Open-Circuited CT Misoperation and Investigation

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***Abstract*—A wire crimping error caused a current transformer (CT) to become open-circuited under load, a relay to operate, and an industrial plant outage. The wiring error was corrected, and the relay, internally damaged by severe overvoltage, was put back into service. Root cause analysis predicted and exposed the damage and led to corrective actions. This paper revisits the IEEE dielectric strength standard, safe design and work procedures regarding CTs, and what happens when a CT is open-circuited under load. The case study emphasizes the critical importance of commissioning tests and root cause analysis to power system reliability.**

I. Review of CT Concepts

Fig. 1 shows the equivalent circuit of a current transformer (CT), referred to the CT secondary side. The CT primary winding current is I_P, the CT ratio is *n*, and the current source I_P/n represents the ratio current. The CT secondary winding resistance is represented by R_S. The nonlinear inductive reactance Z_E represents the CT magnetization branch. The excitation current I_E flowing through the magnetization branch Z_E sets up the flux in the CT. The excitation voltage E_S is due to the flux linkage produced by the magnetizing branch inductance. Impedance Z_B represents the total load, or burden, connected to the CT secondary terminals. The CT secondary terminal voltage V_S appears across the CT burden. The secondary current I_S flows through the CT burden.

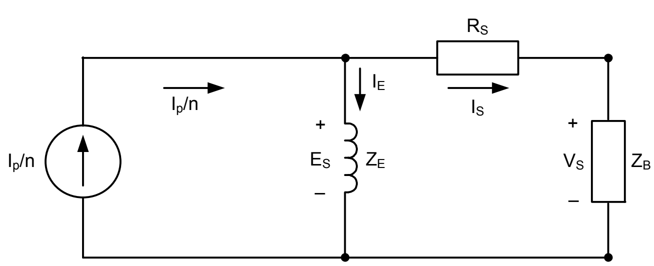


Fig. 1. CT Equivalent Circuit

A typical magnetization curve, or B-H curve, conveys the nonlinear relationship between the magnetic flux density (*B*) and the magnetic field intensity (*H*). The CT secondary excitation curve is an alternate representation of the B-H curve and has a similar shape because the flux density *B* is proportional to the voltage E_S and the magnetic field intensity *H* is proportional to excitation current I_E. The voltage E_S is also proportional to the rate of change of magnetic flux φ.

Fig. 2 shows the manufacturer excitation curve for an ANSI C400 (IEC 100 VA 5P 20) 2000:5 single-ratio CT. The ANSI/IEEE rating defines the voltage developed across a standard burden by a steady-state, symmetrical secondary current equal to 20 times nominal, with less than 10 percent ratio error. The ANSI knee-point voltage is the voltage corresponding to the point in the excitation characteristic where the tangent is at 45 degrees to the abscissa, when the curve is plotted on log-log axes with square decades. This is the point of maximum permeability on the excitation characteristic. While the excitation characteristic has a well-defined knee point, it has no discernible point of saturation [1].

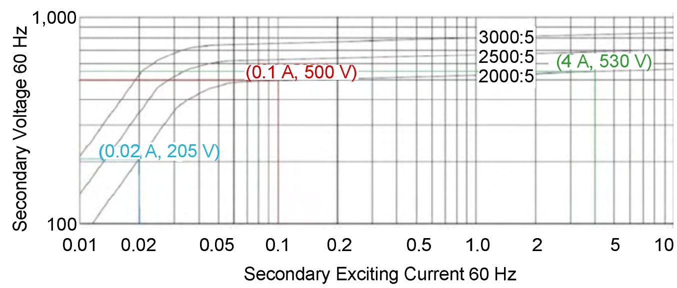


Fig. 2. Excitation Curve for an ANSI C400 2000:5 CT

Fig. 3 shows the graphical relationships between the excitation characteristic (a) and the magnetic flux density (b), excitation current (c), and excitation voltage (d) as functions of time.

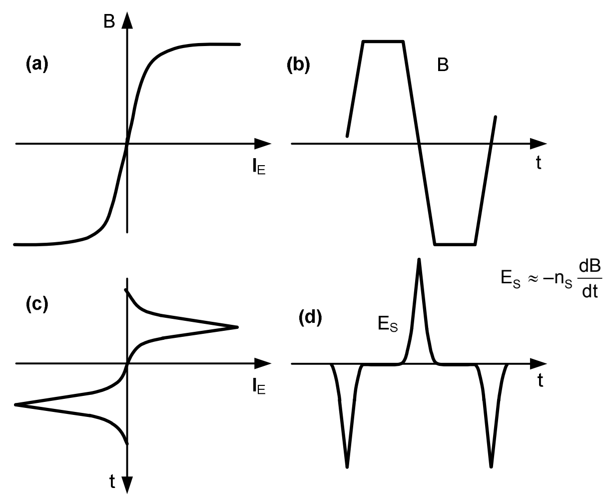


Fig. 3. Excitation Characteristic (a), Flux Versus Time (b), Excitation Current Versus Time (c), and Excitation Voltage Versus Time (d)

When the magnetic flux density *B* or excitation voltage E_S is low, the excitation current I_E is low and the CT behaves almost linearly, with no saturation in the magnetic core. As the burden current or impedance increases, the excitation voltage E_S, the magnetic flux density *B*, and the excitation current I_E also increase. At a given flux density, the magnetizing inductance saturates and the excitation current increases disproportionally with voltage. The secondary current I_S at this point is no longer an accurate replica of the primary current. The CT excitation current I_E creates a difference between the secondary current I_S and the ratio current I_P/n. This difference, I_E, is the CT error.

As indicated in Fig. 3, when the CT is saturated, the rate of change of flux is almost zero (b), and therefore, the excitation voltage is near zero. However, in the linear region, the flux can exhibit a very high rate of change and therefore a very high induced voltage. This produces the voltage peaks shown in Fig. 3d.

It is important to note that in the extreme saturation condition, such as that caused by an open-circuited CT or an infinite load impedance, the peaks that appear in the excitation voltage can be extremely large, even for relatively low ratio currents. From the excitation curve in Fig. 2, we can estimate the nonlinear inductive reactance Z_E of the CT excitation or magnetization branch at various points (see Table I).

TABLE I
EXCITATION BRANCH IMPEDANCE ESTIMATES

	E_S	I_E	Z_E
Point 1	205 V	0.02 A	10.25 kohms
Point 2	500 V	0.1 A	5 kohms
Point 3	530 V	4.0 A	132 ohms

At low excitation voltages and small load currents, the magnetizing branch impedance is very large (10.25 kohms). If the CT is open-circuited, all of the ratio current I_P/n will flow through this extremely high impedance, develop an extremely high excitation voltage E_S, and drive the CT deep into saturation. As the CT saturates, the magnetizing branch impedance approaches a short circuit (132 ohms) and the CT magnetizing current I_E increases nonlinearly with voltage.

