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Superdome Partial Power Outage

Report prepared for:

Entergy New Orleans, Inc.
SMG
Louisiana Stadium and Exposition District

By:
John A. Palmer, Ph.D., P.E., C.F.E.I.
3/21/2013

As requested, this engineer has investigated the partial power outage incident that occurred on February 3, 2013 at the Superdome in New Orleans, Louisiana, interrupting play during the second half of the Super Bowl. This report presents this engineer's preliminary findings and opinions developed in the course of the investigation.

PO Box 908, Kaysville, UT 84037 Office: 801-682-8456 Fax: 801-315-7802 www.PE4n6.com

Background: During the evening of February 3, 2013, play of Super Bowl XLVII between the San Francisco 49ers and the Baltimore Ravens was interrupted during the third quarter for approximately 34 minutes due to a partial loss of electrical power. At the time of the power loss, the electrical load (current) was rebounding after a significant reduction during the half-time show (see Figure 1). Current levels had just exceeded highs encountered during the second quarter, prior to the half-time show, when a switch on the 13.8 kV system opened, disconnecting the west feeder between the utility, Entergy New Orleans Inc (ENOI), and the Superdome.[1] Due to the advanced planning and preparations by the utility and the Superdome electrical personnel, the switch that had operated was bypassed and power to the Superdome restored in approximately 12 minutes. Over the next 22 minutes, the Superdome proceeded through the electrical power system start-up sequence and the lights warmed up before play was resumed.

During the year prior to the Super Bowl, ENOI implemented a number of significant design improvements with the intent of reinforcing system reliability. The modifications included construction of a new vault, identified as Vault 24, to contain a number of motorized load interrupter switches and manual disconnect switches needed to facilitate connection of the loads to appropriate feeders. The modification also included introduction of a tertiary backup feeder to supplement the primary and secondary sources that were already available. The arrangement of the switches and buses in the vault allowed for energization of loads by any of the three sources through automatic switches or for manual bypass around the automatic switches.

Purpose: The purpose of the investigation was to determine the cause of the partial power outage.

Procedure: On February 28, 2013, this engineer conducted a preliminary inspection of the ENOI Vault 24. Available evidence was photographed and documented. A second inspection including relay testing, which was coordinated with S&C Electric Company (S&C), in Vault 24 was carried out on March 1, 2013. Provided documents and other information were reviewed as listed in Appendix A.

Findings and Discussion:

SYSTEM DESCRIPTION. The utility electric power supply to the Superdome is through a primary 24 kV distribution feeder (1508), stepped down by a pair of paralleled three-phase 24/13.8 kV step-down transformers at the location of Vault 24 to a nominal customer voltage of 13.8 kV. Secondary (1505) and Tertiary (2021) backup feeders are also stepped down through dedicated step-down transformers and brought into the Vault at 13.8 kV. Feeders 1505 and 2021 are

[1] The total current being supplied to the Superdome was approaching the 2nd quarter peak, but the current through the feeder that tripped out was higher than the 2nd quarter peak.

each configured to be connected on an automatic basis through normally-open motorized load interrupter switches to a common bus within the Vault 24 switchgear, in the event of a loss of feeder 1508. As the primary supply, Feeder 1508 is connected to the switchgear common bus through a normally closed switch.

Power is normally delivered from the common bus in Vault 24 to the customer (the Superdome) through two feeders tied into Bay 7 and Bay 8 of the switchgear lineup (see Figure 2). The Bay 7 feeder was identified as the East feeder to the Superdome and the Bay 8 feeder was identified as the West feeder. Each stadium feeder was connected through a motorized load interrupter switch and a set of fuses. The switch in each bay was connected to an S&C ZSD relay so that the ZSD relay could initiate opening of the respective switch. During the Super Bowl, the Bay 8 switch opened, resulting in a loss of power to the West feeder and thence to the west side of the Superdome.

