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Transformer Saturation Due to Transmission Line Induction

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SUMMARY

Two unloaded station service transformers encountered thermal failures while connected to an unenergized transmission circuit. Transformer failures due to surges, ferroresonance, faults and overloading have been documented over the years. However in this case, none of these common causes contributed to these failures. The transmission circuit to which the failed transformers were connected was a double circuit line sharing the same tower. When an unenergized circuit is in close proximity with an energized circuit, there would be induced voltage in the unenergized line due to electrostatic and electromagnetic induction. This paper evaluates the conditions which could cause transformer saturation due to induction. The transformer magnetization current could be several hundred times of the nominal magnetization current and could cause thermal issues when the transformer is subjected to prolonged overfluxed saturated condition.

KEYWORDS

Induction, Mutual Coupling, Transformer, Trapped Charges, Saturation.

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INTRODUCTION

ITC Holdings experienced two station service transformer failures at the same position on successive days in June 2015. The failures occurred at a 120 kV substation, shown in Figure 1. The transformers were single phase transformers rated 69 kV / 126.5 V, 50 kVA.

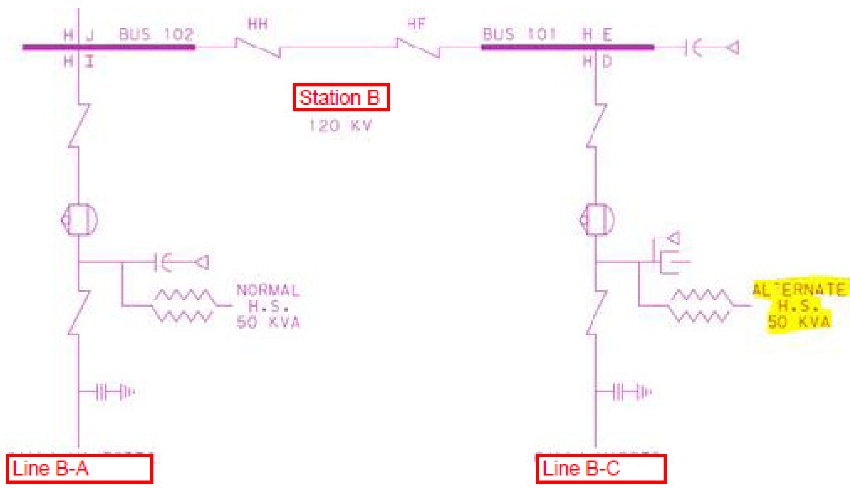

Figure 1: One Line Diagram of 120 kV Substation

Prior to the first incident, the maintenance crew were performing end-to-end tests on the power line carrier between Station B and Station C. The B-C line was kept unenergized and ungrounded overnight for the purpose of testing. The station service transformer remained connected to the unenergized line with the secondary safety switch open. The maintenance crew noticed spewed oil around the tank the next day and removed the transformer for inspection. The crew noticed the oil to be very dark and sent the transformer to the manufacturer for investigation.

A spare transformer was brought in as replacement. The line was left unenergized overnight after installing the new transformer, with the transformer connected to the unenergized line. The transformer secondary side switch was kept open. Prior to energizing the B-C line the next day, the maintenance crew noticed that the voltage at the secondary side of the service transformer was about 28.5 V line-to-ground, which corresponded to about 15.5 kV line-to-ground on the primary side. After all the routine checks, B -C line was energized by closing the breaker at Station B. Immediately the station service transformer exploded.

GENERAL CAUSES OF TRANSFORMER FAILURES

The causes of transformer failures have been studied from the time they were invented. Much information regarding the nature of failure, investigation procedures and remedies has been documented [1,2,3]. The transformer failures can be broadly categorized as below:

- Dielectric failures caused by lightning and switching surges, temporary over voltages and ferroresonance
- Electrical faults

- Transformer core issues such as mechanical damages
- Deterioration of oil and insulation
- Thermal issues in oil, windings and hot spots due to overloading
- Tap changer related
- External causes such as bushings

Over the years, advanced monitoring and protection techniques have been implemented to detect catastrophic failures of transformers. In addition, transformer designs are also continually improved to achieve higher reliability. Nevertheless, transformer failures do occur from time to time. When this occurs, it poses a challenge for the utility engineers to pinpoint the reason for the failure and avoid similar occurrences.

