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Forensic Engineering Analysis of a Sequence of Power Infrastructure Failures Atop an Office Building

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Abstract

A series of equipment failures occurred in a high-rise office building in Puerto Rico. The top 18th floor was occupied by the infrastructure systems of the building to include heating, air conditioning, electrical and plumbing systems, and two 1,500kVA emergency generators that provided power for the entire building when the utility power was not available. The first failure occurred within a 3,000kVA, 13.8kV/480-277VAC stepdown power transformer on a Sunday night — a day after the annual maintenance of the electrical equipment took place. The failure of this transformer resulted in the operation of the two emergency generators — last maintained a month earlier. The second failure occurred in one of the two control panels associated with the fuel day tanks for the emergency generators due to power disturbances (harmonics) in the electrical distribution system in the building. This resulted in an overflow of fuel oil in one of the day tanks (615 gallons) and the spill of approximately 1,000 gallons of fuel oil on the 18th floor and lower floors (including the cellar).

Keywords

Forensic engineering, transformer, generator, harmonics, controls, distribution

Definitions

Real power in an electric circuit is the rate of flow of energy past a given point of the circuit. In a simple alternating current (AC) circuit (consisting of a source and a linear load), both the current and voltage are sinusoidal. If the load is purely resistive, the two quantities reverse their polarity at the same time. The units of real power are measured in watts.

Reactive power in a simple AC circuit is when energy storage elements, such as inductors and capacitors, may result in periodic reversals of the direction of energy flow. The portion of power due to stored energy, which returns to the source in each cycle, is known as reactive power. The units of reactive power are measured in VARs.

Power factor of an AC electrical power system is defined as the ratio of the real power flowing to the load to the reactive power in the circuit. Power factor is measured as a percentage.

Fundamental frequency, often referred to simply as the fundamental, is defined as the lowest frequency of a periodic waverform. In a simple AC circuit, such as the electrical power system in the United States, this is 60 Hertz (cycles per second).

Power quality determines the fitness of electric power for use with consumer devices. Synchronization of the voltage frequency and phase allows electrical systems to function in their intended manner without significant loss of performance or life. The term is used to describe electric power that drives an electrical load and the load's ability to function properly. Without the proper power, an electrical device (or load) may malfunction, fail prematurely, or not operate at all.

Harmonic voltages and currents in an electric power system are a result of non-linear electric loads. Harmonic frequencies in the power grid are a frequent cause of power quality problems. Harmonics in power systems can result in increased heating in the equipment and conductors, misfiring in variable-speed drives, and torque pulsations in motors. Reduction of harmonics is considered desirable. Harmonics are AC voltages and currents with frequencies that are integer multiples of the fundamental frequency. On a 60-Hz system, this could include 2nd order harmonics (120 Hz), 3rd order

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harmonics (180 Hz), 4th order harmonics (240 Hz), and so on. Normally, only odd-order harmonics (3rd, 5th, 7th, 9th) occur on a 3-phase power system.

Current harmonics: In a normal alternating current power system, the current varies sinusoidally at a specific frequency, usually 60 Hz in the United States. When a linear electrical load is connected to the system, it draws a sinusoidal current at the same frequency as the voltage (though usually not in phase with the voltage). Current harmonics are caused by non-linear loads. When a non-linear load, such as a capacitor or an inductor (motor), is connected to the system, it draws a current that is not necessarily sinusoidal.

Voltage harmonics are mostly caused by current harmonics. The voltage provided by the voltage source will be distorted by current harmonics due to source impedance. If the source impedance of the voltage source is small, current harmonics will cause only small voltage harmonics.

Introduction

A high-rise office building located in the business district of San Juan, Puerto Rico was in operation for several years at the time of the event. The first 17 floors were occupied by private institutions, and the 18th floor was dedicated for the infrastructure systems of the building to include heating, air conditioning, electrical, and plumbing systems. In addition, two 1,500kVA emergency generators (A and B emergency generators) were located on the 18th floor, providing electrical power for the entire building when utility power was not available.