ZSD RELAY. The relays in Bay 7 and Bay 8 were Type ZSD relays, catalog number 38930R1-D, manufactured by S&C Electric Company, supplied with the switchgear lineup installed in 2012 (see Figure 3). The ZSD relay has been in production by S&C since the early 1990s and was recommended to ENOI personnel during the Vault 24 design improvement for the specific application. The description of the relay in the instruction manual is as follows:

> The S&C Overcurrent Relay-Type ZSD is designed for application in S&C Metal-Enclosed Gear rated 4.16 kv through 34.5 kv. It is typically applied on three-phase circuits in conjunction with a switch-operator-driven S&C Mini-Rupter Switch or Alduti-Rupter Switch and S&C Closed-Gap Current Sensors, which sense the current in each phase of the circuit. The Type ZSD Overcurrent Relay will trip the switch operator to open the interrupter switch-and thus achieve three-phase isolation of the circuit-after a fault downstream of the current sensors has been cleared by a protective device.[2]

The relay receives current information from current sensors associated with the electrical conductors on the circuits being protected. In this specific application, two sensors were applied per phase to account for two parallel cable runs from the switchgear to the stadium. The relay has two user adjustable settings: the trip level (also known as the pickup) and the elapsed time. The operation of the relay, according to the instruction manual, is as follows: When the relay detects a current monitored by the current sensors in excess of the trip setting (for more than 2 milliseconds), the relay "arms," and the timer begins. If "normal current" resumes (defined in the instruction manual as 3.5 A or greater) before the time delay set on the timer has elapsed, the relay will reset and no switch operation is initiated. If the current drops to zero on any one phase while the relay is armed, the relay will operate and cause the switch to open. A blocking circuit is implemented in the relay so that if the current on any phase

[2] S&C Overcurrent Relay-Type ZSD Instructions for Operation and Adjustment, p. 1.

remains above the trip setting for longer than the time delay setting, the relay will not operate to open the switch until after all phase currents drop below the trip setting (or 600 A, whichever is lower).[3]

Reportedly, the primary purpose of the relay, as described by S&C personnel (consistent with the manual excerpt given above) was to protect against the negative impact of a single phase condition in the event that a fault on one of the feeders should cause a fuse to interrupt the circuit. The fuses on each of the two feeders consisted of parallel 800 A fuses, so that the fuse operation should be anticipated for fault currents in excess of 1600 A. Given the fault current conditions that would most likely create the single-phase condition against which the ZSD was intended to protect (i.e. a fault current high enough to open a fuse), a trip setting of 1600 A would have been more appropriate than the 400 A setting that was used for the relays in both Bay 7 and Bay 8. Nevertheless, reportedly, when the relay was tested subsequent to the outage, S&C personnel stated that the trip of the relay while the current was increasing in proximity to the trip setting should not happen.[4] The expected behavior as reportedly described by S&C personnel who were present for the evaluation immediately after the incident was that the relay would pickup when the current reached the pickup setting, but would not trip unless one of the phase currents went to zero. The manual indicates that

> "The Type ZSD Overcurrent Relay is superior to ordinary overcurrent relays in that it can distinguish between fault current and transformer inrush current. After an overcurrent condition is sensed, the Type ZSD Overcurrent Relay determines whether normal load current returns on all three phases; in instances where normal load current does return on all three phases, no trip signal is sent to the switch operator."[5]

The only definition provided in the manual of "normal load current" is "3.5 amps or greater."[6] Based on this description, no trip should occur unless the current on one or more phases drops below 3.5 amps.

During the testing, behavior of the relay was not entirely consistent with the function described in the instruction manual. Under some circumstances, when the current exceeded the trip setting and then decreased below the trip setting even after the timer had expired, the relay did not operate. In other circumstances, when the current exceeded the trip setting, the relay would operate while the current remained above the trip setting. This inconsistency was apparently due to some conflict between the pickup circuit and the blocking circuit, which is to say that it was a previously unreported instability inherent to the design of the relay. During further testing, it was found that operation above a trip setting of 600 A provided more

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[3] Summarized from ZSD Instructions, pp 2-3, and from United States Patent Overcurrent Protection Device Patent Number 5,170,31

[4] "Super Bowl Power Outage Investigative Report Preliminary" by F.M. Brooks dated February 26, 2013, p. 5

[5] ZSD Instructions, p. 2.