POSSIBLE CAUSE OF STATION B TRANSFORMER FAILURE

The failed transformers were sent to the manufacturer for tear down inspections. They showed excessive heat damage, with the oil and insulation cooked into almost granular beads. The inspection especially showed that the inner section of the HV coil was baked, suggesting that the heat was trapped in the centre of the HV windings with limited access for dissipation. The top of the windings were found to be in original shape and color. Based on this observation, the transformer manufacturer concluded that surges or ferroresonance could not have caused the failure, otherwise there would have been more uniform insulation failures.

The maintenance crew observed about 28.5 V (line to ground) on the secondary side of the transformer prior to the second failure, though the line was not energized. This voltage could have been only due to induction from an adjacent energized line.

TRANSMISSION LINE CONFIGURATION

Station B 120 kV is situated in between Station A and Station C and there is also a 345 kV transmission line between Station A and Station C. The 120 kV and 345 kV lines run on the same tower. A schematic diagram of their arrangement is shown in Figure 2.

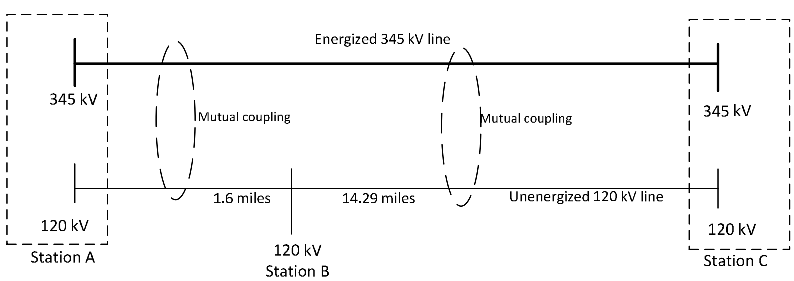

Figure 2: Transmission Line Configuration

Multi-circuit right-of-ways, similar to the B-C line, containing one un-energized circuit in parallel to an energized circuit, experience the effect of induced voltage on the un-energized circuit. This parallel induction is due to the capacitive coupling between the two circuits [4]. The induced voltage due to capacitive coupling also depends on the length of the line as well as the tower configuration of the overhead conductors.

The induced voltage due to a parallel energized circuit is usually a fraction of the energized voltage. However, the presence of any inductive elements along the line such as shunt reactors or transformer magnetizing reactance could introduce resonant conditions. In the case of a transformer, the resonant condition could drive the transformer to saturation, thereby leading to high magnetizing currents. Figure 3 illustrates the resonant circuit condition.

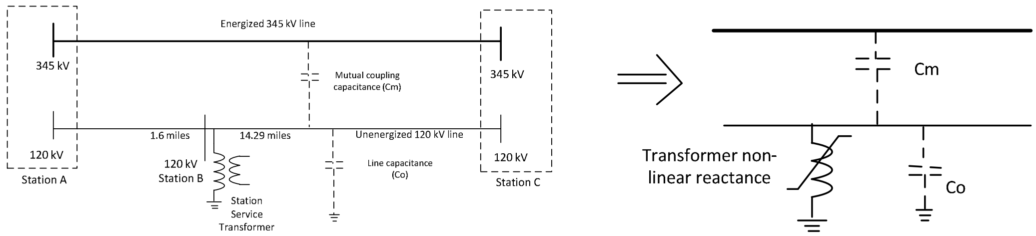

Figure 3 : Mutual Capacitance and Resonant Circuit

SIMULATION AND ANALYSIS

A study was carried out to evaluate the induced voltage on the parallel unenergized 120 kV line using PSCAD simulation. The 345 kV / 120 kV double circuit between Station A and Station C, and the station service transformer were modelled using their actual design values. The load current on the 345 kV line was set to the value that was observed on the day of the transformer failure. The transformer magnetizing characteristic was modelled based on the factory test reports. Figure 4(a) shows the calculated induced voltage on the 120 kV line due to the energized parallel 345 kV line and Figure 4(b) shows the secondary side voltage of the station service transformer connected to Phase A. It can be noticed from Figure 4(b) that the calculated induced voltage is about the same magnitude as that was observed by the maintenance crew.