The annual electrical maintenance of the electrical equipment was part of the building's preventive maintenance program[1,2,3], and it occurred Saturday, February 9, 2008. The electrical maintenance required a complete shutdown of the electrical power system, including shutting down the operation of the two emergency generators. The electrical maintenance that took place included infrared surveys of the electrical distribution system, which took approximately 8 hours. Around 4 p.m., the electrical maintenance was completed — at which time the utility power was restored to the building.

A security guard reported that the two 1,500kVA emergency generators began to operate on Sunday, February 10, 2008 around 10 a.m. At the time, the security guard (under the direction of the building engineer) contacted the local utility to inquire if a power outage in the business district had occurred. When the security guard learned that a power outage had not occurred, he advised the building engineer, who returned to the building to ensure all electrical systems in the building were operating properly.

When the building engineer arrived at the building, he noticed that the emergency generators were still operating; however, he was not alarmed because the generators were capable of providing the necessary electrical power for the building. However, upon further investigation with the utility personnel, they discovered that the 3,000kVA, 13.2kV-480/277 VAC stepdown transformer in the building had failed. This was why the emergency generators had operated since Sunday around 10 a.m.

On February 11, 2008 the building engineer made the necessary arrangements for the evaluation of the 13.2kV-480/277 VAC stepdown transformer failure and to obtain a replacement unit. In addition, he called the maintenance company for the emergency generators to verify that the units would be able to operate continuously for the next few days, which was confirmed by the maintenance company.

A security guard noticed an overflow in the fuel day tanks on the 18th floor on February 12, 2008 at approximately 1 a.m., and he immediately called the building engineer. When the building engineer and his assistant arrived at the building, they discovered a malfunction of the "A" fuel day tank control panel, since all the lights in the control panel were illuminated. The malfunction was determined by the fact that the low- and high-level alarm lights were illuminated, which could not occur under normal conditions. They immediately isolated the fuel line from the "A" fuel day tank using the manual valves and began to recover the spilled fuel from the surroundings.

As a result of the malfunction of the "A" fuel day tank control panel, the building engineer contacted the maintenance company for the emergency generator and requested that it investigate the failure and repair this unit. When personnel from the maintenance company arrived, they confirmed the malfunction of the "A" fuel day tank control panel and proceeded to replace the failed unit as well as the "B" fuel day tank control panel as requested by the building engineer.

The failure of the "A" day tank control panel resulted in the spill of approximately 1,000 gallons on the 18th floor and lower floors, including the cellar. Based on this, the building was vacated for approximately four months until the decontamination and repairs took place.

As a result of the equipment failures and fuel oil spill, the building owner filed a claim with his insurance carrier for damages. The claim was denied because the damages were considered unrelated events. Furthermore, the fuel spill claim was denied because it involved hazardous materials (fuel oil) that were not covered by the policy. Based on this, the insurance carrier advised the building owner to file a single claim for the transformer failure.

In light of the above, the building owner engaged a forensic engineer to investigate the equipment failures and fuel oil spill as well as to determine if these events were related.

Methodology

In order to investigate the sequence of electrical equipment failures that led to approximately 1,000 gallons of fuel oil spill in the building, each equipment failure was investigated separately — starting with the transformer failure.

a. Transformer Failure

The transformer in the building was used to reduce the utility power from 13.2kV to 480/277VAC for use in the building. This transformer is a three-phase 3,000kVA, 13.2kV-480/277 VAC stepdown transformer manufactured in May 2003 (see **Figure 1**). This transformer has five taps on the primary side (13.2kV). Cooling for the electrical room was through a dedicated ventilation system, which brought outside air into the room exhausting to the outside. The electrical room did not have humidity control.

A site inspection was conducted on May 22, 2008 in order to investigate the transformer failure. The site inspection revealed several short circuits in the transformer windings, as shown on **Figures 2** through **6**. In addition, the manufacturer's drawings, operation and maintenance manuals were reviewed in order to determine if the installation of the transformer complied with the manufacturer's recommendations[4].