[6] ZSD Instructions, p. 2.

consistent operation as the blocking circuit setpoint was substantially different from the trip setting. This instability was observed on all of the relays tested (during testing by this engineer, ENOI, and others in coordination with S&C at Vault 24 on March 1, 2013), including the subject (Bay 8) relay and two identical (exemplar) relays. Behavior of the device in a manner contrary to the published functionality of the device constitutes a design defect.

INCIDENT DESCRIPTION. During the Super Bowl, current through the feeders 1508 and 1505 was monitored at the 24 kV level with data recorded every minute. This data is charted in Figure 1.[7] In addition, current was reportedly measured from time to time by Stadium personnel for their two 13.8 kV feeders. This data is illustrated in Figure 4.[8] Both data sources indicate that after a temporary reduction in load from approximately 7:00-7:30 corresponding to the extinguishment of the lights during the half-time show, load increased substantially. The load rose quickly, as expected, peaking on the west feeder at a little less than 400 A before the relay in Bay 8 misoperated (tripped), causing the switch to open, deenergizing the west feeder. The current on the East feeder was never measured to be as high as the current in the West feeder.

Based on testing and observations performed after the incident, the subject relay was determined to be set at the time of the incident to approximately 400 A pickup current with a 2 second time delay (later identified as the factory default settings). As the current rose to the pickup setting, the relay armed. After the 2 second time delay, because of the design defect of the relay manifest as an instability as described above, the relay tripped even though none of the phase currents had dropped below 3.5 A, causing the switch to open, initiating the power outage. Tripping of the relay in the absence of any fault or undesirable operating condition constitutes a relay misoperation. Thus a relay misoperation was the cause of the partial power outage.

The misoperation of the relay occurred because the relay had a previously unreported instability in the range of the pickup setting and the pickup setting was in the range of normal operating conditions. Had the relay pickup setting been in excess of the maximum load current anticipated, the misoperation would not have occurred. Thus an inappropriate pickup setting was a contributing factor to the relay misoperation.

Reportedly, at the time of the incident, ENOI and Stadium personnel were unclear about the cause of the outage. Because of concerns about the possibility of closing a circuit breaker onto a faulted cable, the decision was made not to close the tie between the east and west stadium buses and feed the entire stadium through the East feeder. Rather, the existing bypass arrangement was utilized to supply the West Feeder from the 1505 secondary backup source. Evaluating the situation and executing the switching sequence required approximately 12

[7] Plotted from SCADA data for Feeders 1508 and 1505 consisting of voltage and current measurements at a 60 second capture rate from 10:00 a.m. to 10:00 p.m.
[8] Plotted from data provided in Appendix 2 and Appendix 3 of the Brooks Report

minutes, after which the Stadium executed their power-up sequence to restore power to the west side of the stadium. Had the entire load been applied to the East feeder, there is a significant probability that the Bay 7 relay (which was determined to have the same settings as the Bay 8 relay) would have operated and deenergized the East feeder due to the same relay instability condition which would have been encountered as the stadium was powered back up.

COMMUNICATION ISSUES. When the equipment was being purchased, ENOI sent an inquiry to S&C regarding how to protect against the possibility that a fault on one cable would cause a fuse to open resulting in a single-phase condition at the customer bus: "In reference to the communication option of the switch gear -- is there a way for us to know if the Fault Fiters [fuses] dropped out other than the customer experiencing an outage and calling ENOI?"[9] The ZSD relay was the manufacturer's recommendation to address the concern: "if one or three fuses blew, then the relay would signal to the motor operator to open the blades. The contacts would be wired to the customer's RTU to send a signal to their Distribution Operations Center to let them know the motor had opened the blades."[10] Nevertheless, communications provided to this engineer for review did not describe the operation of the ZSD relay or indicate that other things besides a blown fuse might result in the relay tripping. The manual's description of the operation is confusing and ambiguous, and gives little guidance with regard to setting the relay:

