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Forensic Engineering Analysis of an Electrical Substation Fire in a Manufacturing Plant in Brazil

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Abstract

A cable splice failure in one of the cables associated with one of the 6 MVAR capacitor banks in an electrical substation at a manufacturing plant in South America caused a fire in the 88/4.16kV electrical substation. The fire caused the plant to stop production for approximately 29 days while temporary repairs were made. Operating two shifts per day/seven days a week, and stopping for maintenance once a year, the manufacturing production generates approximately $750,000 in revenue per day. The cable splice failure caused an electrical short circuit in the substation 4.16kV distribution system for approximately 120 seconds. The cable splice failure ignited the adjacent cables in the cable tray, causing damage to various sections of the 4.16kV cables, three 88kV disconnect switches, and four 88kV – 4.16kV transformers. The cable fire in the electrical substation resulted in property damages and business interruption losses with an estimated value of $20 million. The four 88kV – 4.16kV transformers that were in service at the time of the substation fire were exposed to voltage transients and electromagnetic forces produced by the short-circuit currents for approximately 120 seconds.

Keywords

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

Definitions

Ferroresonance or nonlinear resonance is a type of resonance in electric circuits that occurs when a circuit containing a nonlinear inductance is fed from a source that has series capacitance, and the circuit is subjected to a disturbance such as opening of a switch. Ferroresonance can cause overvoltage and overcurrent conditions in an electrical power system, and can pose a risk to transmission and distribution equipment as well as operational personnel.

Introduction

A manufacturing plant in South America that began operations in the mid-20th century went through several expansion cycles to meet increased product demands. The plant expansions required increases in the supply of electrical power from the local utility and its own 88kV to 4.16kV electrical substation located within the plant.

The electrical power for the plant is provided by the local utility via two 88kV overhead transmission lines. Only one of the 88kV lines is required to meet the power demand from the plant, and the second is used as a secondary power source in case of an outage (**Figure 1**).

The electrical substation is located on the southeast corner of the property. Initially, the substation consisted of two 88kV – 4.16kV, 7,500kVA stepdown transformers labeled Transformer Nos. 1 and 2. As the plant expanded in subsequent decades, two additional 88kV – 4.16kV, 15,000kVA step-down transformers were added (Transformer Nos. 3 and 4). These transformers were located adjacent to the existing Transformer Nos. 1 and 2 (see **Figure 2** and **3**).

To improve the power quality of the electrical system in the plant, two 6.0 MVAR, 4.16kV capacitor banks with filters were installed in the 1990s. The 6.0 MVAR, 4.16kV capacitor banks are connected to two 4.16kV switchgear — one connected to Transformer No. 3 and the other to