- The maintenance of the electrical equipment in the building took place on February 9, 2008 starting at 10 a.m. At that time, the transformer was de-energized, thus allowing it to cool down for approximately 6 hours.

- Although these transformers typically were supplied with cabinet space electric heaters, the one supplied for this building was not. Cabinet space electric heaters are required when transformers are installed in environments subject to high humidity levels.

- The transformer instruction manual provided the following guidelines:

  a. Transformers that operate in high humidity environments must be dried for an appreciable time period.

  b. Under severe environment conditions and extended shutdown periods, transformers should be inspected for visible signs of moisture before re-energizing. Where humidity is encountered, the transformers must be dried as specified in their instruction manual[4].

  c. Moisture is detrimental to most insulation systems. As such, transformers that have been exposed for long periods of high humidity when moisture is visible on insulation surfaces must be dried before being energized.

  d. The process of drying is accomplished by the application of hot air, radiant heat, or internal heat in order for the hot air to rise through the windings.

  e. Insulation resistance tests, which are used on liquid-filled transformers, are of little value on dry-type transformers, such as the one in this case. The nature of insulation used in dry-type transformers is such that the megger and power factor readings are not reliable and may be misleading.

- The transformer was placed back in service at approximately 4 p.m. upon completion of the maintenance on February 9, 2008.

- A moisture inspection of the transformer was not performed prior to placing it back in service.

- The National Climate Data Center (NCDC) reported that 0.04 inches of water precipitation occurred in San Juan, Puerto Rico on February 9, 2008 with an average temperature for the day of 77 degrees Fahrenheit, signifying the presence of elevated humidity.

- Evidence of multiple short circuits was visible in the center and right sides of the primary windings of the transformer.

- A previous transformer failure occurred on a similar transformer in 2002 following an extended shutdown similar to the 2008 shutdown. An investigation following the 2002 transformer failure revealed high levels of moisture in the transformer windings.

b. Fuel Oil Control Panel Failure

The "A" and "B" emergency generators were located on the mezzanine of the 18th floor with the corresponding fuel day tanks. Since the "A" and "B" fuel day tanks do not hold sufficient fuel for the emergency generators to operate for extended periods of time, these fuel day tanks are supplied with fuel from two 5,000-gallon fuel tanks located in the cellar. The fuel from these two tanks is supplied through two 15.6 gpm fuel pumps; only one pump is required for the "A" and "B" fuel day tanks to be refilled, with the second pump as backup (see **Figures 7** through **10**).

The "A" and "B" control panels were mounted on top of the day tanks, and they control the operation of the 15.6 gpm fuel pumps through the local control panel located in the cellar. When a low level signal from the fuel day tanks is received, the day tank control panels send the signal to the 15.6 gpm fuel pump local control panel. The local fuel pump control panel provides a permissive signal to the 15.6 gpm fuel pump to start supplying fuel to the fuel day tanks. Once the fuel day tank levels are satisfied, then the low level signal from the "A" and "B" fuel day tank control panels is removed, and the fuel pump stops pumping fuel to the day tanks.

The "A" and "B" fuel day tanks include low- and high-level switches, which provided a signal to their respective control panels. In addition, the day tanks included a rupture basin signal that also went to the "A" and "B" fuel day tank control panels. These control

Figure 1
Transformer 13.2kV – 480/277V.

Figure 2
Transformer short circuit #1.