> Adjust the 400- to 2400-ampere trip-level detector for the level of phase current above which the Type ZSD Overcurrent Relay is to respond. This setting should be high enough to preclude nuisance trippings.[11]

Thus, without making reference to normal load current, the instructions are ambiguous about the appropriate trip-level setting for the relay. The manual provides no context to indicate what current settings would lead to nuisance tripping. In fact, to function consistent with the intent described in the above-referenced communication, the most reasonable setting would be approximately equal to the fuse rating. Yet, this was not communicated to the end user in the manual or other written communications, and the manual suggests that no trip will occur unless one or more of the phase currents drops to below 3.5 A.

Instead, the manufacturer supplied and installed the ZSD relays with their factory default settings (400 A pickup and 2 second delay) together with the fuses (combined rating of 1600 A) that were intended to protect the same circuits, without setting the ZSD relays to a setting compatible with the fuses. Furthermore, S&C assisted in the sizing of the Fault Fiter fuses in the

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[9] Email from Chung Hui to Chuck Ball dated July 14, 2011, in Email String "Monday am Superdome MESG Metal Plate over S&C Switch Gear" concluding with email from Jim Bishop to Shelby Grosz dated 7/19/11
[10] Email from Jim Bishop to Ed Steppan dated July 15, 2011 in Email String ending 7/19/11
[11] ZSD Instructions, p. 6

context of a protection coordination study, with which they also assisted.[12] The assistance with fuse sizing was subsequent to the decision to include the ZSD relay in the switchgear, yet no direction, suggestion, or comment was given to prompt ENOI to modify the relay settings to other than factory default values. Finally, after installation, ENOI contracted with S&C to send a technician to Vault 24 after the completion of construction and installation to check out and commission the switchgear lineup and provide training. The S&C technician apparently did not modify the ZSD relay settings, or indicate to any ENOI personnel that the settings needed to be modified or validated. Even after the incident, the S&C technicians who were present in the first inspections did not criticize the setting of the relay as improper, even though the load currents were known to have been on the same order of magnitude as the relay pickup setting. After the unexpected behavior of the relay, S&C personnel asserted that the relay setting was improper and should have been adjusted after installation by ENOI personnel.

<u>Conclusion:</u> Based on this engineer's training, education, experience, and available evidence, in the context of the investigation that was performed, this engineer has developed the following conclusions to a reasonable degree of engineering certainty:

1. The cause of the power outage was a misoperation of the relay.
2. A contributing factor to the misoperation of the relay was the unstable operating condition of the relay around the setpoint of the subject relay due to a design defect.
3. A contributing factor of the outage was the inappropriate current trip level setting of the relay, which was the factory default value.
4. A contributing factor to the inappropriate setting was inadequate communication between the manufacturer and the utility.

The opinions and conclusions expressed in this report are based on the information available to the engineer as of the date of this report. If additional information becomes available that affects these opinions and conclusions, this engineer reserves the right to supplement this report.

Palmer Engineering and Forensics, LLC.

John A. Palmer, PhD., P.E., C.F.E.I.
President

PROFESSIONAL ENGINEER
No. 7390658-2202
JOHN A. PALMER
3/21/2013
STATE OF UTAH

John A. Palmer, Ph.D, P.E., C.F.E.I.
I am the author of this document
Kaysville, Utah
2013.03.21 12:48:31 -06'00'

[12] Email String "RE: Superdome" concluding with email from Chuck Ball to Keith Kliebert dated 3/14/2012.

Appendix A: Provided Documents Reviewed

Documents

- S&C Overcurrent Relay-Type ZSD Instructions for Operation and Adjustment
- United States Patent Overcurrent Protection Device Patent Number 5,170,311
- S&C Overcurrent Relay-Type ZSD Photo Sheet 551-700
- Field notes and switching orders by ENOI personnel
- "Super Bowl Power Outage Investigative Report Preliminary" by F.M. Brooks dated February 26, 2013
- SCADA data for Feeders 1508 and 1505 consisting of voltage and current measurements at a 60 second capture rate from 10:00 a.m. to 10:00 p.m.