A C400 2000:5 CT with 1,000 A primary current (2.5 A secondary) and an extremely high burden to replicate an open-circuited CT condition was simulated using Mathcad®. The nonlinearity of the magnetizing branch impedance versus time is displayed in Fig. 4. The flat spots (near short circuit) in the magnetizing branch inductive reactance occur during alternating half cycles of the CT saturation, when flux is relatively flat in Fig. 3a and b. During these times, flux is not changing, so the excitation voltage is near zero and the magnetizing current I_E is large. The very large and thin spikes in the magnetizing branch inductive reactance occur during the transition times when flux is increasing or decreasing rapidly in Fig. 3a and b. During these periods, the reactance increases to very large values, which creates similarly shaped brief, but extremely high, voltage spikes.

These peaks represent dangerous overvoltages, which can damage CTs, protective relays, and the insulation of the secondary wiring, as well as expose personnel to dangerous primary-level voltages (thousands of volts) on the terminal blocks and test switches of switchboard panels and switchgear.

This demonstrates why CTs should never be left with the secondary open and the primary connected. Reference [2] from 1936 describes a scheme where thyrites were installed across CT secondary terminals to prevent dangerously high voltages. Distribution reclosers occasionally have a 100-ohm resistor connected across the CT secondary terminals, in parallel with the protective relay burden, so that the CTs are not open-circuited when the control cable and relay burden are manually disconnected.

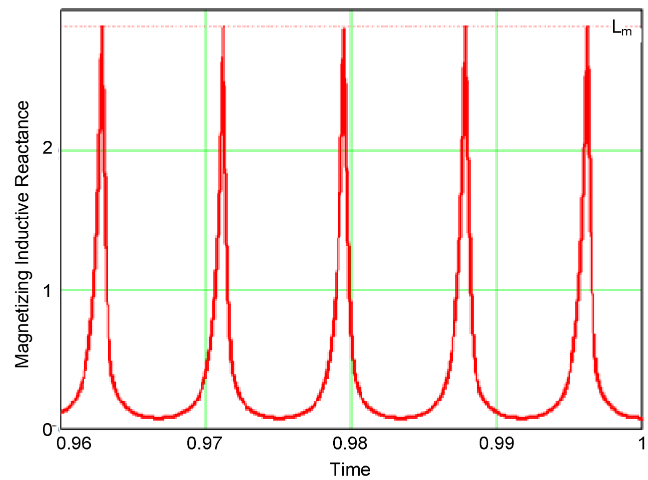


Fig. 4. Magnetizing Inductive Reactance Versus Time

Shorting terminal blocks and CT test switches allow technicians to short CTs while open-circuiting relay inputs for testing and troubleshooting. New test switch designs are completely finger-safe, with no exposed metal or blades. One utility in Oklahoma specifically mentions in their design standard several preferred wiring methods, including placing the crimp dimple of a ring lug on the back side of the lug barrel and placing the lug back side out so that the crimp can be visually inspected. These design and operating practices reveal the great care taken to avoid open-circuiting a CT.

II. IMPORTANCE OF STANDARDS AND TYPE TESTING

IEEE and IEC environmental standards and type tests were developed to ensure that protective relays for critical infrastructure meet minimum design criteria. Examples include the IEEE C37.90-1989 and IEC 60255-5:1977 dielectric strength tests. When a fault occurs, ground potential rise may cause high voltages to develop at the end of CT cabling. Dielectric strength standards and tests are intended to ensure that a protective relay subjected to high fault-induced voltages and transients in wiring will not be damaged and will operate dependably, securely, and safely. The IEEE dielectric strength test mandates that a relay between insulation and ground and between any two circuits shall withstand twice the rated voltage plus 1,000 Vrms, with a minimum of 1,500 Vrms. These severe testing requirements take into account the harsh environments typical of utility and industrial applications and the critical importance of reliable power systems [3].

Note that open-circuited CTs also can produce extremely high voltages on CT cabling and all equipment connected to it, but dielectric withstand standards were not designed to protect against these circumstances. Said another way, no matter how well a relay is designed, if we put primary system voltage levels on the circuit board, we can expect the relay to fail at some point.

Consider that the North American Northeast blackout of 2003 was aggravated by improper operator action because of a lack of up-to-date information from the supervisory control and data acquisition (SCADA) system. A remote terminal unit (RTU) had been installed with two redundant power supplies that both failed because of ground potential rise. Self-test monitoring did not alert the operator that the RTU had failed. Fail-safe design practices, such as reporting full-scale or zero values for all data fields during loss of communications or for watchdog timer failures, were not in place. Two power supplies, installed for redundancy, did not improve the availability of the system. The equipment was not substation-hardened, designed, and type-tested to meet IEEE C37.90. Further, no independent testing had been done to detect the product weakness [4].

Many consumers and regional reliability entities mandate protective relays be designed and tested to meet these standards. In this way, standards and type tests provide a repeatable and objective way to validate equipment and compare the designs of different manufacturers [5]. Fig. 5 shows circuit boards from the overcurrent relays of two different manufacturers. Relay A has 2 optoisolated inputs and 5 output contacts. Relay B has 15 inputs and 10 output contacts. Relay A sacrifices 13 inputs and 5 outputs in order to have increased component spacing and larger creepage distances.

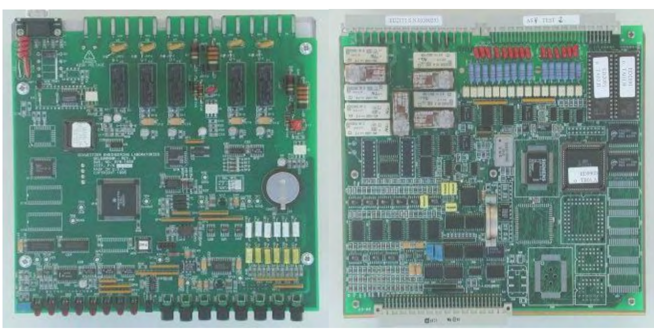


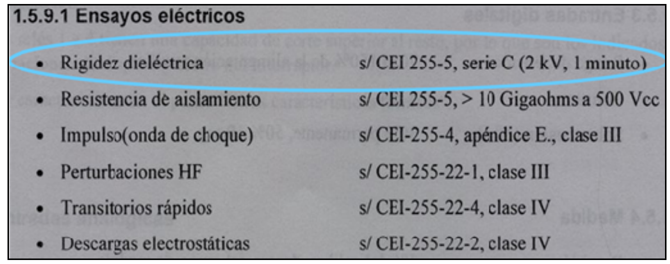
Fig. 5. Manufacturer A (Left) and B (Right) Circuit Boards

Both of the relays in Fig. 5 include specifications in their instruction manuals. Both claim to exceed the 1,500 V minimum dielectric strength requirement. As shown in the top of Fig. 6, Relay A claims a 3,000 Vdc withstand capability on contact inputs. Relay B (bottom of Fig. 6) claims a 2,000 Vdc withstand capability on contact inputs. Both claims exceed the IEEE standard.