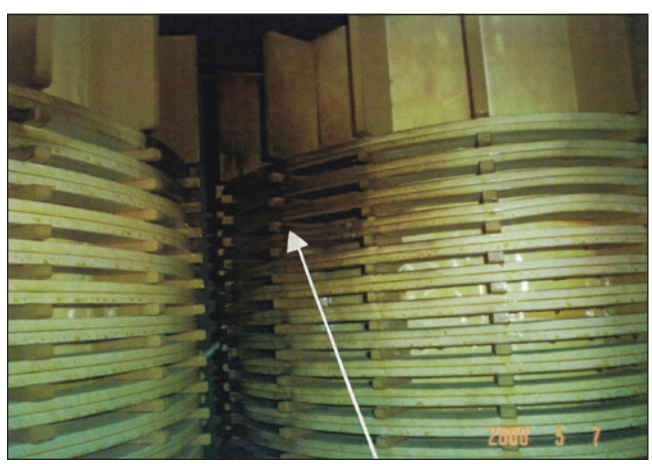

Figure 3
Transformer short circuit #2.

Figure 4
Transformer short circuit #1 close-up.

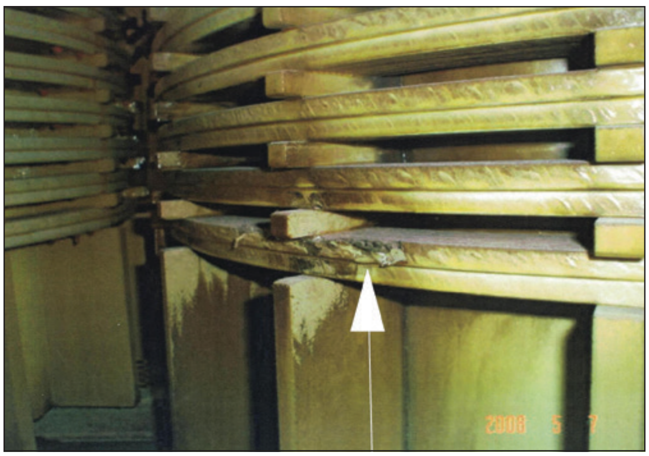

Figure 5
Transformer short circuit #2 close-up.

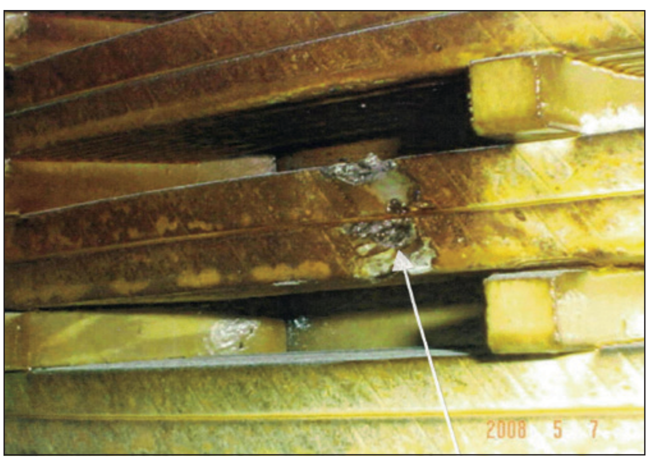

Figure 6
Transformer short circuit #3 close-up.

panels used the signals to process the information within these panels (see **Figures 11** and **12**). A signal was sent from these control panels to the emergency generator control panels located in the emergency generator room and to a remote alarm panel located in the lobby of the building.

The "A" and "B" fuel day tanks had a containment basin, which held approximately 615 gallons. The containment basin was designed to hold the fuel from these day tanks in the event that there was a rupture in either tank. In addition, this containment basin had a level switch, which provided a local audible alarm on the 18th floor in the event of either fuel day tank rupture.

In order to determine the cause and origin for the fuel day tank control panel "A" failure, a test protocol was developed to test both control panels. The tests were performed at a local laboratory in San Juan, Puerto Rico. The tests included internal and external visual inspections of the panels to determine if there were any visual indications of defects or failures in control panel A.

Following the visual inspections of both control panels, functional tests were performed on both units to verify their operation. The control panel operation tests involved simulating various levels of fuel in the tank, starting with empty to full level and then full to empty. The fuel tank levels were gradually changed to verify the following panel indications: empty, 10%, 25%, 50%, 75%, 85%, 90%, 95%, and full conditions. One functional test was performed in control panel "B" and two functional tests on control panel "A" in order to verify repeatability.

