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Investigation and Root Cause Analysis of Transformer Metering Destruction by Arc Flash

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Abstract

An arc flash and fire in the secondary compartment of an industrial facility utility transformer resulted in destruction of newly installed electrical metering equipment. Inherent to this type of event are two loss-of-evidence challenges: extremely high heat burns or melts everything nearby, and urgency to restore normal operation may prevent comprehensive examination of the scene. The facility contractor's operations staff conducted an initial root cause analysis. The contractor's management called on an external forensic team to provide an independent assessment. Having an established investigation methodology allows the forensic examiner to better understand what was, and was not, evaluated by facility staff and prevents confirmation biases. This paper examines the facility's report, addresses shortcomings in its conclusions, and goes on to detail the methods and reasoning behind the forensic team's findings. The methodology presented in this paper is applicable to a wide range of industrial electrical fires.

Keywords

Arc flash, arc blast, electrical fire, work process, confirmation bias, methodology, root cause, fishbone diagram, forensic engineering

Introduction

Electrical system failures often exhibit sudden onset, short duration, and significant destruction. Such failures may arise from a variety of causes[1,2]. Among these are vandalism, age, installation or maintenance errors, or environmental conditions. These may result in an immediate event or produce a latent precursor.

When a failure in large, high-energy electrical gear produces a robust short circuit (e.g., introducing a highly conductive object, often metallic), then phenomena known as arc flash and arc blast are almost certain to result. Briefly, arc flash with blast is an event in an electrical system that releases megajoules of power in milliseconds in the form of an intense electrical arc and attendant heat-induced blast wave[3].

Since electrical failure events accompanied by arc flash and blast tend to be spectacular, it can be easy to focus on the event itself. However, such occurrences, whether immediate or delayed, are the end state of a cascade of contributors. Forensic analysis of both the event site and/or remains — as well as organizational dynamics and work processes — requires an integrated approach to fully reveal root causes. In an operating industrial facility, there can be significant pressure to quickly clean up equipment and restore electrical service. As with most fire sites, debris and photographs of the site may be all the physical evidence available to the investigator. However, analysis of work documents and unbiased interviews of associated personnel are essential to revealing what led to the event.

Background

The client operated an industrial plant that included large rotating machines. It is common[4,5] to power high-current equipment like this at 4,160 volts three-phase to keep feeder cable size manageable. The client had such equipment in one of its buildings and wished to add power usage monitoring.

The client's engineering group produced a design for added electrical metering in the 4,160-volt secondary side of the utility transformer supplying the building. The engineers also prepared the work packages that would facilitate installation of the new electrical meters and associated components.

The client's electrical workers assembled all specified parts and materials and performed the installation across a holiday outage. At the completion of the new installation,

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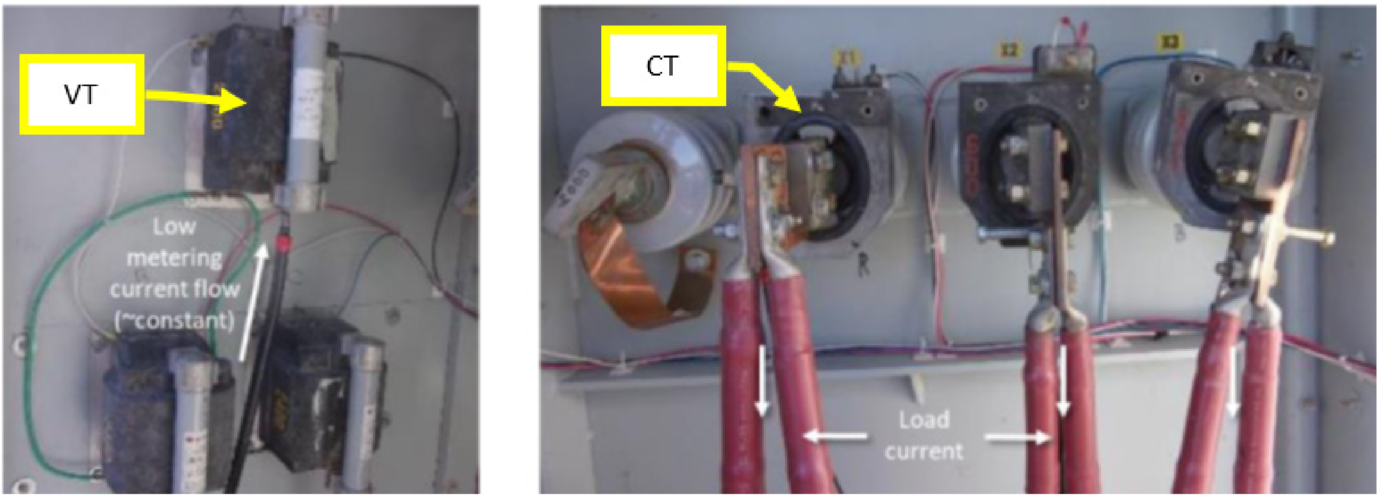