A dielectric test is quite simple to perform with the correct equipment. Fig. 7 is a screen capture from a video taken during dielectric strength, or HiPot, type testing of Relays A and B.

However, few utilities and industrial consumers actually test relays today to prove the claims of manufacturers. It is recommended that they do, either directly or through a third-party validated test laboratory. Fig. 8 shows the dielectric breakdown of Relay B at 1,500 V.

Dielectric:	IEC 60255-5:1977 IEEE C37.90-1989 2500 Vac on analog inputs; 3100 Vdc (3000 Vdc for Plug-in Connectors option) on power supply, contact inputs, and contact outputs



1.5.9.1 Ensayos eléctricos

• Rigidez dieléctrica	s/ CEI 255-5, serie C (2 kV, 1 minuto)
• Resistencia de aislamiento	s/ CEI 255-5, > 10 Gigaohms a 500 Vcc
• Impulso(onda de choque)	s/ CEI-255-4, apéndice E., clase III
• Perturbaciones HF	s/ CEI-255-22-1, clase III
• Transitorios rápidos	s/ CEI-255-22-4, clase IV
• Descargas electrostáticas	s/ CEI-255-22-2, clase IV

Fig. 6. Manufacturer A and B Dielectric Specifications

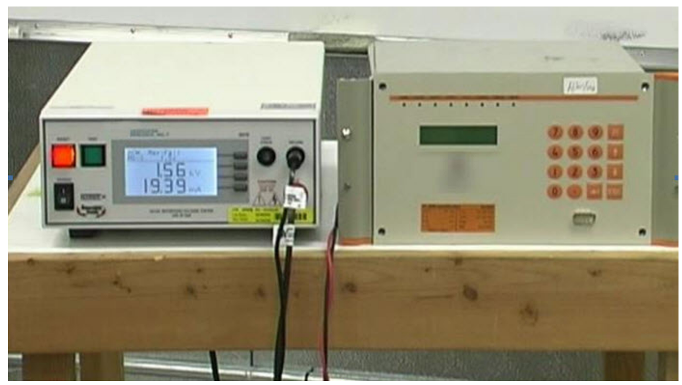


Fig. 7. Dielectric Strength Type Testing

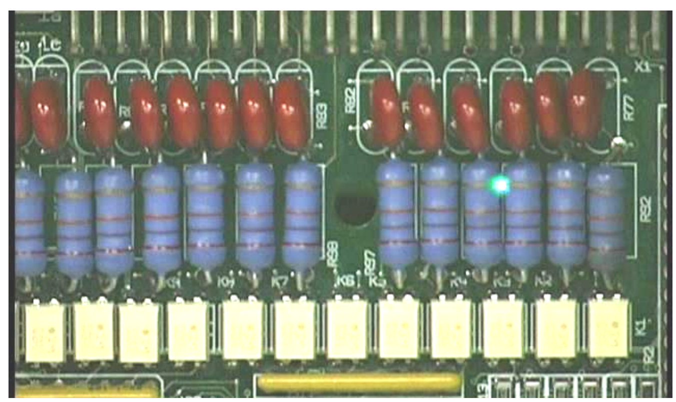


Fig. 8. Dielectric Breakdown of Relay B at 1,500 V

Relay A withstands a continuous voltage of 4,000 V in this test. This speaks to the dielectric withstand capability of its design and its ability to operate reliably in the presence of ground potential rise and other fault-induced transients. However, any relay will eventually fail given a high enough voltage because relays are not designed to withstand primary-level voltages such as those developed by open-circuited CTs.

III. Case Study Application Details

The application under study in this paper is a microprocessor-based overcurrent relay installed in switchgear in an industrial plant (see Fig. 9). CTs from the main and bus tie breakers are paralleled and wired to the relay. One breaker is normally closed while the other breaker is normally open.

Fig. 9. Switchgear Breaker, Relay, and Controls

The three phase currents are measured individually. The phases are then connected residually, and a separate neutral current input, called IN, on the relay measures the sum of the phase currents. The relay is capable of providing light-based arc-flash protection, although fiber-optic sensors have not yet been installed. A simplified protection connection diagram is shown in Fig. 10.

Important settings for the application are shown in Fig. 11. Only four elements are enabled to trip—the individual phase time-overcurrent elements and the separate neutral time-overcurrent element. Phase elements (51A, 51B, and 51C) have a 2,000 A primary pickup, while the neutral 51N has an 800 A primary pickup. The 51N element operates from measured 3I0—the physical sum of IA, IB, and IC. The relay also calculates the mathematical sum of the phase currents, called IG. The IG element is not enabled to trip in this application. Both IG and IN are available as analog channels in event reports.

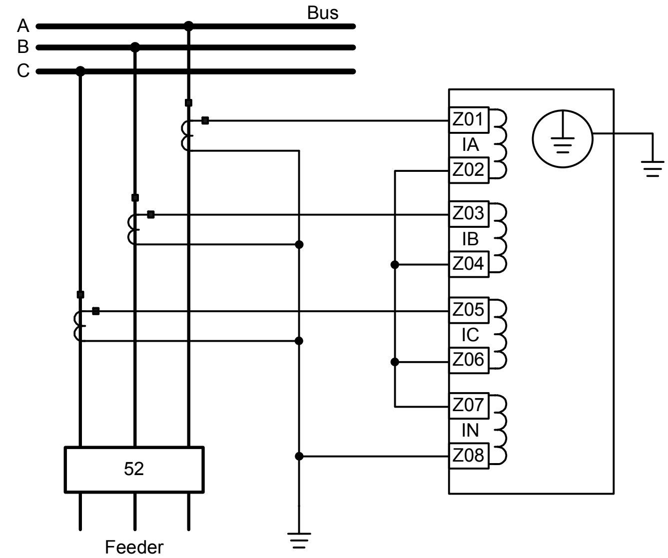


Fig. 10. Simplified Protection Connection Diagram

```
Settings –

PHROT    := ABC      FNOM     := 60
CTR      := 400      CTRN     := 400
PTR      := 120.00   DELTA_Y  := DELTA
VNOM     := 106.00
51AP     := 5.00     51AC     := U4    51ATD    := 4.50
51BP     := 5.00     51BC     := U4    51BTD    := 4.50
51CP     := 5.00     51CC     := U4    51CTD    := 4.50
51N1P    := 2.00     51N1C    := U3    51N1TD   := 5.00
TR       := ORED51T #Any Time-Overcurrent Trip
```