Drawings

- "S&C Arc-Resistant Metal-Enclosed Switchgear 13.8 kV 8 Bays Outdoor" by S&C Electric Company (10 Sheets)
- "Detail Wiring Diagram For Remote Control Box QCMA-13900" by S&C Electric Company
- "Control Cabinet for Remote Operation" by S&C Electric Company
- "System Diagram Two-Micro-AT/Three Source Transfer Scheme (Sources may be paralleled) for CDA-832922 with remote control box (QCMA-13900)" by S&C Electric Company (5 sheets)
- "Interconnection Wiring Diagram Two-Micro-AT/Three-Source Transfer Scheme (Sources may be paralleled) for CDA-832922 with remote control box (QCMA-13900)" by S&C Electric Company (8 sheets)
- "S&C Switch Operator Type AS-30 Schematic Wiring Diagram" by S&C Electric Company
- "S&C Switch Operator Type AS-30 Detailed Wiring Diagram" by S&C Electric Company
- "Derbigny 230 kV Substation Station Oneline" by Entergy New Orleans, Inc. (2 sheets)
- "Joliet 230 kV Substation Station Oneline" by Entergy New Orleans, Inc. (2 sheets)
- "Superdome Switching Vault: Primary Cable One-Line" by Entergy
- "Entergy Superdome Protection Coordination Curves" by Entergy Services, Inc.

Email Communications

- Email string "RE: Entergy/Superdome S&C Switchgear - Lockout Reset Feature" concluding with email from Keith Kliebert to Shelby Grosz dated 7/26/2012
- Email string " RE: Fault Fiter Fuses for Superdome" concluding with email from Jim Bishop to Shelby Grosz dated 3/19/2012
- Email string " FW: Field Service quote for Entergy (New MESG at the Superdome)" concluding with email from Jim Bishop to Shelby Grosz dated 7/20/2011
- Email String "RE: Superdome" concluding with email from Chuck Ball to Keith Kliebert dated 3/14/2012

- Email String "Monday am Superdome MESG Metal Plate over S&C Switch Gear" concluding with email from Jim Bishop to Shelby Grosz dated 7/19/11