Figure 7
Fuel day tank "A" with control panel.

Figure 8
Fuel day tank "A" with control panel.

Figure 11
Fuel day tank "A" control panel (front view).

Figure 9
Fuel day tank "A" and catch basin.

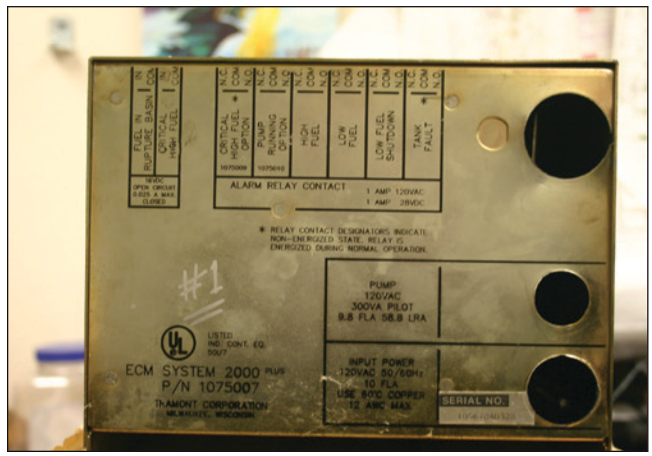

Figure 12
Day tank "A" control panel (rear view).

Figure 10
Fuel day tank "A" catch basin.

The results of the visual and functional tests for both control panels showed that they operated properly. It was concluded that the control panel "A" malfunction was a time-specific malfunction that took place on or about February 12, 2008 and not a long-term effect.

c. *Power Disturbances and Harmonics*

In addition to testing the fuel day tank control panels, power quality monitoring tests were performed on the electrical distribution system in the building with the aid of a local electrical contractor. The power quality monitoring included the incoming 13.2kV electrical power service from the utility, the 480 VAC emergency generator power, and the 120/208 VAC electrical power panel RP2-17, which provided power to the fuel day tank control panels.

The results of the visual and functional tests for the electrical power service from the utility, emergency generator, and power panel RP2-17 revealed a high level of harmonics that exceeded the industry standard levels. The harmonic levels recorded for power panel RP2-17 greatly exceeded the recommended industry standard levels. The results were as follows:

120 VAC POWER PANEL RP2-17			
	Phase A	***Phase B***	***Phase C***
Voltage Harmonics (total)	5.25%	5.3%	5.4%
Current Harmonics (total)	65%	39.5%	8.5%

EMERGENCY GENERATOR			
	Phase A	***Phase B***	***Phase C***
Voltage (THD)	6.22%	6.44%	6.01%
Current (THD)	11.20%	11.77%	11.39%

ELECTRICAL PANEL RP2-17			
	Phase A	***Phase B***	***Phase C***
Voltage (THD)	5.25%	5.30%	5.40%
Current (THD)	65.00%	39.50%	8.50%

Table 1
Voltage and current total harmonic distortion (THD) content (percentage).

In accordance with Institute of Electronics & Electrical Engineers (IEEE) Standard 141, 1993 revision, *Recommended Practice for Power Distribution for Industrial Plants*[5], the recommended maximum harmonic content for operating electronic equipment in industrial facilities is less than 5% for total harmonics with a maximum individual harmonics content of 3%. As shown in **Table 1**, the total harmonic current content for power panel RP2-17 is more than 21 times higher than the recommended value in this standard.

In addition, IEEE Standard 141, Paragraph No. 9.2 – Importance of Understanding Effects of Harmonics, states the following[3]:

"In addition to these new non-sinusoidal loads, more power factor improvement capacitors are being applied in industrial systems and in electric utility transmission and distribution systems for both voltage control and release of system capacity. With the addition of each new capacitor bank, the system's resonant frequency is lowered (see 9.6). With the resonant frequency lowered, the systems become more susceptible to natural resonance with non-sinusoidal loads. With the lowering of the system resonance, power systems are now becoming more and more impacted by the flow of the characteristic harmonic currents produced by these loads.