Fig. 11. Important Settings for This Application

A main-tie-main automatic transfer scheme is in place to transfer plant load to an alternate source within seconds of primary source loss. Local diesel generators provide emergency backup only. Plant loads are especially vulnerable to voltage sags and comply with CBEMA and SEMI F47 curves. Total plant load was greater than 18 MW and increasing at the time of the event.

IV. Open-Circuited CT Causes Outage

The industrial plant experienced an outage caused by a trip of the overcurrent relay. The initial outage lasted at least 15 minutes due to the breakers being locked out and personnel trying to determine root cause, restart in an orderly manner, and not close back into a fault.

There was no fault, but the root cause was not determined immediately. So the breaker was closed, only to trip again. This led to a near complete plant outage, some equipment failure, and some processes requiring weeks to restart.

Industrial plant personnel requested assistance from the relay manufacturer to help determine root cause of the original trip. Event records were downloaded and analyzed. Fig. 12 shows one of the first records. The phase-to-phase voltages are balanced, the three phase currents are balanced, the calculated IG current is zero, but the measured IN current is about 800 A primary. The 51N element is shown picking up and dropping out.

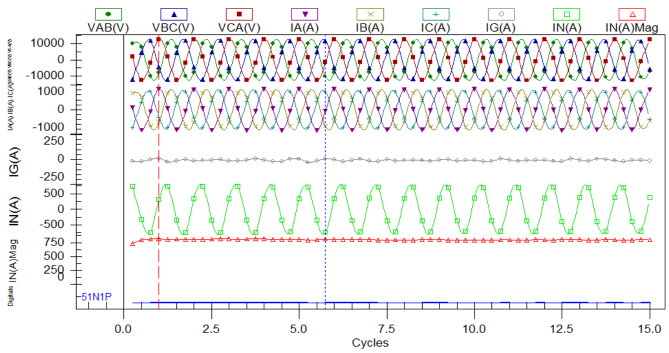


Fig. 12. 51N1P Picking Up and Dropping Out

Fig. 13 shows the phasors at Cycle 5.75. Note that IN is equal to the sum of IA and IB currents (or –IC).

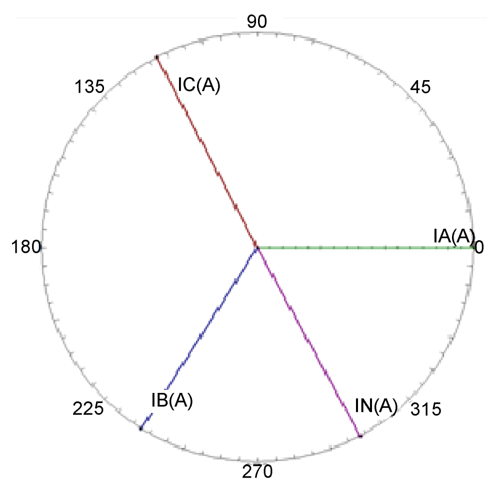


Fig. 13. Phasors at Cycle 5.75 in Fig. 12 Event

As the load was increased, the 51N element eventually picked up continuously and started timing to trip. Fig. 14 shows the element timing to trip.

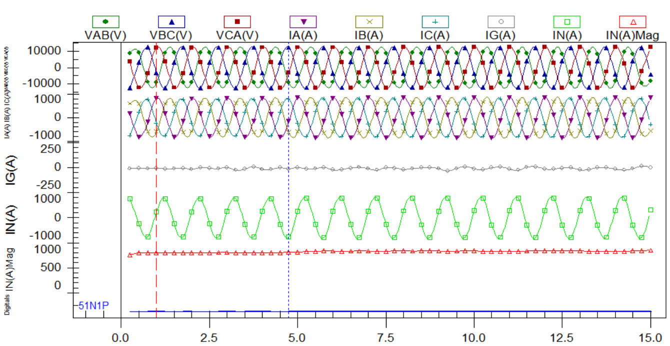


Fig. 14. 51N1P Element Timing to Trip

When 51N1P finally asserted continuously, IN was equal to 817 A primary, just above pickup. At this current level and with an IEEE very inverse curve and a time dial setting of 5, the 51N element would take over 7.5 minutes to trip (see Fig. 15). Load current continued to increase, however, and IN increased in magnitude to over 900 A primary at the time of the trip. This sped up the trip time.

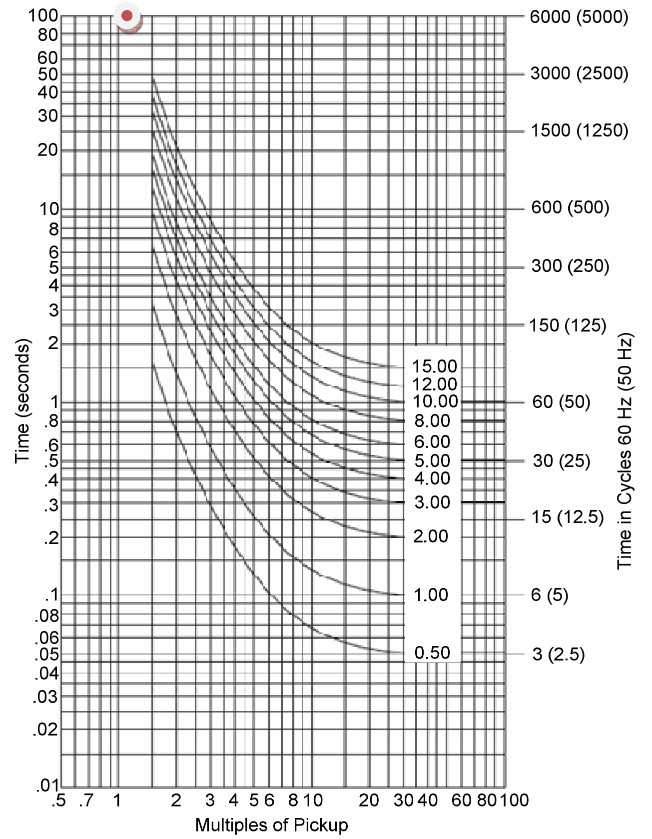


Fig. 15. IEEE Very Inverse Curve

At the time of the trip in Fig. 16, note that the phase-to-phase voltages are balanced, the three phase currents are balanced, the calculated IG current is zero, and the measured IN current is near 1,000 A primary. The balanced phase voltages and currents indicate that there was no fault at the time of the trip.