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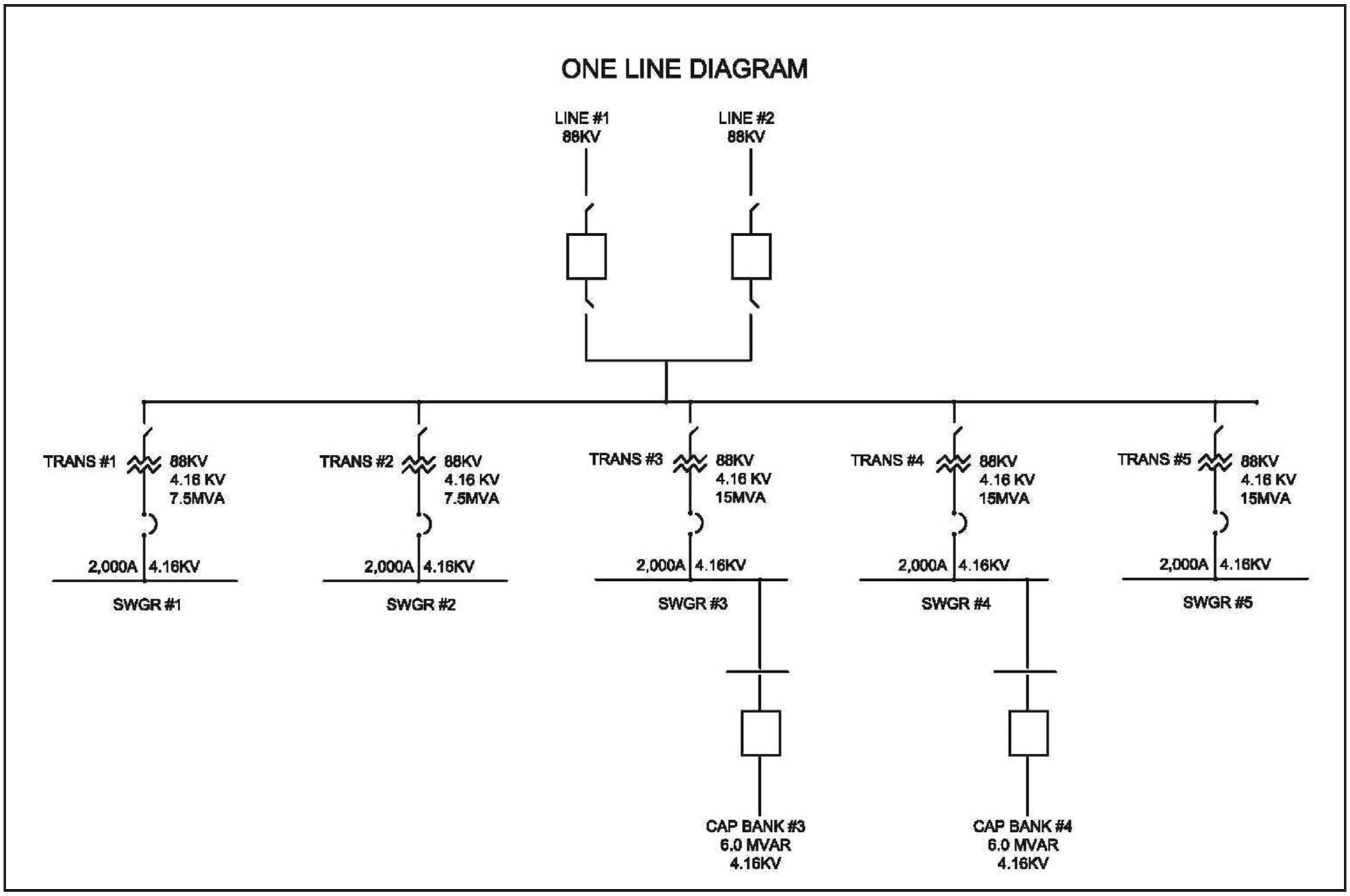

Figure 1
One-line diagram of substation.

Transformer No. 4.

As the plant continued to grow, a new 88kV – 4.16kV, 15,000kVA step-down transformer was installed in the early 2000s (Transformer No. 5). The installation of this transformer required both 4.16kV, 6 MVAR capacitor banks to be relocated to make room for this new

Figure 2
Partial view of substation (north view).

Figure 3
Partial view of substation (south view).

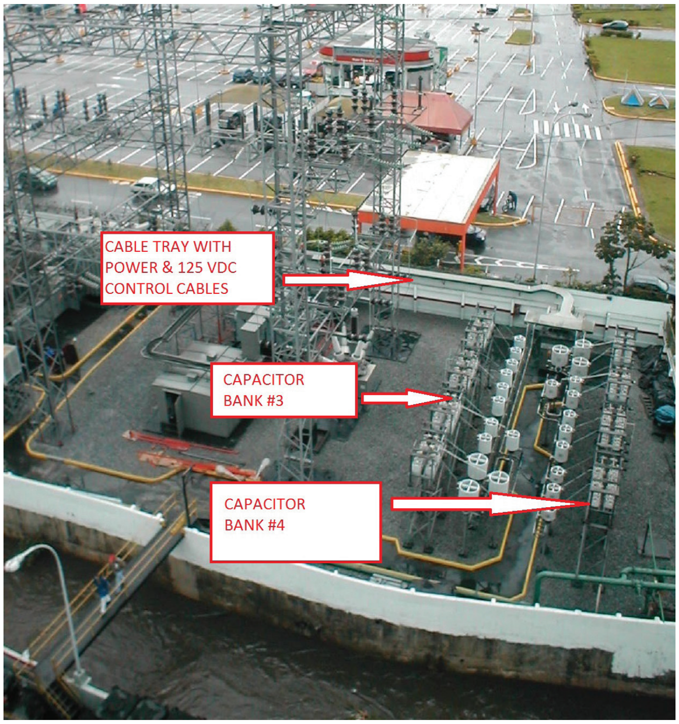

Figure 4
Relocated capacitor Bank #3 and #4.

