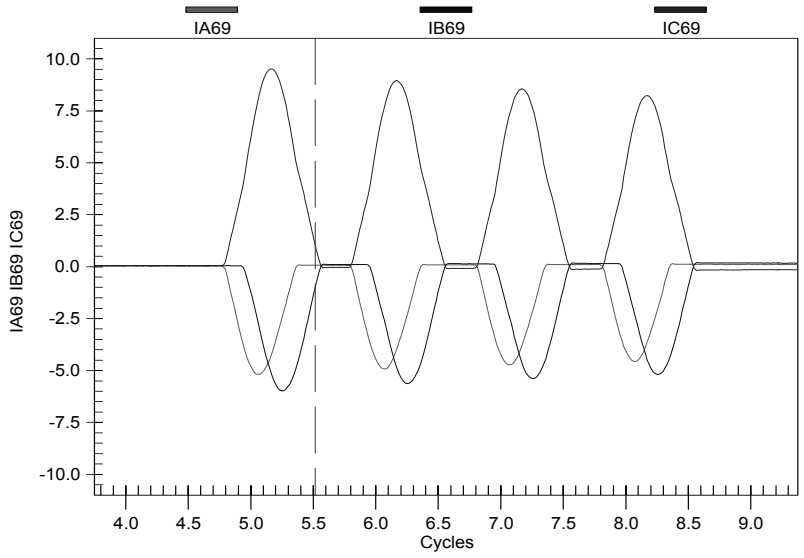
Section XIII

Raw Event Data Confirms Saturation



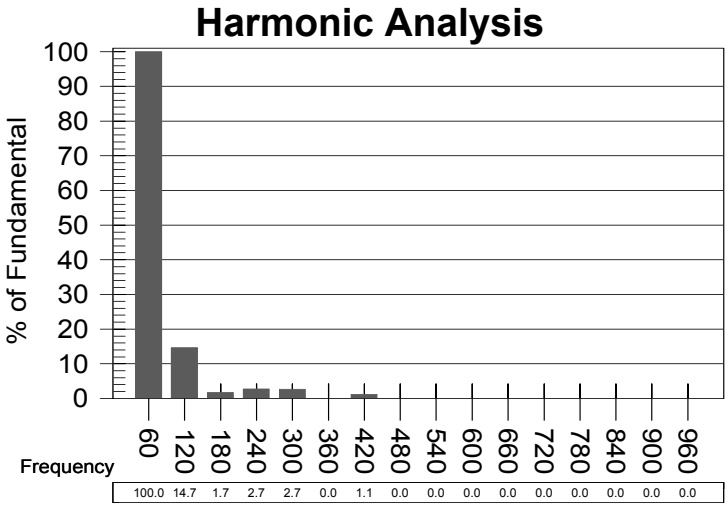
Section XIII

Raw Waveforms During Energization



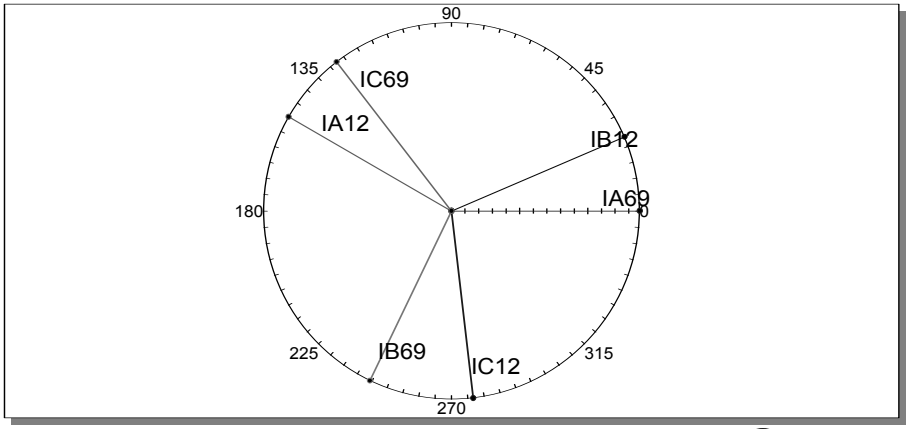
Section XIV

Traditional Second-Harmonic Blocking Fails to Restrain During Energization



Section XIV

Incorrect Phase-Angle Compensation

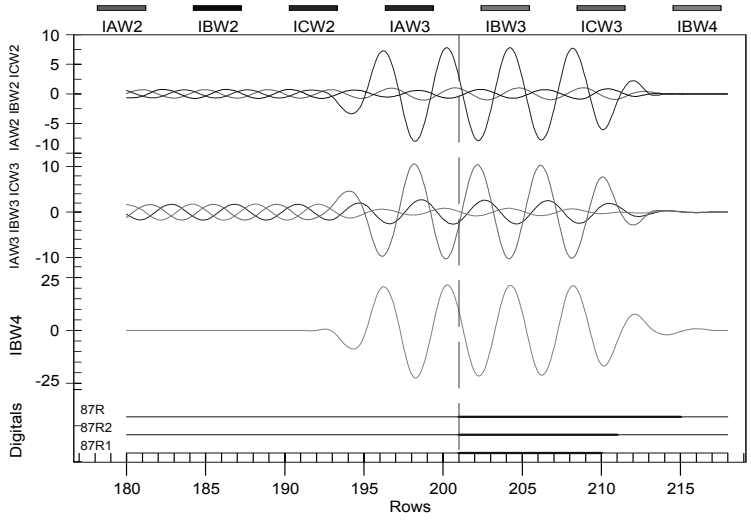


WDG1 (12) Phase-Angle Compensation = 12