Figure 1
Newly installed VTs and CTs inside secondary compartment.

devices added to the interior of the transformer secondary compartment included three voltage transformers (VTs) on the left wall to step each of the three 4,160-volt phases down to 120 volts for connection to the power meter. Around each of three phase legs coming out of the transformer is a current transformer (CT) measuring amps and connected to the power meter. Photos of the completed installation were taken to submit with the work package completion, as shown in **Figure 1**. These images provided an important basis for comparison.

Approximately two days after installation was completed and the system was energized, a catastrophic failure occurred inside the utility transformer secondary compartment that burned wiring and damaged or destroyed components. The thermal overpressure was sufficient to blow open the locked transformer compartment doors.

Figure 2 shows the extensive heat damage to cables and equipment. The outer jackets on the large load cables were charred. Insulation on the medium-sized cables connected to the VTs was burned away in several places; one cable was missing a 12-inch section. The VTs were so damaged that all were scrapped.

Figure 3 shows the arc erosion of the large copper connector plates, erosion and melting of one cable end, and destruction of the VT "A" fuse clip. The loss of copper (erosion) at corners and edges is characteristic of arc endpoints: highly localized hot spots vaporized conductor material wherever arcs originated. Insulation in the nearby area melted due to the heat radiated from these arcs.

Figure 4 shows destruction of the "A" phase VT fuse due to textbook "arcing through char"[6,7] — a phenomenon

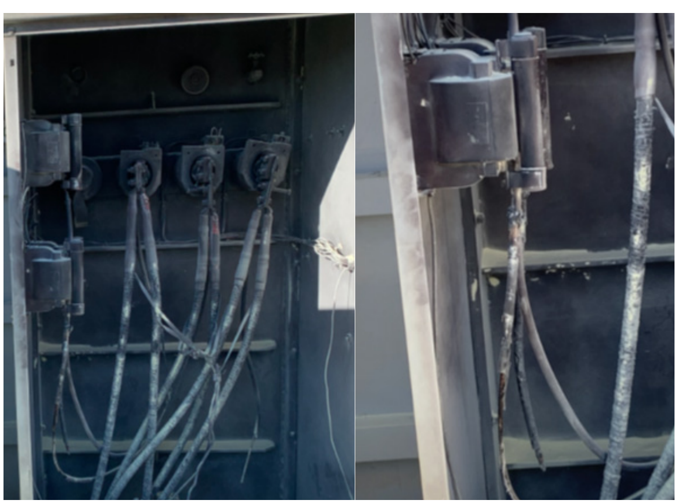

Figure 2
Post-event photos.

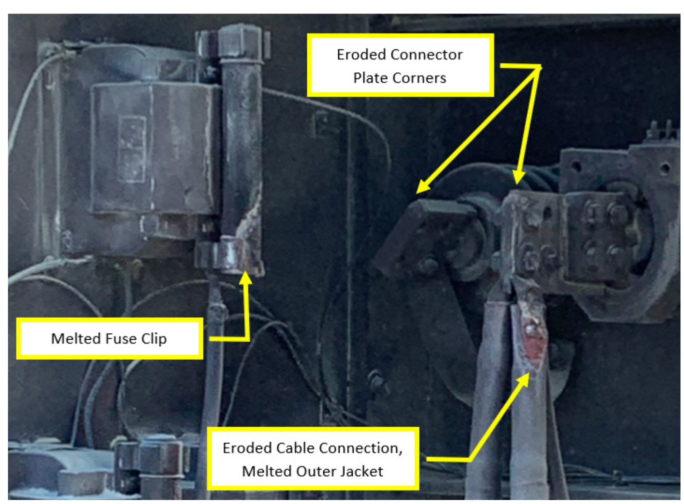

Figure 3
Arc erosion of connectors and cables.