Appendix B: Figures

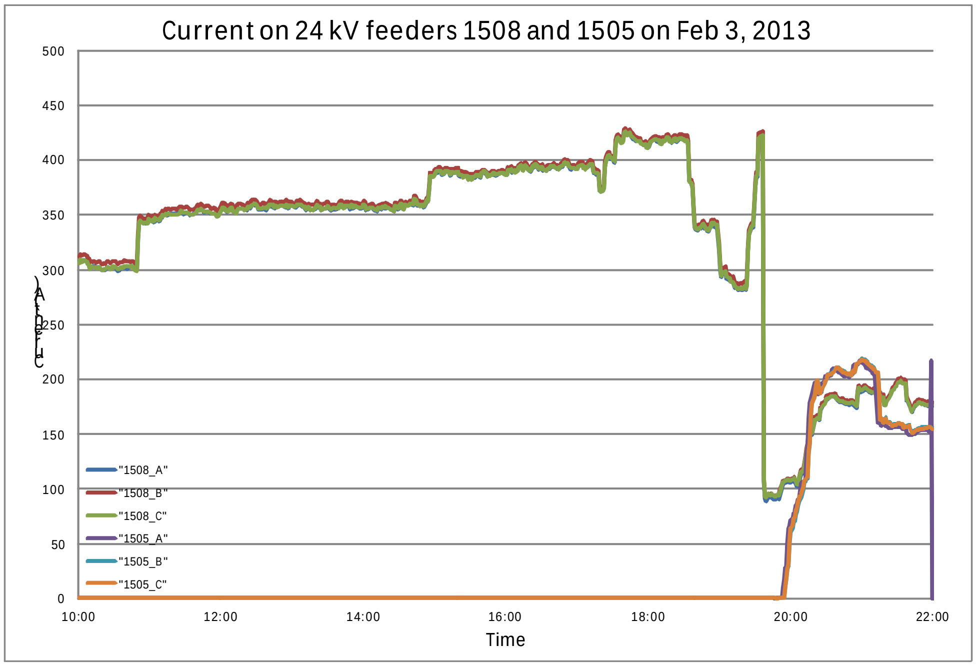

Figure 1: Plot of current in the 24 kV Entergy feeders supplying power to the Superdome. Partial loss of power occurred at 7:37 p.m.

Figure 2: Bay 7 (center) and Bay 8 (right) of the Vault 24 switchgear lineup.

Figure 3: Photograph of subject relay from Bay 8 during bench testing after the outage.

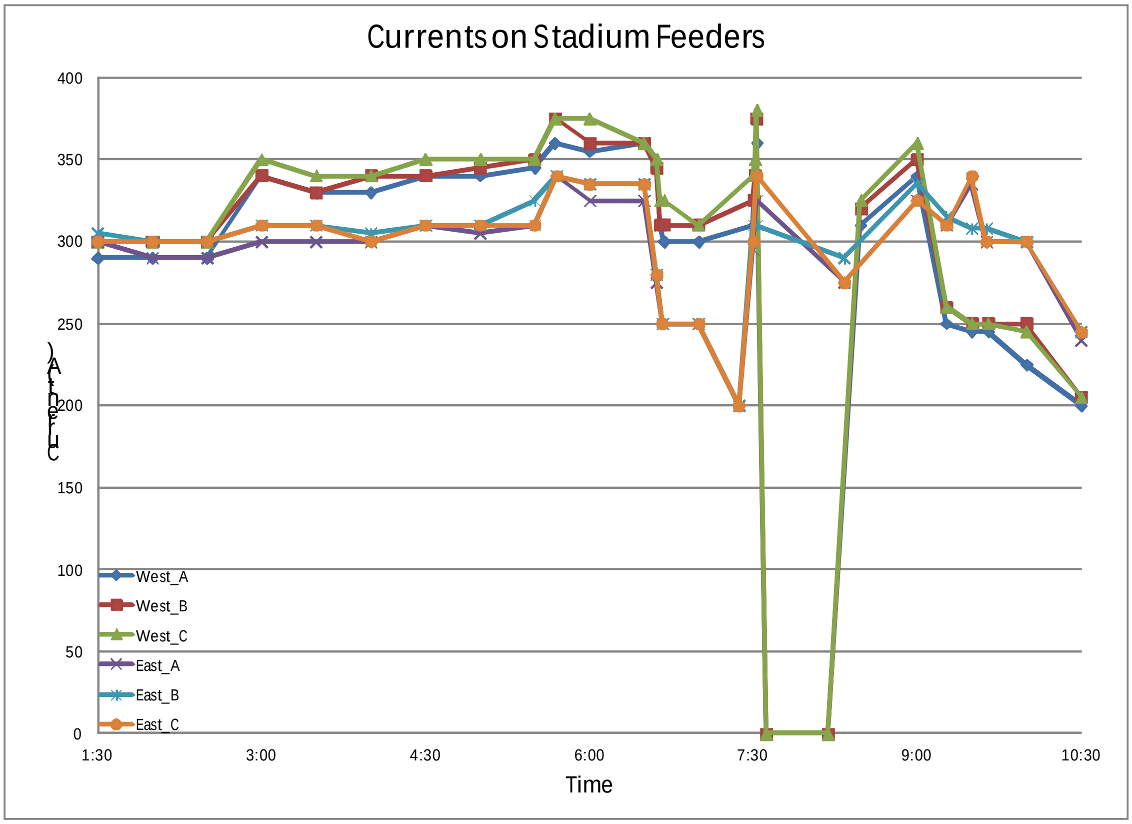

Figure 4: Graph of currents on east and west feeders to Stadium.