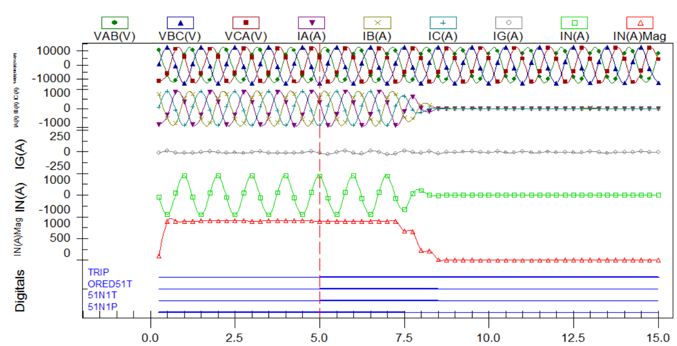


Fig. 16. 51N1T Trip

There are two questions to be answered concerning the trip event. *First, why was the relay measuring IN neutral current while the three phase currents were balanced?* Because the 51N element caused the trip, this question understandably became the first priority and focus of the initial investigation. *Second, how can IG be zero while IN is large?* This question only was asked and noticed later in the investigation.

Event records confirm that the breaker was closed before the theory of an IN wiring problem was developed and resolved (Fig. 17). IN measuring significant current when no fault existed on the system led investigators later to suspect a wiring problem. As is the case too many times, operators were urgently trying to restore power to critical loads, and in their haste, the breaker was closed before root cause was known. After the breaker was closed, significant IN current was still present while phase currents were balanced. This led to a subsequent relay trip.

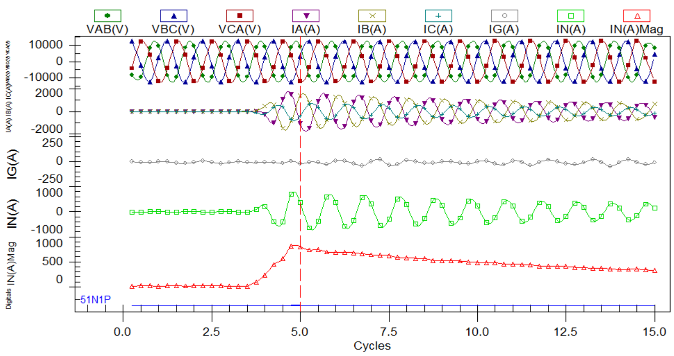


Fig. 17. Breaker Is Closed Without Root Cause Known

After several days of investigation, the source of the IN current was discovered. A ring lug on the nonpolarity or neutral terminal of IC on the relay had not been crimped during the initial switchgear installation. For almost one year, the stripped wire end had made good enough contact to carry current. All of the ring lug barrels had a wire label on them. The IC nonpolarity terminal appeared to be heat shrink-wrapped around the barrel of the lug, whereas all other labels were loosely wound around their lugs. It is suspected that heat generated by load current through this loose connection heat shrink-wrapped the label tightly around the barrel.

After about one year of service in this condition, and two weeks prior to the misoperation, a metallic EIA-232 serial cable was connected between the relay and an automation controller to enable SCADA control and communication. It is suspected that this data cable was touching the C-phase current wire and put enough pressure on it to cause the wire to push free of the ring lug barrel and the shrink-wrapped label (see Fig. 18).

Once the wire slipped and fell free of the barrel, an open circuit in the C-phase circuit (downstream of the IC nonpolarity terminal and before the neutral bus) was created. This explains why IN equaled the sum of IA and IB currents (or –IC). About 2.5 A secondary current was flowing through each phase at the time. Fig. 18 is a photograph of the open-circuited CT wire after the misoperation.

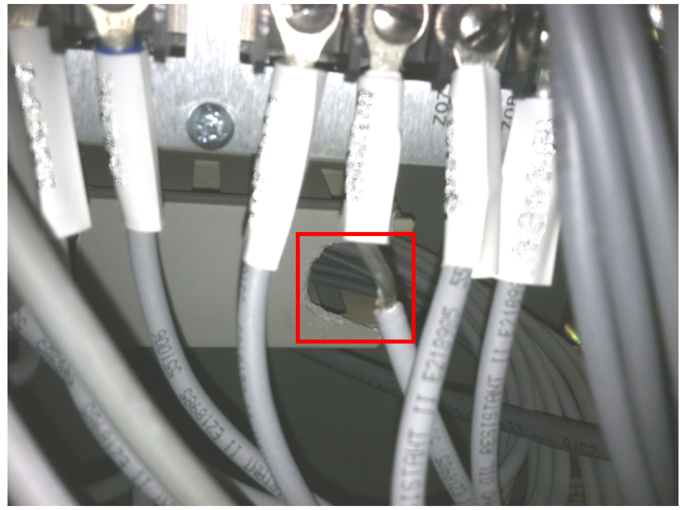


Fig. 18. Photograph of the Open-Circuited CT Circuit

The wire labels installed over the barrel of the ring lugs likely made visual detection of the original problem (no crimp) difficult. Subsequent relay testing, commissioning tests, and normal metering did not expose the problem because the stripped wire made decent enough electrical contact. Nonetheless, these tests should be performed because they do catch the majority of wiring problems.

The Oklahoma utility mentioned previously uses only uninsulated ring lugs and dictates that the barrel be installed to the outside and that wire and terminal labels be on the wire (versus covering the barrel) to make visual inspections easier and more effective. Fig. 19 shows the actual ring lug next to an example crimped lug. Beyond these wiring standards and visual inspections, *physically tugging on each wire to ensure the crimp is secure* is recommended as part of future commissioning checklists.