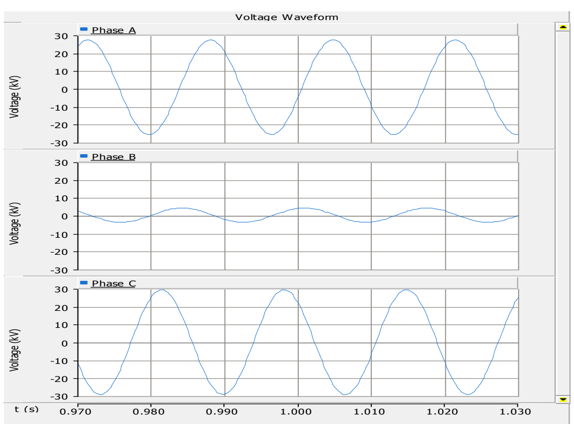

Figure 4(a) : Induced Voltage on the 120 kV line

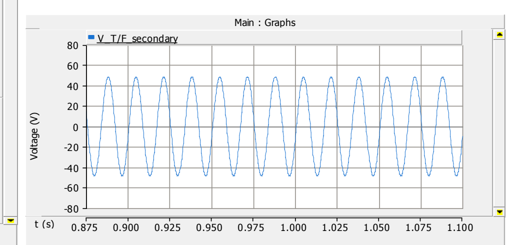

Figure 4(b) : Transformer Secondary Voltage

The transformer primary (magnetizing) current was calculated to be 0.85 mA which was well below the nominal design value of 1.7 mA.

EFFECT OF LINE TRAPPED CHARGES

A study was carried out to evaluate the impact of the trapped charges left on the 120 kV line at the time of de-energization and its impact on the station service transformer. The effect of trapped charges, especially in long EHV lines, has been a subject of interest for a long time and their impact is normally considered in switching studies. However in this study, the impact of trapped charges in combination with the induced voltage due to mutual coupling has been analyzed for possible transformer saturation.

Studies were performed with 10%, 50% and 90% trapped charges left on the 120 kV line to represent the random nature of switching operation. Figures 5(a) to 5(c) show the voltage on the unenergized 120 kV line for the three scenarios studied.

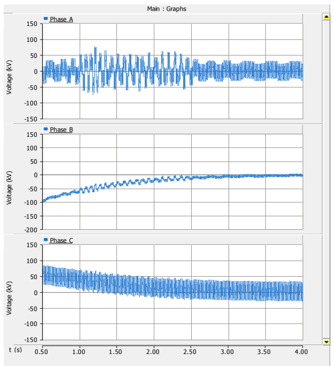
Figure 5(a): With 10% Trapped Charges

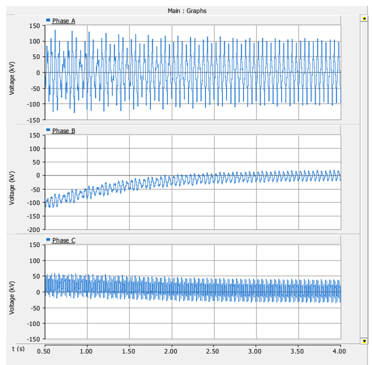
Figure 5(b): With 50% Trapped Charges

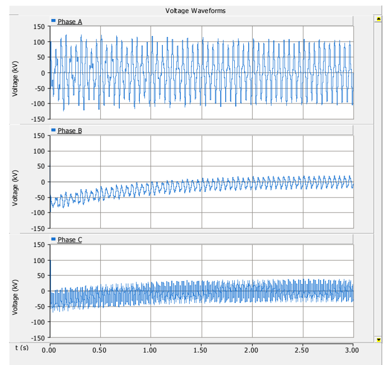
Figure 5(c): With 90% Trapped Charges

It can be noticed from Figure 5(a) that with small amount of trapped charges, the Phase A voltage settles down to a value corresponding to only the induced value pretty quickly. On the other hand, with large amount of trapped charges, a high voltage of as much as 130% is established on Phase A at the time of line disconnection and this voltage is sustained for a prolonged period. Eventually this voltage would settle down to a value just corresponding to the induced voltage value. Due to smaller time step and longer computational time, simulation was halted before the voltage reduced down to just the induced voltage.