Appendix C: Credentials

Curriculum Vitae

PALMER
ENGINEERING & FORENSICS
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Curriculum Vitae of

JOHN A. PALMER, PH.D., P.E., C.F.E.I.

P.O. Box 908
Kaysville, UT 84037
(o) (801) 682-8456
(c) (801) 682-6732
(e) japalmer@PE4n6.com

SYNOPSIS

Dr. Palmer has extensive experience in cause and origin analysis of electrical accidents, electrical equipment failures, electrical fires, structural fires, vehicle fires, and explosions. He also performs product testing and design review. He has consulted on cases involving industrial processes, electric machinery and systems, elevators, consumer electronics, control systems, electric shock and electrocution. Dr. Palmer's education and research experience includes a vast array of aspects relating to electrical engineering, electric power, control systems, and electromechanical systems. An area of particular emphasis throughout his career has been his focus on electric power equipment, including transformers and electric machines and drives. He has conducted power system fault studies, protective device coordination, and load flow studies. Dr. Palmer's extensive experience includes electro-magnetic fields and high-voltage systems. His responsibilities and research often include working with thermodynamics, fluid dynamics and liquid dielectrics. Career research projects include: analytical and computational assessment of overheating of pipe-type underground cables; experimental, analytical and computational assessment of static electricity problems in large power transformers; modeling of pulsed linear induction motors; distributed generation; and optical and ultrasonic diagnostic and monitoring tools for power equipment. Dr. Palmer's research has led to the development of a controller device for a power transformer cooling system, resulting in a patent. In addition, he has taught principles of electromechanical energy conversion, power systems, power electronics and power quality. He has authored over twenty journal and conference publications.

EDUCATION

Rensselaer Polytechnic Institute

Ph.D. Electric Power Engineering — 1996

Thesis: Dynamics of Streaming Electrification in Large Power Transformers

M.Eng. Electric Power Engineering — 1992

Thesis: Effect of Harmonics on Current Carrying Capacity of HPFF Cable

Brigham Young University

B.S. Electrical Engineering — 1991

Power Emphasis, Math Minor

REGISTRATION

Registered Professional Engineer in Utah, Colorado, Alabama, Wyoming, Florida and Arizona
Certified Fire and Explosion Investigator (NAFI)

EXPERIENCE

Palmer Engineering and Forensics, LLC, Kaysville, Utah
President 2009 – Pres

University of Utah, Salt Lake City, Utah
Adjunct Instructor – Electrical Engineering Department 2011-Pres

Knott Laboratory, LLC, Centennial, Colorado
Manager, Electrical Engineering and Fire Investigations 2005 - 2009
Senior Engineer 2000- 2005

University of Colorado Denver, Denver, Colorado
Adjunct Instructor – Electrical Engineering Department 2006-2008

Colorado School of Mines, Golden, Colorado
Assistant Professor – Division of Engineering/Center for Adv. Ctrl of Elec Pow Systems 1996-2000

NEI Electric Power Engineering, Inc., Arvada, Colorado,
Consulting Engineer 1999-2000

Rensselaer Polytechnic Institute, Troy, New York
Research Assistant 1991-1996

EXPERT TESTIMONY

Dr. Palmer has provided expert testimony in various jurisdictions across the country. He has been qualified as an expert witness and has provided litigation support in cases involving personal injury, product defects, intellectual property, and class action lawsuits.

PROFESSIONAL AFFILIATIONS

Dr. Palmer is a member of the following technical and professional societies:

- NSPE - National Society of Professional Engineers
- NAFI - National Association of Fire Investigators
- NFPA - National Fire Protection Association
- ASME - American Society of Mechanical Engineers
- NAFE – National Academy of Forensic Engineers
- IEEE - Institute of Electrical and Electronics Engineers
  - Industrial Application Society
  - Power Engineering Society
  - Dielectrics and Electrical Insulation Society