Harmonic currents flowing in power circuits can induce harmonic voltages and/or currents in adjacent signal circuits. The present-day use of microprocessors for control of processes and power systems results in equipment using low-level signals that are subject to noise or interference from outside sources."

The effect of harmonics in the current and voltage waveforms shown in **Figure 13** were very similar to the results obtained from the power quality monitoring tests in the electrical distribution system in the building, which are shown in **Figures 14** and **15**.

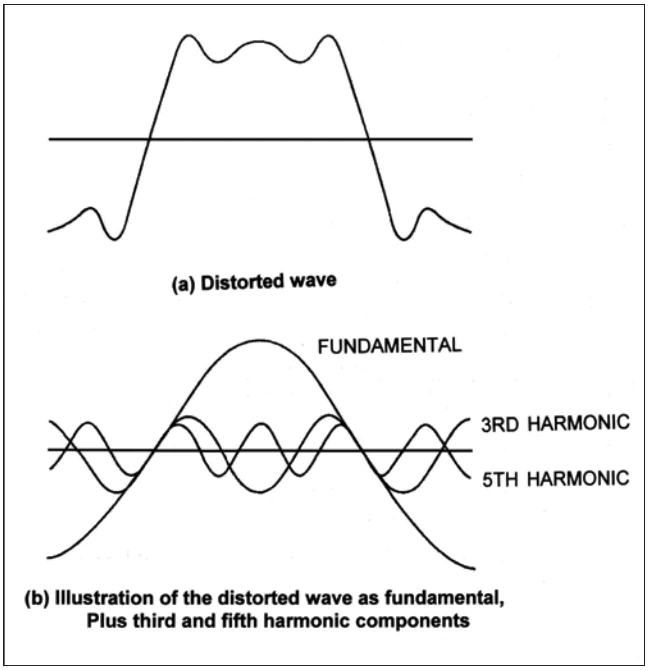

Figure 13
Voltage or current waveforms with harmonic distortions. Upper waveform illustrates with total voltage or current waveform. Lower waveform illustrates the fundamental (60 Hz waveform) and the 2nd & 3rd harmonic waveforms.

Furthermore, IEEE Standard 141, Paragraph No. 9.8.2.5 - Electronic Equipment[3] states the following:

"Power electronic equipment is susceptible to misoperation caused by harmonic distortion. This equipment often is dependent on accurate determination of voltage zero crossings or other aspects of the voltage waveshape. Harmonic distortion can result in a shifting of the voltage zero crossing or the point at which one phase-to-phase voltage becomes greater than another phase-to-phase voltage. These are both critical points for many types of electronic circuit controls, and misoperation can result from these shifts.