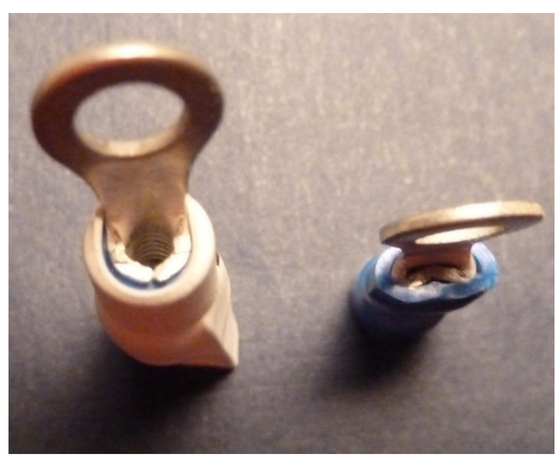


Fig. 19. Photograph of the Actual Ring Lug (Left) and Example Crimped Lug (Right)

Once the open circuit was discovered, the ring lug was crimped correctly, the wire was reinstalled, and the breaker was closed. Fig. 20 shows an event report that was triggered 11 days after the initial trip. The voltages and three phase currents are balanced, *and IG and IN are both near zero*. Now that everything appeared normal, some assumed that the work was over and that the problem had been solved. The breaker and relay remained in service for over two weeks.

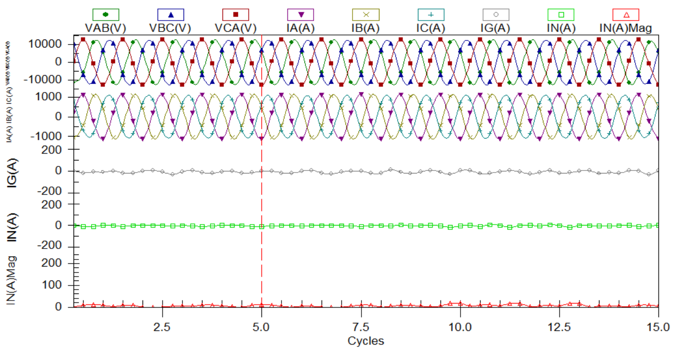


Fig. 20. Event Triggered After Crimp Fixed

V. Open-Circuited CT Causes Relay Damage

The second question from the event analysis remained unnoticed and unanswered at the time that the crimp was fixed and the breaker was closed again. Only during later investigation did engineers focus on how IG could be zero while IN was so large during the events that showed the relay trip (Fig. 12, Fig. 13, Fig. 14, Fig. 16, and Fig. 17). After all, IG is equal to the mathematical sum of the three phase currents, while IN is equal to the physical summation. *More to the point, how could the relay measure C-phase current when a physical open or break in its circuit was visible* (Fig. 18)? Further, once the open circuit was fixed and restored to service, how was the relay measuring normal and expected values for IG and IN (as in Fig. 20)?

Recall from the review of CT concepts that an open-circuited CT can develop dangerously high voltages. At the time of the relay trip, the C-phase CT was carrying nearly 1,000 A primary, or 2.5 A secondary, current. When the C-phase neutral connection became open-circuited, the only load or path for the CT secondary current to flow through was the very high magnetizing branch impedance (Table I, Point 1). This would have developed a very high voltage spike, driving the CT deep into saturation and decreasing the magnetizing impedance. During the next half cycle, this process would start all over again.

A theory was developed that would explain why the relay measured C-phase current while simultaneously having an open C-phase circuit external to the relay (see Fig. 21). The dangerously high voltages must have exceeded the dielectric strength of the relay, damaged the relay, and created a short circuit. In order for the relay to measure C-phase current, the short circuit to ground must have developed internal to the relay, downstream of the C-phase current-sensing element but upstream of the open circuit at the relay terminal block.

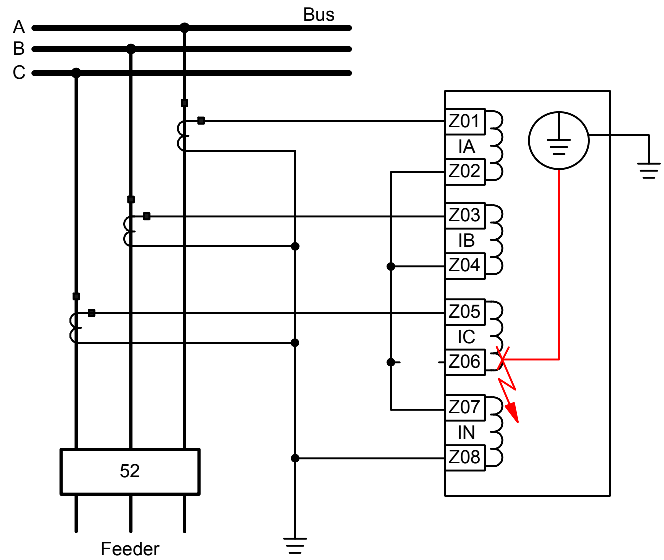


Fig. 21. Theory of Why IG and IN Did Not Match

To prove this theory in the laboratory, the relay manufacturer conducted a dielectric strength test on a circuit board from a like make and model relay. A video recording was made of this test. The relay specifications state that its analog inputs will withstand up to 2,500 Vac. This exceeds the IEEE standard minimum by 1,000 V. Voltage was applied between the polarity of IC (terminal Z05) and the relay ground. At approximately 3.4 kV, the relay failed the dielectric test. The test was repeated, and in the second test, we can observe a visible flash (see Fig. 22). No permanent damage was observed on the relay under test, primarily because the dielectric test equipment automatically shuts down the high voltage for safety when measured leakage current exceeds a threshold of about 300 mA.

Fig. 22. Video From Dielectric Strength Test

The relay current terminals are shown in more detail in the next few figures. Fig. 23 is a profile view of the relay hardware. The bottom terminal block is for the current connections. The diagram or sticker on the side of the relay simply explains the connections and terminal numbering. Terminal Z05 is C-phase polarity. Terminal Z06 is C-phase nonpolarity. Recall in this application that Z06 is the terminal that was open-circuited.

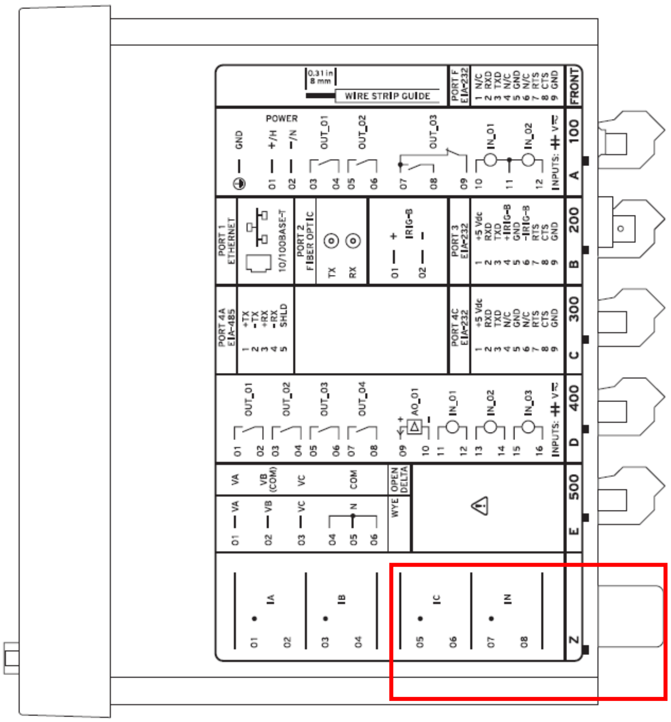


Fig. 23. Profile of Relay Hardware

Fig. 24 is a view of the relay rear-panel layout. The CT connections are made to the Z terminal block on the bottom. Terminal Z05 is the fourth screw from the right, and terminal Z06 is the third screw from the right.