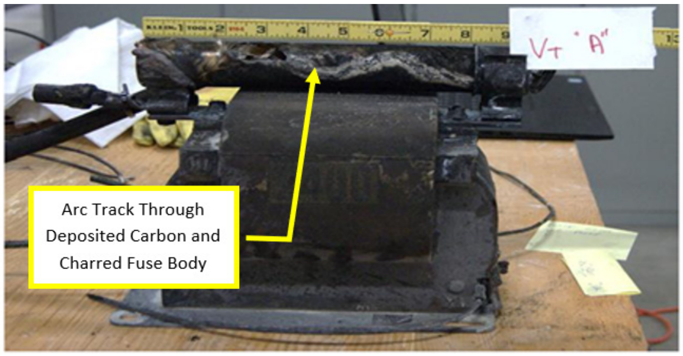

Figure 4
Post-event VT with arc tracking across destroyed fuse.

where carbonized material becomes an electrically conductive path. All these indications pointed at a powerful arc event — likely an arc flash.

Analytical Methodology

Informed by best practice (e.g., Liptai et al[8]), the independent forensic team divided the analysis of (and reporting on) the subject event into five main activities.

1. Prior to a site visit, collect and examine available documentation, client-performed analyses, and reports. Evaluate work packages and company directives. Develop a detailed timeline based on client-reported conditions supported by facts. Develop hypotheses and lines of questioning in preparation for the site visit.

2. Conduct a site visit to gather information through direct inspection of failed equipment and operating environment. Conduct interviews with managers, engineers, operators, and technicians.

3. Identify systemic contributors, such as those arising from the design, use of policies and procedures, and causes stemming from relationships between organizations. Evaluate barriers to failure that did not function as intended. Identify decision-making errors and causes arising from corporate culture. Examine how the various stakeholder organizations learn from accumulated knowledge.

4. Develop most probable cause as supported by documentation, verifiable conditions, and interviews. Conduct additional validation, including calculations, modeling, and simulations.

5. Assemble the report including recommendations.

Activity 1 — Initial Analysis

The client provided the team with all the prior root cause analysis and report materials. While this report correctly documented failures in configuration management, it fell short in lack of depth. Further, the client's investigators hypothesized a difficult-to-observe phenomenon called "circulating current" that can occur in a three-phase delta transformer secondary — the subject transformer was 34,500 volts primary and 4,160 volts secondary. This "circulating currents" condition arises from unbalanced transformer phase-to-phase loading for an extended period, resulting in winding overheating and insulation damage.

The forensic team found this conclusion flawed for two reasons: It did not explain the burned VT primary cables or the over-pressure that blew the doors open, and the transformer secondary was wye configured — not delta. Further, the client's report conclusion was not supported by reported or observed operating conditions.

Evaluation of the work packages required collecting both client's company procedures and policies as well as the work packages themselves. Organizational procedures for safety and work are the implementing documents for such standards as OSHA (29 CFR 1910 sub-parts I, R, and S)[9], NFPA 70 *National Electrical Code* (NEC)[10], and IEEE C2 *National Electrical Safety Code* (NESC)[11]. Understanding relevant standards is integral to correct evaluation of work planning based on them.

The client's electrical team kept accurate time records of activities and milestones during the installation evolution. The plant emergency responders also kept records of call-out and response times, and a report of "site secured." This aggregated information allowed the forensic team to assemble an initial timeline of activities, completion, and failure. Adding details gleaned from the utility company's supervisory control and data acquisition (SCADA) system history allowed precise determination of when the modified transformer was re-energized, the moment of failure onset, and duration of the failure event.

Activity 2 — Site Visit and Inspection

Research of work documentation and the timeline left the forensic team with questions that made a site visit necessary. After arriving at the client's plant and inspecting the restored transformer, the team divided into two task groups: evaluate debris and organize interviews.