Transformer No. 5 (**Figure 4**). The power cables in the trays were spliced with additional cables to reach the relocated capacitor banks (**Figure 5**).

When the 4.16kV, 6 MVAR capacitor banks were relocated to make room for the new Transformer No. 5, the circuit breakers associated with the capacitor banks were also relocated close to the capacitor banks, approximately 100 meters away from their original location.

The power cables for the capacitor banks were spliced in the cable tray, which was located on the outside wall along the property line. This cable tray also contained 125 VDC control cables used for the protection and control of the 6.0 MVAR, 4.16kV capacitor banks.

The electrical power for the 4.16kV, 6 MVAR capacitor banks was derived directly from the 4.16kV busbars in the substation. In light of this, the spliced power cables (from the 4.16kV substation busbars to the relocated circuit breakers and capacitor banks) were not protected by the 4.16kV distribution system in the substation, since the spliced power cables became an extension of the substation 4.16kV busbars.

In 2014, a cable splice failure occurred in one of the power cables associated with the capacitor bank connected to Switchgear No. 4. The cable splice failure was detected by the protection system of the circuit breaker in Switchgear No. 4, which tripped the capacitor bank and prevented damages to other equipment in the substation. When the failed cable splice was repaired, the capacitor bank was restored to service.

Figure 5
Cable tray for capacitor bank cables.

In the spring of 2015, a second cable splice failure occurred in one of the power cables associated with one of the capacitor banks. The cable splice failure caused a short circuit and a fire in the cable tray where the power and 125 VDC cables for the capacitor banks were located (**Figure 6** through **9**).

The fire in the cable tray caused the catastrophic failure of the entire 125 VDC control system in the substation. This prevented the 88kV and 4.16kV circuit breakers in the substation from providing the protection and control for all the equipment in the substation. The only

Figure 6
Capacitor bank cable splices.

protection left for the substation was provided by the local utility company on the 88kV overhead transmission lines.

As a result of the short circuit in the power cables associated with both capacitor banks and the failure of the protection system cables, the 88kV incoming power from the utility continued to provide electrical power to the substation and sustained the short circuit in the cables associated with the capacitor banks. The short circuit in the cables for both capacitor banks remained for approximately 120 seconds, as depicted on the voltage graph recorded by the voltage recorder (**Figure 10**). In addition, the voltage graph in the voltage recorder shows that while the short circuit was occurring, the voltage in the incoming 88kV system went into overvoltages as much as 11kV (27%). In addition, the voltage in the secondary side of the 88 - 4.16kV transformers went into oscillations ranging in voltage from 0.5kV to 4.16kV.

Figure 7
Cable tray with cable splice failure.

Figure 8
Cable splice failure.

Since the voltage recorder in the substation does not have the resolution to detect the amplitudes and frequencies of the voltage oscillations in the 88kV incoming power from the utility, the author was not able to

Figure 9
Cable tray with cable splice failure.