The higher voltages observed with large trapped charges drive the transformer to saturation and thereby producing high magnetizing current. Figure 6(a) to 6(c) show the transformer magnetizing current for the three scenarios.

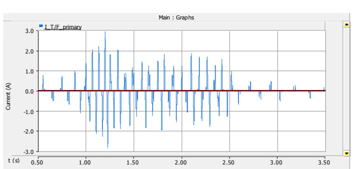
Figure 6(a): Transformer Current With 10% Trapped Charges

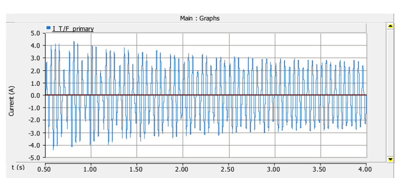
Figure 6(b): Transformer Current With 50% Trapped Charges

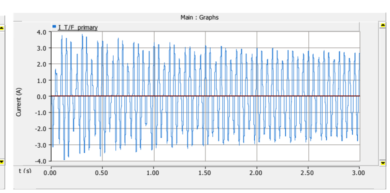
Figure 6(c): Transformer Current With 90% Trapped Charges

It can be noticed from Figures 6(b) and 6(c) that the magnetizing current could be as high as 4 amperes (crest), which is about 1600 times the nominal magnetizing current value. This high transformer magnetization current was due to the cumulative effect of induced voltage and the trapped charges left during the line opening. When a transformer is subjected for a prolonged time with this amount of high magnetizing current, it could cause thermal issues.

A simulation was also carried out to illustrate the impact of the induced voltage by considering just the trapped charges without the mutual coupling with the adjacent circuit. The transformer voltage and current for this scenario are shown in Figures 7(a) and (b), respectively. It can be noticed that the voltage on the unenergized line was not sustained without the induced voltage.

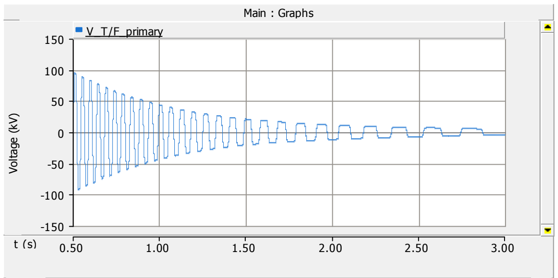

Figure 7(a): Transformer Voltage Without Mutual Coupling

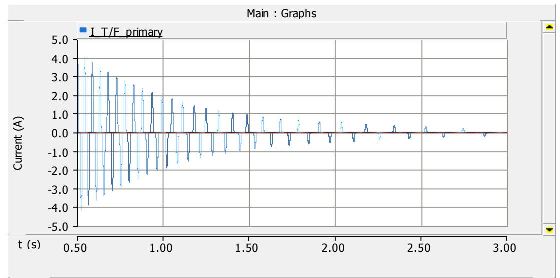

Figure 7(b): Transformer Current Without Mutual Coupling

CONCLUSION

Two station service transformer failures were encountered at the same location. The tear down inspections did not show failures due to dielectric failure; rather, it was due to excessive heating. The transformers were connected to unenergized line, and the secondary was open during the failures. Simulations were carried out to evaluate the induced voltage on the primary side of the transformer due to an adjacent energized line. Various scenarios were studied which could have caused excessive transformer current. The studies showed that the combined effect of induced voltage from the adjacent energized line and the trapped charges left on the unenergized line could provide conditions to cause transformer saturation and thereby very high magnetizing current. When a transformer is subjected to prolonged overfluxing, the resulting very high magnetizing current could cause overheating.

BIBLIOGRAPHY

[1] J&P Transformer Book, 12th Edition, 2007.

[2] IEEE Guide for Failure Investigation, Documentation, Analysis and Reporting for Power Transformers and Shunt Reactors, IEEE Std C57.125, 2015.

[3] Arvind Kulshreshtha, "Thermal Failure of Transformers", International Conference on Condition Monitoring and Diagnosis, Beijing, 2008.

[4] Horton,R. and Wallace, K., "Induced Voltage and Current in Parallel Transmission Lines: Causes and Concerns", IEEE Transactions on Power Delivery, October 2008.