The debris evaluation was possible because the

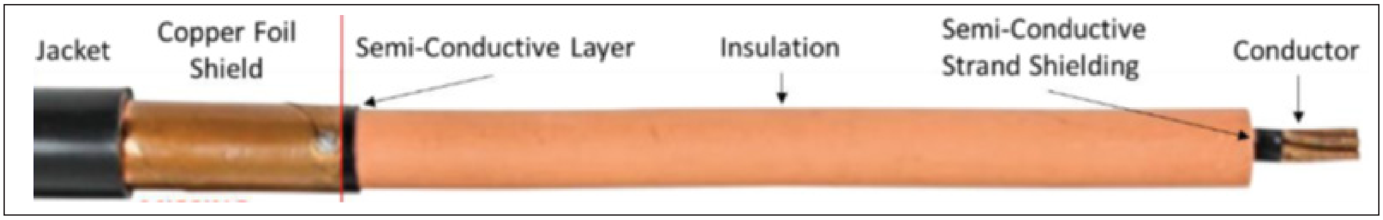

Figure 5
Medium-voltage electrical cable components.

client collected all remaining parts and pieces from the transformer secondary compartment. This included all mounting hardware and connection plates replaced as part of the restoration.

Examining Debris

The team arranged cable and component debris on a workbench. This addressed two analysis goals: understanding the relationships of failure indications (burn and melt points) and identifying the most likely point of initial failure. These, in turn, contributed to the sequence of events timeline, explaining why it took almost two days for the failure to occur.

A critical piece of information came from careful examination of the VT cables. Medium-voltage cable consists of six layers[12] (**Figure 5**): the central current-carrying conductor, a semi-conductive shield, insulation, another semi-conductive layer, a wound copper foil shield layer, and a protective outer jacket. When properly terminated and grounded, the copper foil shield equalizes the strong electric field (**Figure 6**) across the cable's insulation to prevent concentrated energy and burn-through.

Not all wiring in the compartment was burned. Some escaped damage, allowing direct examination of installed material. An example (**Figure 7**) shows the cables between utility transformer secondary and VT primaries were missing both the copper foil shield and the protective jacket.

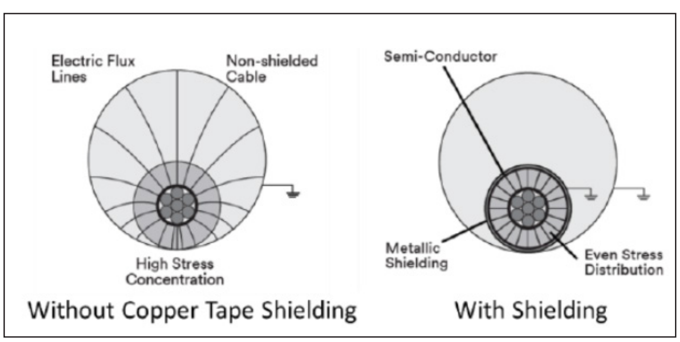

Figure 6
Electric field illustration from 3M power cable splicing and terminating guide[12].

This was evidenced by the absence of cable type identification print, the still visible "semi-conductive layer" print on this undamaged piece, and the spiral grooves showing where edges of the wound copper foil shield had been.

Using photographs of the open secondary compartment, the team used 3-point perspective[13] to create a geometric model of the compartment interior. This model revealed the cable from the transformer to the Phase "B" VT looped down and behind the others, laying against the edge of one of the transformer structural ribs or against another VT cable. Once energized, this would have allowed a concentration of electric field to produce a hot spot to form in the deficient cable, yielding burn-through and arcing. Chafing due to vibration of the unrestrained cable due to magnetic effects may have exacerbated friction erosion of the exposed semi-conductive insulation layer.

Accumulated contributors set the stage for a catastrophic arc flash involving all three transformer terminals