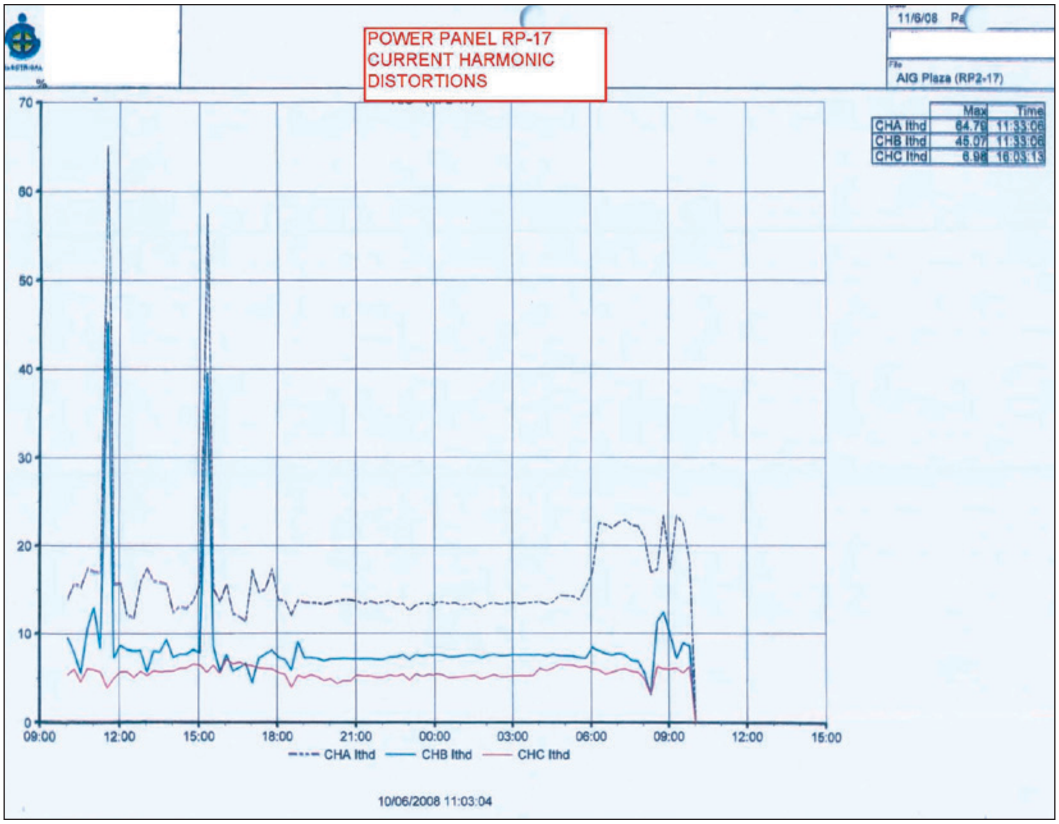

Figure 14
Power panel RP2-17 – current harmonic distortions.