WDG2 (69) Phase-Angle Compensation = 1

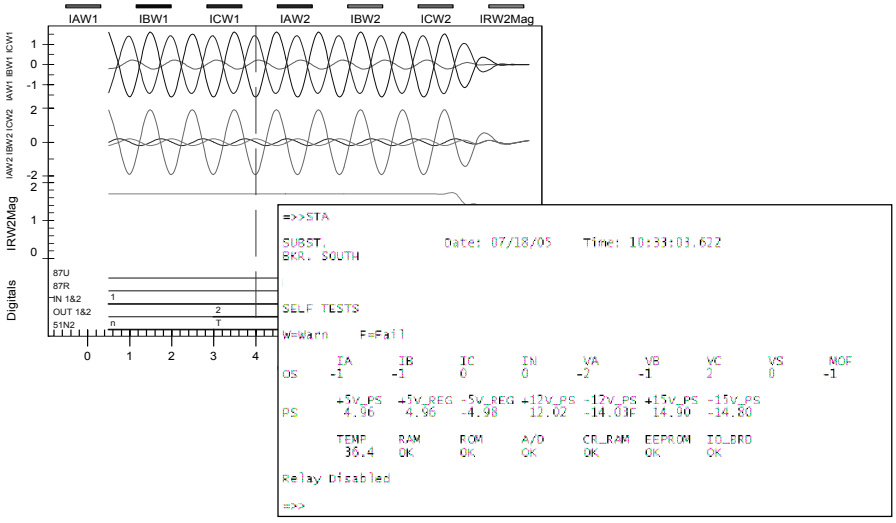
Section XV

Unfiltered Zero-Sequence Component Causes Autotransformer Trip



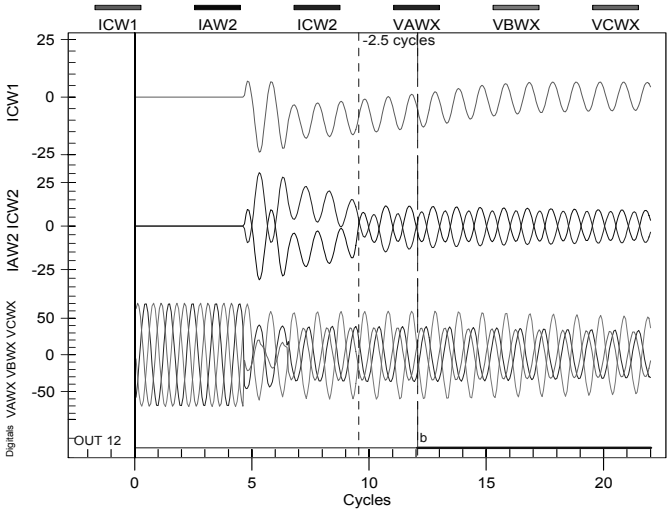
Section XVI

One Relay's Data Explains Another's Operation



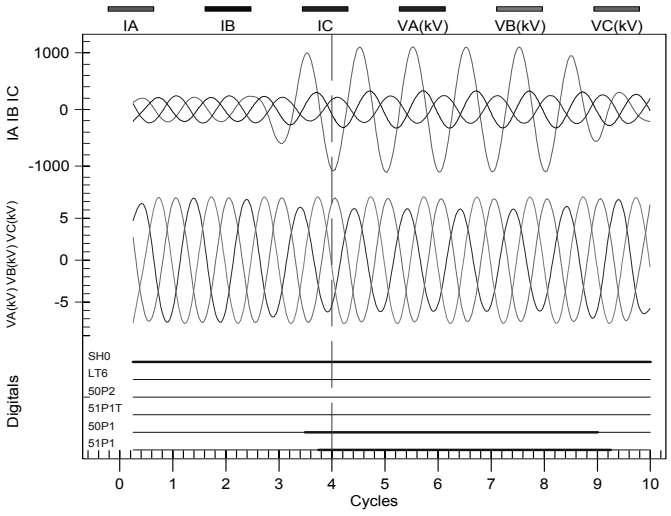
Section XVIII

DC Offset and Unequal CT Performance Cause Trip



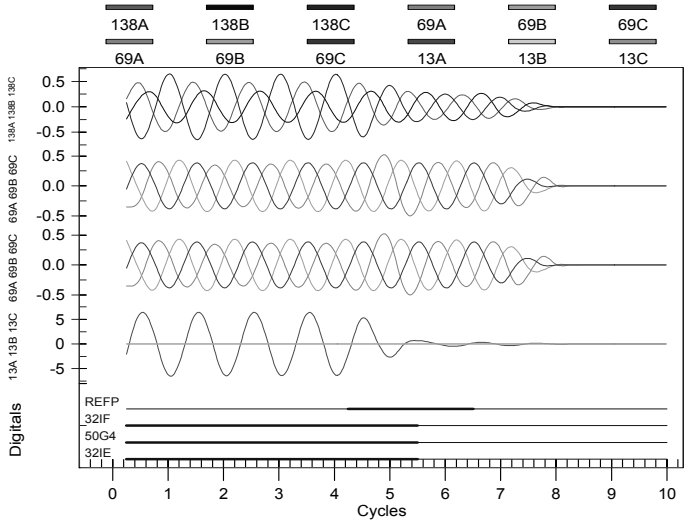
Section XIX

Use Data From All Relays to Determine Fault Location