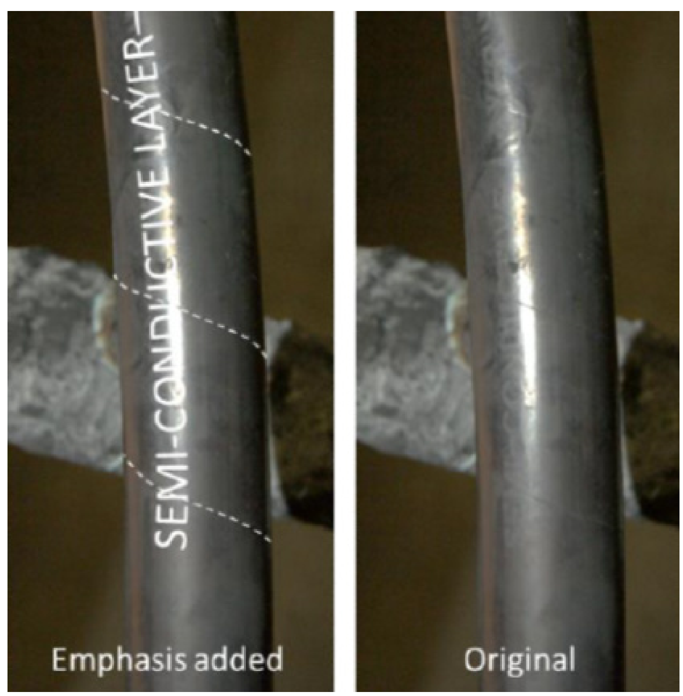

Figure 7
Faulty VT cable as installed.

and the exposed parts of the VTs. A conductive plume from the initial Phase "B" cable arc likely billowed up inside the secondary compartment. Such a plume was created around the initial arc flash (**Figure 8** event #1) when conductor material was vaporized yielding carbon from incinerated cable insulation and, more importantly, copper vapor[14,15]. The plume triggered additional arc events (**Figure 8** event #2) when convection carried metal vapor away from the initial arc flash location, dramatically increasing the conductivity of the air around the exposed transformer terminals and other equipment. But the question remained: What chain of technical and organizational precursors allowed this event to occur?

Activity 3 — Evaluate Culture and Procedures; Conduct Interviews

While the physical reconstruction of the debris was key to understanding the physics of "what" happened, careful dissection of the client's organizational dynamics was central to identifying direct causal and contributory factors explaining "why" it happened. The forensic team found several ingrained institutional issues. These issues are included in an Ishikawa "fishbone" diagram[16,17], as shown in **Figure 9** and in the details following. Out of the full set of factors identified, the items and paths highlighted in red were those the team found to be most-likely

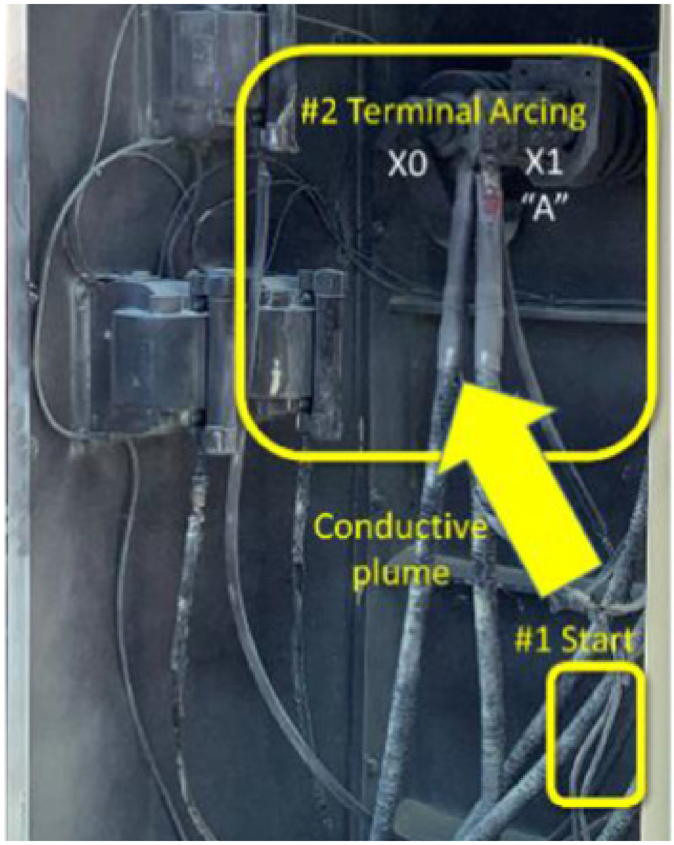

Figure 8
Arc flash propagation most-likely sequence.