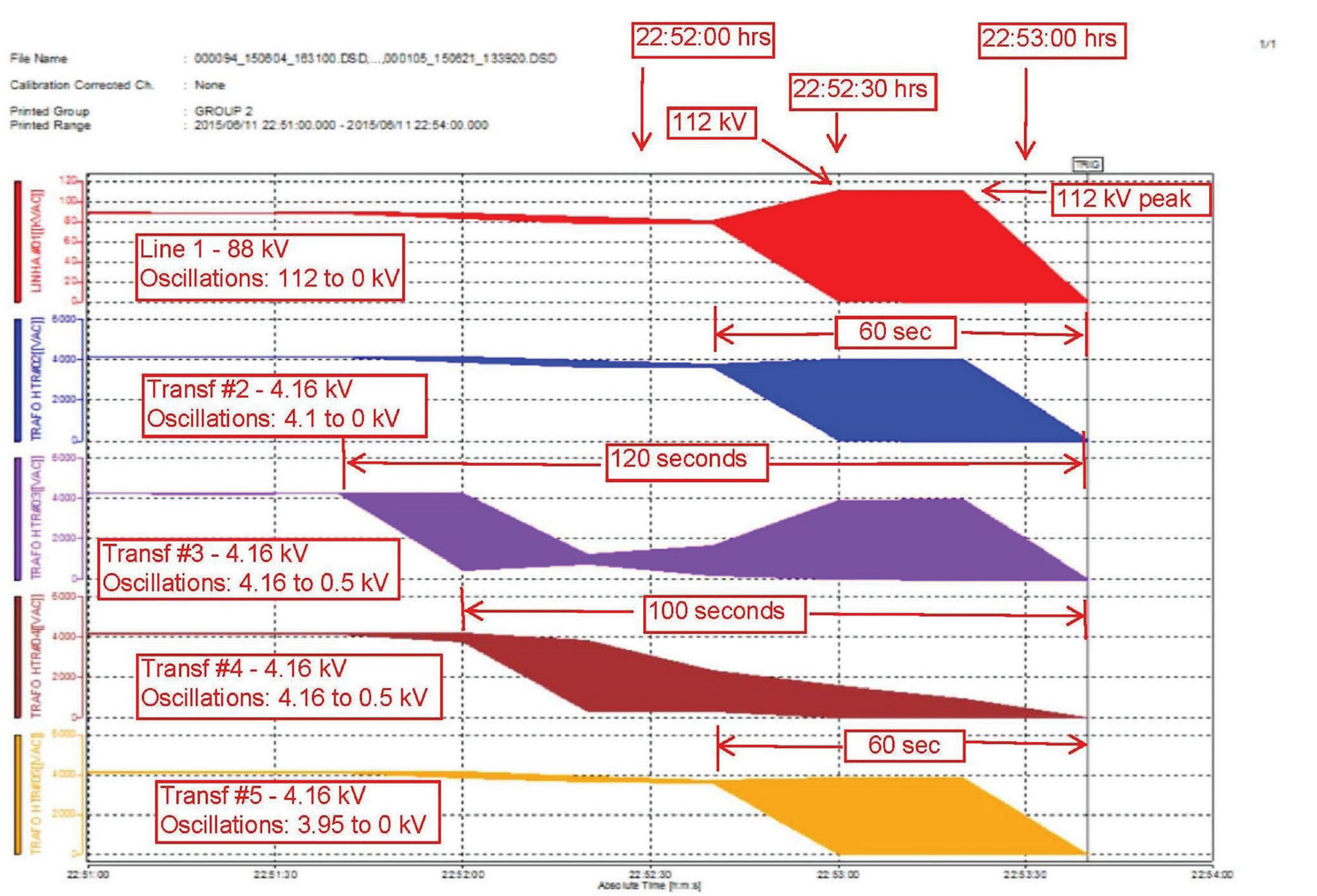

Figure 10
Recorder graphs — 88kV utility overhead line and customer Transformers 2 through 5.

determine if ferroresonance occurred during the 120 seconds of sustained short circuits in the substations. This substation did not have a sequence-of-event recorder that would have captured the electrical transient events and provided detailed information of the voltage amplitudes and frequencies of the electrical transient.

Given the fact that overvoltages of as much as 27% occurred in the 88kV incoming power from the utility, it is very likely that the cause of these overvoltages was the result of a ferroresonance[1,2,3,4] condition produced by the electrical transients in the substation after the splice failure.

Ferroresonance is a type of resonance in electric circuits that occurs when a circuit containing a nonlinear inductance is fed from a source that has series capacitance, and the circuit is subjected to a transient such as opening of a switch, short circuit, etc. Ferroresonance can cause overvoltage and overcurrent conditions in an electrical power system, and can pose a risk to transmission and distribution equipment as well as to operational personnel.

The 88kV – 4.16kV substation configuration at the time of the fire had four 88kV – 4.16 kV stepdown transformers, two 4.16kV filters, and the transmission lines that provided the inductance required for ferroresonance to occur. In addition, the two 4.16kV, 6 MVAR capacitor banks and the transmission lines provided the capacitance required for ferroresonance to occur. Therefore, it is very likely that the oscillations and overvoltages in the 88kV incoming line were the result of a ferroresonance condition in the substation that occurred when the short circuit and fire occurred in the substation.