With a theory and a dielectric test on a like make and model relay in hand, the industrial plant was advised that they had a damaged relay in service that needed to be removed from service and repaired immediately. After switching loads to an alternate source, the breaker and relay were removed from service for thorough inspection.

Fig. 25 shows a photograph of the relay involved in this event with its rear panel removed. Compare Fig. 24 and Fig. 25. The CT terminals are visible, as are the internal instrument transformers themselves. The internal magnetics are mounted to the top of a circuit board identical to that in the video shown in Fig. 22.

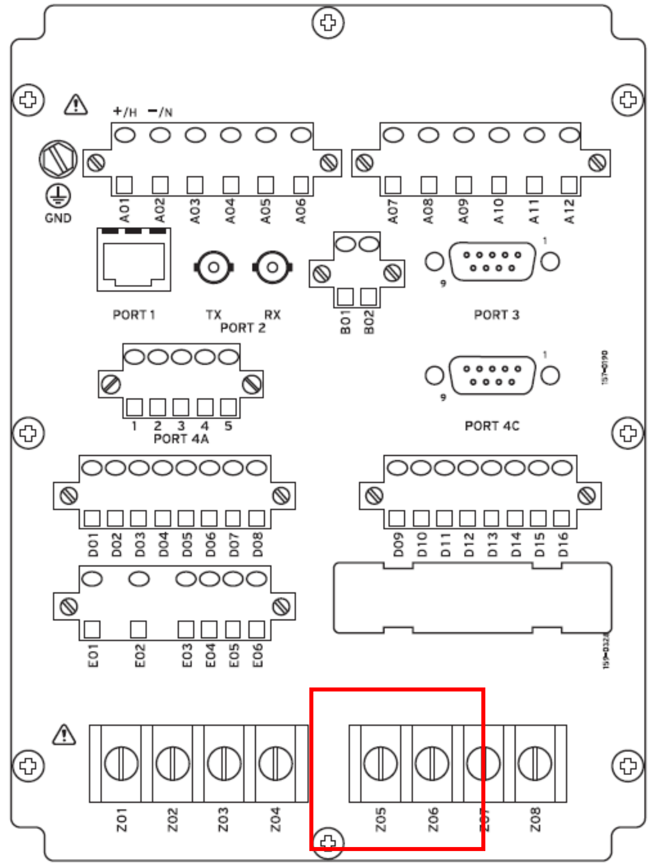


Fig. 24. Rear-Panel Layout of Relay Hardware

Fig. 25. Relay Rear Panel Removed to Expose Inside

When the CT board was removed from the relay, the first obvious sign of damage was the heat and arcing evidence on the bottom inside of the relay chassis, directly under the CT board (see Fig. 26).

Fig. 26. With CT Board Removed, Heat and Arc Damage Evident

Once the CT board was out of the relay, the circuit board damage and arc-induced short circuit were clearly visible (see Fig. 27). The circuit board on the left in Fig. 27 is the damaged board. On the right is the sample board used in the laboratory test and video.

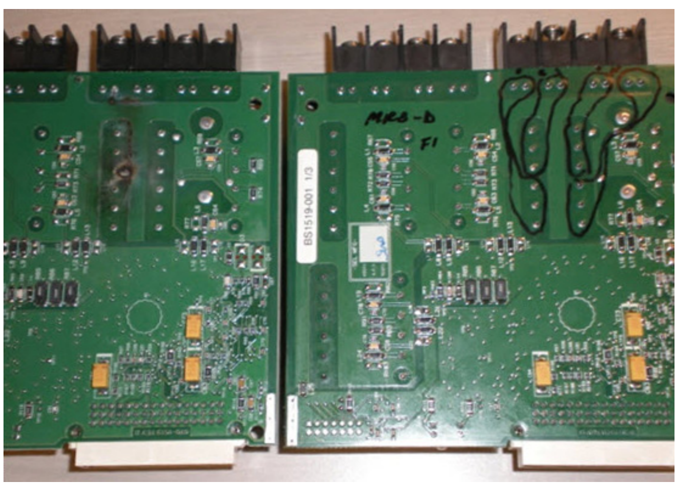


Fig. 27. Damaged Relay Board (Left) and Board From Dielectric Strength Test Video (Right)

Fig. 28 is a close-up view of the damaged board. The relay transformers are mounted on the opposite side of the board. The red highlighted area, where the worst damage is, shows three through-hole pins that connect the nonpolarity Z06 terminal side of IC. The arc-induced weld from the third pin connects to a slightly lighter shade of green vertical area, which is a copper ground or reference plane in the printed circuit board. The open-circuited CT did indeed develop dangerously high voltage spikes, and these caused a dielectric breakdown, damage, and a short circuit to ground inside the relay. Once established, this short circuit to ground provided the path for current to flow through the C-phase-measuring element within the relay to ground, while external to the relay, the neutral element only saw the sum of IA and IB currents.

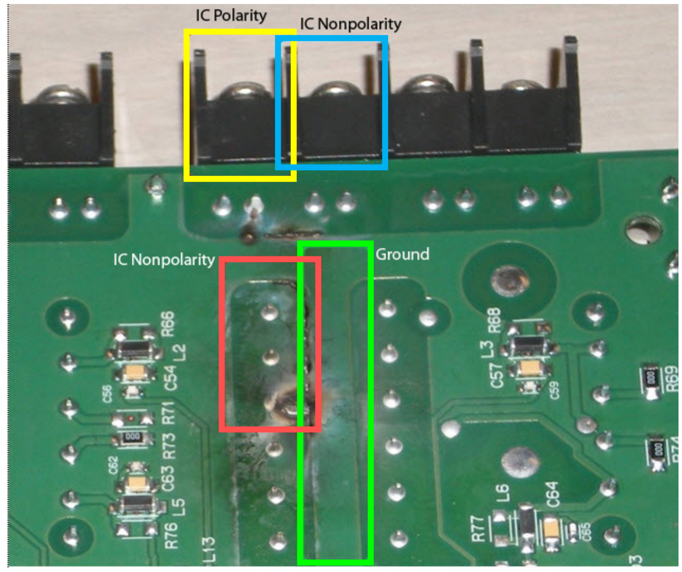


Fig. 28. Closer View of Damaged Board and Arc-Induced Weld Between Z06 and Ground

The impedance from Z06 to ground was measured at 16.8 ohms. This represents the impedance of the arc-induced weld on the circuit board (see Fig. 29).