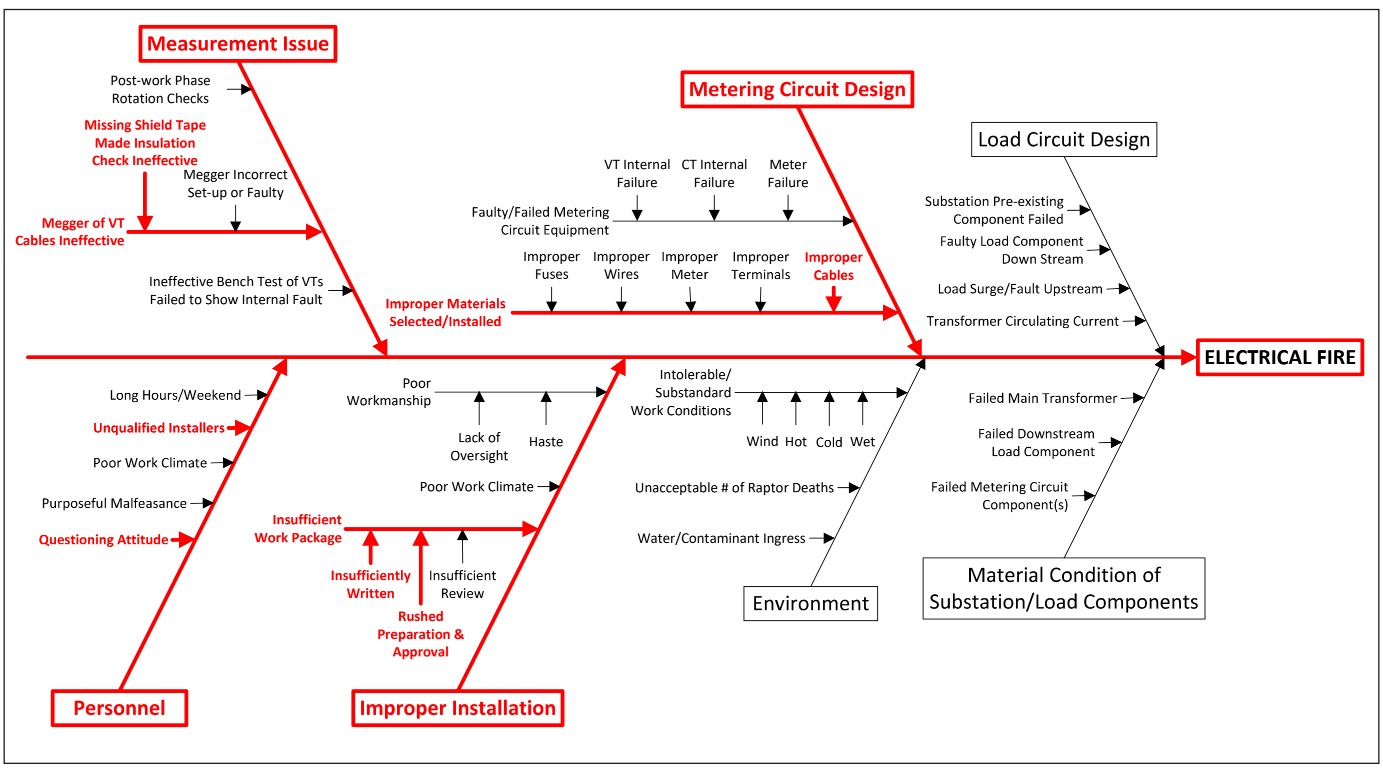

Figure 9
Ishikawa diagram.

primary contributors.

Documentation analysis and interviews revealed key missteps in the work package development and its processing.

1. The engineering team reused a previous design for a 480-volt installation, including stock details. The NEC and NESC treat systems below 1,000 volts differently from those above 1,000 volts. Design checking did not point out that the new work was for a 4,160-volt system with quite different requirements from the 480-volt example.

2. The work package itself reused the prior 480-volt material, including copying the "480V" system voltage designation. This led to the incorrect assignment of task team: In accordance with company policy and the labor agreement, industrial electricians were assigned. Had the system voltage been correctly identified, 4,160-volt qualified utility linemen would have been selected.

3. The work package was further designated "lowest level of risk" because utility workers would isolate the main service prior to work commencing. However, linemen were not on hand to confirm the transformer was de-energized. This violation of lockout/tagout protocol[18] could have resulted in the deaths of workers both because the utility crew could have incorrectly implemented the isolation, and the assigned team would not have carried appropriately rated test instruments to check the transformer's condition.