Since four of the 88kV – 4.16kV transformers and their associated switchgear were energized during the fire, they were exposed to high short-circuit currents and electrical voltage transients. In addition to the short circuits that occurred in the cable tray where the power and control cables for the 4.16kV capacitor banks are located, other short circuits occurred in the 4.16kV switchgear Nos. 3 and 4, resulting in fires around them and damaging these 4.16kV switchgear and cables around them (**Figure 11** through **16**).

Methodology

Due to the need to restore the electrical power for the plant to continue operating, temporary repairs were performed to the 88kV and 4.16kV substations in order for the plant to return to service within approximately 29 days. The temporary repairs included installing new cables, cable trays, replacing one of the 4.16kV switchgear, and repairing the other damaged 4.16kV switchgear.

Prior to returning the five 88kV – 4.16kV transformers to service after the fire, oil samples were taken from the transformers to analyze the effect that the short circuits and fire had on them. The oil samples showed elevated levels of carbon dioxide to carbon monoxide ratios. These values were compared to industry-recognized levels for similar transformer size and ratios. The levels of carbon dioxide to carbon monoxide levels are used to determine the health of the insulation in the transformer windings. Ratios that are higher than the industry-recognized levels reveal weakening of the insulation in the transformer windings, as was the case with Transformers 2, 3, 4, and 5. Transformer 1 at the time of the fire was not

Figure 12
4.16kV switchgear fire damage.

Figure 11
Cable tray fire damage.

Figure 13
4.16kV switchgear damage.

Figure 14
4.16kV switchgear fire damage.

Figure 15
4.16kV circuit breaker damage.

Figure 16
88kV - 4.16kV transformer damage.

in service. See **Figure 2** for the transformer oil sample results. The oil in Transformers 2, 3, 4, and 5 tanks was replaced prior to returning these transformers to service.

The forensic investigation of the damages in the electrical substation was performed after the temporary repairs were completed. Several site visits were conducted by the author starting in February 2016 in order to review the technical documents related to the substation and to investigate the damage to the various pieces of equipment. The results of these investigations are now detailed.

Cable Splice Failure

The cable splice failure and fire occurred at night when daytime weather featured scattered clouds with temperatures reaching 90°F. The temperature at that time was reported as approximately 72°F with a relative humidity of 89% and a barometric pressure of 29.93 inches. Since the cable splice was consumed by the fire, a detailed failure analysis of the components could not be performed.

OIL ANALYSIS OF TRANSFORMERS AFTER FIRE

		Hydrogen	Oxygen	Nitrogen	Methane	Carbon Mo	Carbon Dio	Ethelyne	Ethane	Acetylene	Interface	Water	CO2/CO
Date		(H)	(O)	(N)	(CH2)	(CO)	(CO2)	(C2H4)	(C2H6)	(C2H2)	Dielectric	Content	Ratio
6/15/15	Transf. 1	12	23160	43838	1.5	16	398	1.7	0	0			24.9
6/15/15	Transf. 2	11	1588	63665	238	79	4226	53	485	0	63	10	53.5
6/15/15	Transf. 3	7	1602	79834	78	223	2865	9.5	63	0.3	60	12	12.8
6/15/15	Transf. 4	20	1764	46308	53.6	97	2149	16.2	85.8	0	59	21	22.2
6/15/15	Transf. 5	13	9547	48177	5.6	790	1291	0	0.2	0	95	5	1.6

Figure 17
Transformers 1, 2, 3, 4, and 5 oil analysis after fire.

Transformer No. 2

The voltage graph of the secondary winding of Transformer No. 2 recorded by the voltage recorder during the fire shows that Transformer No. 2 went into oscillations for approximately 60 seconds. The voltage oscillations ranged between 0kV and 4.16kV (**Figure 10**).

In addition, the voltage graph of the primary winding of Transformer No. 2 (88kV) recorded by the voltage recorder during the fire shows that the primary winding voltage went into oscillations for approximately 60 seconds, ranging from 0kV to 112kV for approximately 60 seconds or as much of as 27% of its rating (**Figure 10**).