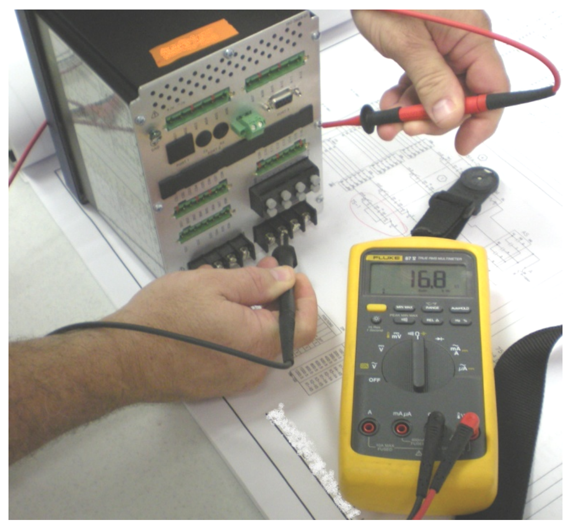


Fig. 29. Impedance Between Z06 and Ground

On all of the other current channels, this should and did measure as an open circuit (infinite ohms). This explains why the relay, when returned to service as shown in Fig. 20, appeared normal. The external CT path wiring had a much lower impedance than the arc-induced weld to ground, so most of the current flowed through IC and on to the neutral bus.

VI. Conclusion

Standards provide best known methods and minimum acceptable requirements. It is recommended that users verify the claims and specifications of manufacturers. Robust designs ensure that critical protection systems will operate reliably even when exposed to fault-induced transients.

Standards, however, are not enough to make any design bulletproof. Even relays designed and tested to greatly exceed IEEE and IEC dielectric standards will fail at some point if subjected to primary-level voltages.

Open-circuited CTs can create dangerously high voltage spikes. Great care must be taken in design, commissioning tests, and operation to ensure that CTs carrying load current are not open-circuited.

In this case study, a CT wire was not properly crimped and was in operation for about a year with no noticeable effects. The addition of a communications cable added just enough pressure to the CT wire to cause it to fall free of the ring lug barrel and open-circuit the CT. A neutral overcurrent element tripped an industrial plant offline.

The open-circuited CT and the resulting high voltage damaged the protective relay. This was not noticed due to haste during the emergency or simply missed because of lack of experience. Because of this, a damaged relay was put back in service, unknowingly putting the plant at risk again. Fortunately, the problem was discovered eventually and corrected before any further problems were experienced.

The damaged relay was discovered through event report analysis and observing a strange anomaly—calculated 3I0 and measured neutral currents not matching. There is a key lesson to be learned—root cause analysis is not complete until every question has been answered thoroughly.

There are literally thousands of wires and terminations in substation control buildings and switchgear lineups. This case study is a vivid reminder *that just one wire* terminated improperly can damage equipment, cause dangerous working conditions for personnel, and cause power outages. That is a slim margin of error and should reinforce the criticality of proper design, peer review, commissioning tests, and more. It is recommended that commissioning procedures include visual inspection of, and physically tugging on, each crimp connection.

VII. Commentary

The following quote seems particularly relevant with respect to this case study. In the Summer 2007 Issue of *PAC World Magazine*, the late Walt Elmore, an icon in our industry, was quoted as follows:

> **PAC WORLD**: What advice would you give to the … engineers in our field?
>
> **WALT ELMORE**: Find out why! To accept something the way it's always been done is not acceptable. There is too much of that—accepting things the way they are. Not delving into it. I don't know whether it's a matter of availability of time or what. People just don't seem willing to devote the effort and time to look into things anymore. That's a fact!! I think it would be good if, when you reach a little stumbling block, that you really got into it to find out why you're about to do something, particularly in relaying.

VIII. Acknowledgment

The author expresses his deep appreciation to engineers Tony Lee and Raymond Sanchez for their assistance with root cause analysis and the writing of this paper.

IX. References

[1] S. E. Zocholl, *Analyzing and Applying Current Transformers.* Schweitzer Engineering Laboratories, Inc., Pullman, WA, 2004.

[2] G. Camilli and L. V. Bewley, "Surge Protectors for Current Transformers," Transactions of the American Institute of Electrical Engineers, Volume 55, Issue 3, March 1936, pp. 254–260.

[3] IEEE Standard C37.90-1989, IEEE Standard for Relays and Relay Systems Associated With Electric Power Apparatus.

[4] E. O. Schweitzer, III, D. Whitehead, H. J. Altuve Ferrer, D. A. Tziouvaras, D. A. Costello, and D. Sánchez Escobedo, "Line Protection: Redundancy, Reliability, and Affordability," proceedings of the 64th Annual Conference for Protective Relay Engineers, College Station, TX, April 2011.

[5] S. Muller-Cachia, A. Akhtar, and S. Hodder, "Utility Perspective on Environmental Type Testing Requirements for Modern Digital Protective Relays," proceedings of the 40th Annual Western Protective Relay Conference, Spokane, WA, October 2013.

X. Biography

David Costello graduated from Texas A&M University in 1991 with a B.S. in Electrical Engineering. He worked as a system protection engineer at Central Power and Light and Central and Southwest Services in Texas and Oklahoma and served on the System Protection Task Force for ERCOT. In 1996, David joined Schweitzer Engineering Laboratories, Inc. as a field application engineer and later served as a regional service manager and senior application engineer. He presently holds the title of technical support director and works in Fair Oaks Ranch, Texas. David has authored more than 30 technical papers and 25 application guides and was honored to receive the 2008 Walter A. Elmore Best Paper Award from the Georgia Institute of Technology Protective Relaying Conference. He is a senior member of IEEE, a registered professional engineer in Texas, and a member of the planning committees for the Conference for Protective Relay Engineers at Texas A&M University, the Modern Solutions Power Systems Conference, and the I-44 Relay Conference.

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