   In addition to the missing lockout/tagout documentation, the work packages also did not include the electrical hazard analysis required by NFPA 70E[18]. While the associated IEEE 1584[19] analysis results would not have informed the forensic investigation (1584 calculations do not apply to the interior of enclosed equipment), they would have been an important factor in proper safety preparations.

4. Planners scheduled the work as a sub-part of other plant utility changes during a holiday outage. Since planners believed there was adequate time, they identified the metering addition as "routine work." While the metering addition was itself believed to be minor, the overall effects of the outage were not. Planners perceived a rush to assemble work packages, and there was not adequate time allowed for travel to the job site. Even with a clear plan and careful staging of correct tools/parts, completing all installation tasks in the time allowed would have been difficult. The time pressure on the electricians led to missed or skipped inspections and verifications.

The interview team focused on three main sub-organizations: the engineers and work planners, the electrical workers, and the emergency responders. The team conducted interviews in group settings and took great care to establish a cooperative and non-confrontational atmosphere. The interview with the electricians showed this group to be professional, dedicated, and safety conscious. However, their responses brought to light several organizational weaknesses:

1. Questioning Attitude — Through the course of this investigation, it was apparent important questions went unanswered, and assumptions went unchallenged. The design relied heavily on examples and stock details — why wasn't there a tailored design drawing? The work package said "480V," but the task was on a 4,160-volt system — nobody pointed out the difference and stopped work. Had anyone checked the parts and materials provided? Why didn't the electricians insist on lockout/tagout paperwork?

2. Skills and Qualifications — The assigned electricians were not familiar with the properties of, or termination methods appropriate for, 4,160-volt cable. The electrical team foreman was responsible for kitting materials and parts. This is the person who selected the piece of sub-standard cable for connecting the VTs. How was someone clearly unfamiliar with the properties of 4,160-volt cable qualified to make this selection? The history of the deficient cable was completely unknown — how was scrap material allowed to remain in working stock, and how many months or years had it been in the outdoor storage yard?

3. Codes and Standards Compliance — The cable material used for the VT connections was altered from its manufactured form and did not meet installation requirements of NEC Article 311[10]. The altered and deficient nature, and unverifiable provenance, of the cable material also violated

several requirements of 29 CFR 1910.399[9].

The interview with the first response team served to narrow the field of possible causal contributors. The fire fighters had experience with previous electrical events and knew to capture information the forensic team would need, including:

- The transformer doors were open when they arrived, with the latch arms bent. This revealed a significant blast over-pressure inside the secondary compartment.

- There was no evidence of animal involvement. Animals crawling or landing on high-voltage equipment can cause an arc flash. That was not what happened in this case.

- There was minor flaming that they extinguished with dry chemical. The large load cables were just charred rather than consumed. This belied a short-duration event like arc flash rather than a prolonged fire.

Activity 5 — Report and Recommendations

The team prepared and presented a report that described all aspects of data collection, analysis, and conclusions. This report included recommendations for process and procedure improvements that would help the client avoid the cascade of avoidable errors that led to the investigated failure.

Summary

Electricity is not readily observable and often considered mysterious. Therefore, when a failure occurs, initial assessment may ascribe the event to equally mysterious or unobservable phenomena. To avoid succumbing to these biases, forensic analysis of an electrical system failure must be planned and systematic. It must include both a technical reconstruction of the physical events and a comprehensive examination of organizational and work-related climate, procedures, and processes.

In this investigation, the team organized work into five main tasks: initial research and analysis, site visit to perform reconstruction and interviews, thorough evaluation of interview results and correlation to research knowledge, aligning measured facts and data with knowledge of the physics and with organizational contributors to develop a most likely sequence of events, and preparation of the final report.

Conclusion

This investigation demonstrated the validity of the methodology for planning and conducting a forensic analysis of an electrical arc flash event even when the only available physical evidence from the site was debris and photographs. By staying focused on engineering principles supported by defensible facts that explained all the observed conditions, the team avoided the pitfalls of confirmation bias or rushing-to-judgement and agreeing with the results of an inadequate initial analysis.

This fundamental methodology can be applied to a variety of electrical failure and fire investigations. It is based on the understandings that “electricity is governed by physics, not magic” and “human behavior can be understood.” It allows a forensic investigator to approach electrical events with the confidence that underlying causes and contributors are discoverable. Sometimes these precursors may have occurred in the unknown past and have little initially apparent connection to the final failure.

Acknowledgements

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