The oil analysis performed by a laboratory on oil samples taken from Transformer No. 2 the day after the accident shows a ratio of CO_2/CO of 53.495 (4226/79). IEEE Standard C57.106-2006[5] indicates that a CO_2/CO ratio greater than 15 is an indication of insulation degradation in a transformer winding (**Figure 17**).

Transformer No. 3

The voltage graph of the secondary winding of Transformer No. 3 recorded by the recorder during the fire shows that Transformer No. 3 went into oscillations for approximately 120 seconds. The voltage oscillations ranged between 0.5kV to 4.16kV (**Figure 10**).

In addition, the voltage graph of the primary winding of Transformer No. 3 (88kV) recorded by the voltage recorder during the fire shows that the primary winding voltage went into oscillations ranging from 0kV to 112kV for approximately 60 seconds or as much of as 27% of its rating (**Figure 10**).

In addition, the oil analysis performed on oil samples from Transformer No. 3 the day after the accident show an acetylene[6] content of 0.3 ppm. The results of the oil analysis performed on this Transformer No. 3 six months prior to the fire revealed that the acetylene level was 0.0 ppm. Acetylene content in large concentrations greater than 0.5 ppm is the result of a thermal process such as local overheating, and in small concentrations due to partial discharge, which decomposes the mineral oil. Although the acetylene level obtained after the cable splice failure did not exceed 0.5 ppm, the fact that it increased from 0.0 ppm to 0.3 ppm after the cable splice failure is an indication that this Transformer No. 3 experienced localized overheating and partial electrical discharges in its windings caused by the short circuits in the cables associated with Capacitor Bank #3 (**Figure 17**).

Transformer No. 3 also experienced short circuit currents of as much as 31,600A for as long as 120 seconds. These high short circuit currents caused high electromagnetic forces in the primary and secondary windings overstressing the mechanical supports of the transformer windings and core.

Transformer No. 4

The voltage graph of the secondary winding of Transformer No. 4 recorded by the voltage recorder during the fire shows that Transformer No. 4 went into oscillations for approximately 100 seconds. The voltage oscillations ranged between 0.5kV to 4.16kV (**Figure 10**).

In addition, the voltage graph of the primary winding of Transformer No. 4 (88kV) recorded by the voltage recorder during the fire shows that the primary winding voltage went into oscillations ranging from 0V to 112kV for approximately 60 seconds, with overvoltages of as much of as 27% of its rating (**Figure 10**).

The oil analysis performed by a laboratory on oil samples taken from Transformer No. 4 after the incident shows a ratio of CO_2/CO of 22.15 (2149/97). Again, industry standards indicate that a ratio greater than 15 is an indication of the transformer winding insulation degradation (**Figure 17**).

Transformer No. 4 also experienced short circuit currents of as much as 28,500A for as long as 120 seconds. These high short circuit currents caused high electromagnetic forces in the primary and secondary windings, overstressing the mechanical supports of the transformer windings and core.

Transformer No. 5

The voltage graph of the voltage recorder shows that while the short circuit was occurring in the cables of Capacitor Banks #3 and #4, the voltage in the secondary winding of Transformer No. 5 went into oscillations ranging from 3.95kV to about 0kV for approximately 60 seconds (**Figure 10**).

In addition, the voltage graph of the primary winding of Transformer No. 5 (88kV) recorded by the voltage recorder during the fire shows that the primary winding voltage went into oscillations ranging from 0kV to 112kV for approximately 60 seconds with overvoltages of as much of as 27% of its rating (**Figure 10**).

88 kV Utility Overhead Line #1

The voltage graph of the 88kV line 1 recorded by the voltage recorder during the fire shows that the 88kV line 1 went into oscillations 60 seconds after the short circuit occurred in the cable splices, and such oscillations remained for approximately 60 seconds. The voltage oscillations first went up from 88kV to approximately 112kV, then leveled off at 112kV for about 20 seconds, and then went down to 0kV in the next 20 seconds. The voltage oscillations coincided with the start of voltage oscillations in Transformer Nos. 2 and 5, which is an indication that the voltage disturbances in the utility 88kV system directly affected Transformer Nos. 2 and 5 (**Figure 10**).

The voltage signal for the voltage recorder is connected to the 88kV potential transformers in an open "Delta" configuration as shown on the one-line diagram (**Figure 1**). The voltage signal for the secondary windings of Transformer Nos. 2, 3, 4 and 5 is connected to the 4.16 kV potential transformers in an open "Delta" configuration.