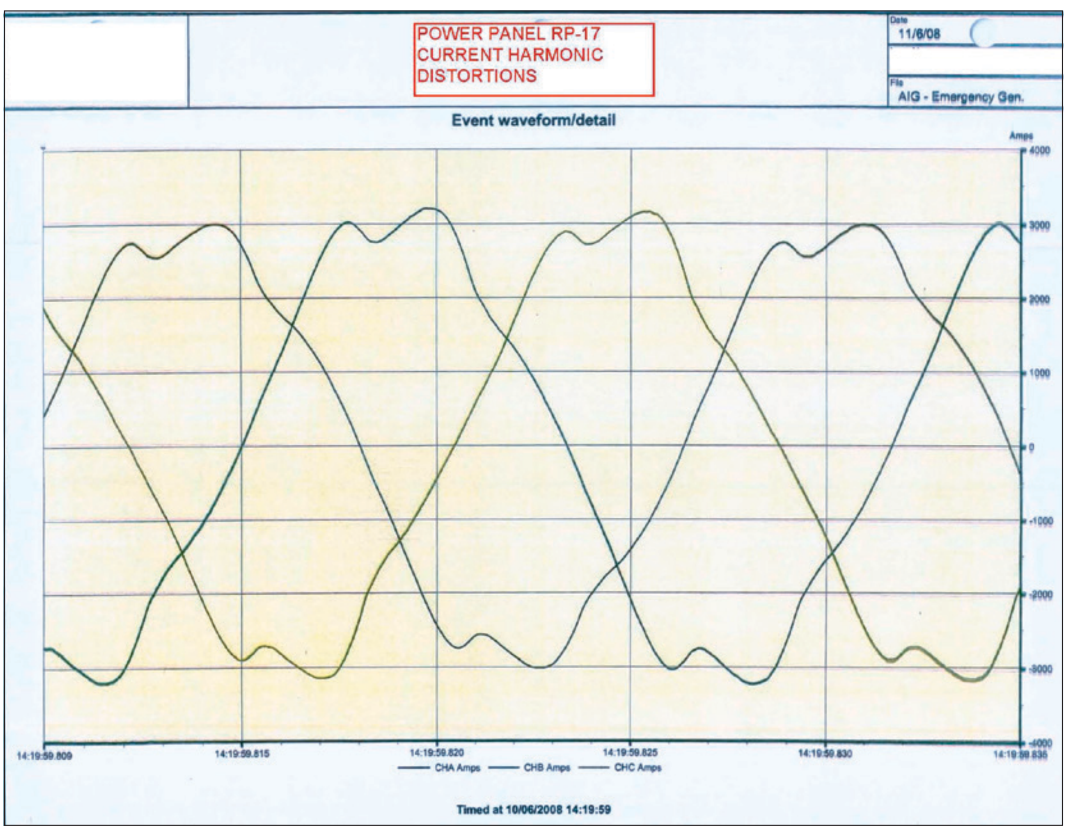

Figure 15
Power panel RP2-17 – sine wave current and voltage harmonic distortions.

Other types of electronic equipment can be affected by transmission of AC supply harmonics through the equipment power supply or by magnetic coupling of harmonics into equipment components. Computers and allied equipment, such as programmable controllers, frequently require AC sources that have not more than 5% harmonic voltage distortion factor, with the largest single harmonic being no more than 3% of the fundamental voltage. Higher levels of harmonics result in erratic, sometimes subtle, malfunctions of the equipment, which can, in some cases, have serious consequences. Instruments can be affected similarly, giving erroneous data or otherwise performing unpredictably. Perhaps the most serious of these are malfunctions of medical instruments."

In addition, industry standard IEEE 241, 1990 revision, Paragraph No. 3.12.3 - Harmonic Producing Equipment[2], states the following:

"Capacitors do not generate harmonics. However, the reduced reactance of the capacitor to the higher frequencies may cause excessive harmonic current in the circuit containing the capacitors. In cases of resonance, this current may be very large and may overheat the capacitors. In addition, the high currents may induce interference with communication, signal, and control circuits."

Based on the above, it is evident when the 3,000kVA, 13.2kV-480/277 VAC stepdown transformer failed, the two emergency generators operated in order to provide electrical power to the building. When the emergency generators operated, the fuel day tank control panels "A" and "B" operated with distorted voltage and current waverforms supplied by Panel RP2-17. The distorted voltage and current waveforms were most likely due to the current and voltages harmonics created by the capacitor banks, which were installed in 2002 (see **Figures 14** and **15**). The distorted voltage and current waveforms have adverse effects in communications and electronic equipment, such as the fuel day tank control panels "A" and "B" as stated in industry standards IEEE 141[3] IEEE 241[2] and IEEE 519[5]. The adverse effects include misoperations of electronic equipment, as was the case with the fuel day tank control panel "A" on February 11, 2008.

The building personnel responded to the fuel overflow event when notified by the security guard, and proceeded to control and collect the fuel overflow in the building. The building engineer stated that the fuel day tank control panel "A" had clearly malfunctioned as manifested by the fact that the low- and high-level alarm lights were both illuminated at the same time. Illumination of the low- and high-level alarm lights could not have happened unless the control panel "A" malfunctioned. The building engineer further stated that the fuel overflow was due to the malfunction and consequent failure of control panel "A" to properly control the fuel flow from the main tanks in the cellar to the day tank "A" located on the 18th floor.

Conclusion

The forensic engineer concluded that the fuel oil spill atop of the high-rise office building was a single event, resulting from a sequence of failures starting with the transformer failure that provided the electrical power to the building. The transformer failure was the result of energizing it without following the manufacturer's recommendations to inspect and remove the humidity in the windings after being de-energized for a period of time in a high humidity environment. As a result of the transformer failure, the emergency generators in the building operated for approximately 37 hours when one of the day tank fuel control panels malfunctioned due to a high level of harmonic content on the electrical distribution system in the building[5,6,7]. The day tank fuel control panel malfunction resulted in the fuel oil spill as described.

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