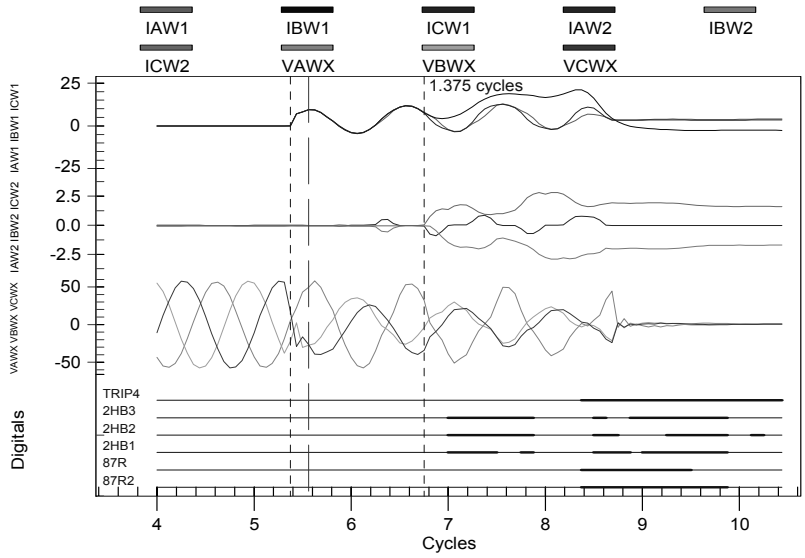
Section XX

Use Data From All Relays to Determine Fault Location



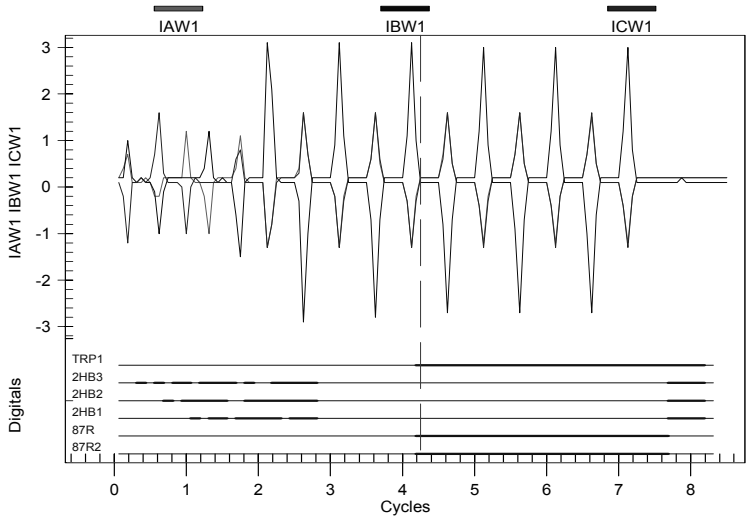
Section XX

Breaker Problem Causes 87T Trip



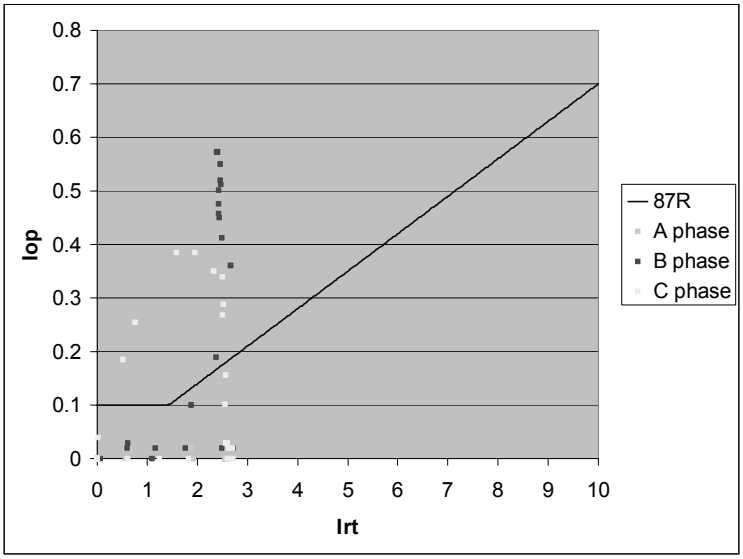
Section XXI

Transformer Overexcitation Causes 87T Trip



Section XXII

CTs Saturate During Motor Start



Section XXIII

Conclusions

- Microprocessor-based relays simplify installations with improved tools and by allowing the use of wye-connected CTs
- However, transformer differential installations remain complicated
- Thorough commissioning practices must be followed to discover wiring and settings errors before energization

Conclusions

- Technology has not replaced the contribution of a knowledgeable engineer and technician
- Event report analysis is invaluable to understanding and solving problems
- Developing proficiency with troubleshooting and event analysis requires practice and experience