The waveforms recorded by the voltage recorder show the voltages for the 88kV and 4.16kV transformer windings in Transformer Nos. 2, 3, 4, and 5 before, during, and after the short circuit occurred. The waveforms are depicted in **Figure 10**, and show a sampling rate of 20 seconds with a scan interval of 1 second (default setting). The voltage recorder records the maximum and minimum voltage values for every scan interval. That is, the voltage oscillations shown on the graphs for the 88kV and the secondary windings of Transformer Nos. 2, 3, 4, and 5 clearly show that oscillations took place following the short circuit in the cable splice. Prior to the short circuit in the cable splices for Capacitor Banks #3 and #4, the waveforms show straight lines, which is representative of the maximum and minimum voltages for the 88kV and 4.16kV systems. Since this recorder does not record the information that an oscillograph would, the author cannot determine the frequency of the oscillations.

Conclusion

The forensic engineering analyses concluded that the cable splice failure associated with the power cables for the capacitor bank caused a short circuit and fire in the 4.16kV distribution system in the 88kV – 4.16kV electrical substation of the plant. Since the substation's 125VDC control system was damaged due to the fact that the 125 VDC control cables for the capacitor banks were routed in the same cable tray as the power cables, the substation's protection system did not operate, thus allowing the short circuit to remain for approximately 120 seconds while the fire in the substation was raging.

The state-of-the-art cable installation practices for 4.16kV power and 125 VDC control cables require that these cables be installed in separate cable trays or with metal barriers separating the power and control systems in order to prevent failures such as those described above.

The 88kV circuit breakers in the utility 88kV overhead transmission system were extremely slow to sense the short circuit in the customer's 88kV – 4.16kV substation and did not trip the 88kV overhead transmission line when the cable splice failure occurred. This allowed the electrical power to continue to flow to the substation for approximately 120 seconds while the short circuit was occurring in the substation and the fire was raging.

Since the 88kV circuit breakers in the utility 88kV overhead transmission system did not trip for the first 120 seconds after the cable splice failure, the four 88kV – 4.16kV stepdown transformers were exposed to very high short circuit currents and electromagnetic forces damaging these transformers.

The overvoltage and frequency oscillations in the incoming utility 88kV transmission line appear to be the result of a ferroresonance condition in the substation that occurred when the short circuit occurred in the substation. The ferroresonance condition occurred due to the inductance and capacitance in the 88kV – 4.16kV substation provided by the transformers, filters and capacitors that were energized during the duration of the short circuit (120 seconds).

References

1. Price E. Voltage transformer ferroresonance in transmission substations. 25th Annual Conference for Protective Relay Engineers. Texas A &M University, March 1977.

2. Rudenberg R. Transient Performance of Electric Power Systems. New York (NY): McGraw Hill Company; 1950.

3. Martinez E, Antonova G, Olguin M. Ferroresonance phenomenon in CFE, its origin and effects. 39th Annual Western Protective Relay Conference. Spokane, Washington. October 16-18, 2012.

4. Jacobson D, Menzies R. Investigation of station service transformer ferroresonance in Manitoba Hydro's 230kV Dorsey Converter Station. International Conference on Power System Transients. Rio de Janeiro. June 24-28, 2001.

5. IEEE C57.106-2002. Guide for acceptance and maintenance of insulating oil in equipment. Piscataway (NJ); Institute of Electrical and Electronics Engineers.

6. ABNT NBR 7070 - 2006. Sampling of gases and mineral insulating oil of electrical equipment and free and solved gases analysis. Rio de Janeiro; Associacao Brasileira de Normas Tecnicas.

Bibliography

ASTM D1816 – 2012. Standard test method for dielectric breakdown boltage of insulating liquids using VDE electrodes. West Conshohocken, PA; ASTM International.

ASTM D3612 – 2002r2009. Standard test method for analysis of gases dissolved in electrical insulating oil by gas chromatography. West Conshohocken, PA; ASTM International.

IEC 60156 Ed. 2.0-1995. Insulating liquids - determination of the breakdown voltage at power frequency. Geneva, Switzerland; International Electrotechnical Commission.