Switching Events and Ferroresonance: Field Experience and Solutions

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Abstract—**Abstract— Repeated primary fuse failures of 34.5 kV voltage transformers (VTs) were observed during routine switching operations at an industrial substation, resulting in nuisance trips and reduced system reliability. Conventional investigations did not identify equipment or protection-related causes. A detailed electromagnetic transient (EMT) study using Electromagnetic Transients including DC (EMTDC) demonstrated that ferroresonance, initiated under lightly loaded switching conditions, produced excessive VT primary currents that exceeded fuse ratings. The interaction between cable capacitance, nonlinear VT magnetizing inductance, and system grounding created sustained oscillatory behavior. Several mitigation measures were evaluated, including VT secondary resistive loading, fuse uprating, and grounding configuration adjustments. Simulation results, supported by field observations, confirmed that the introduction of secondary damping effectively suppressed oscillations and prevented further fuse failures. The study highlights the importance of transient analysis in identifying ferroresonance and provides practical mitigation strategies for similar cable-fed medium-voltage systems.**

Index Terms—**Ferroresonance, EMTDC, industrial power systems, PT Fuse Failure, Switching Transients, voltage transformer.**

I. INTRODUCTION

Voltage Transformers (VTs) are critical components in medium-voltage industrial power systems, providing essential voltage signals for protection, control, metering, and operational monitoring. Their reliability is therefore directly linked to both system protection dependability and overall plant availability. Despite their importance, VTs failures are often treated as secondary events, with investigations focusing on fuse ratings, relay settings, or suspected manufacturing defects rather than on the underlying power-system phenomena that may be stressing the device.

In industrial substations that employ long underground cable feeders, Gas-Insulated Switchgear (GIS), and lightly loaded operating conditions, the electrical environment can be particularly severe during switching operations. These systems inherently contain significant distributed capacitance, while VTs and power transformers introduce non-linear magnetizing inductance due to core saturation. The interaction between these elements can give rise to complex transient behaviors that are not adequately captured by steady-state or short-circuit studies.

One such phenomenon is ferroresonance, a non-linear resonance condition that can be initiated by routine switching events such as dead-bus energization, transfer switching, or feeder isolation. Unlike classical linear resonance, ferroresonance may result in sustained overvoltages, highly distorted waveforms, and excessive currents that persist well beyond the initiating event. The unpredictable nature of ferroresonance makes it particularly hazardous, as equipment may be subjected to severe electrical stress without obvious external indications until failure occurs.

At a 34.5 kV industrial substation under study, the primary fuses of the VTs had repeatedly failed over several years. These failures typically occurred during switching operations rather than during system faults or abnormal loading. As a result, the plant experienced nuisance protection trips, loss of voltage measurements, and occasionally wider disturbances across the facility.

Early corrective efforts were primarily focused on managing operational impacts—for example, adjusting relay logic and alarm responses. While these measures helped reduce the immediate consequences, they did not address the underlying issue, and the fuse failures continued to occur.

After recognizing that conventional analysis methods were not yielding clear answers, a detailed electromagnetic transient (EMT) study was conducted to determine the underlying cause of the problem. The goal was not only to explain why the VT fuses were operating, but also to understand the system conditions that made this behavior possible and to identify practical and cost-effective ways to mitigate it.

This paper presents the results of that investigation. It includes a brief review of ferroresonance theory, the development of a detailed Electromagnetic Transients including DC (EMTDC)-based model of the system, a comparison of simulation results with field observations, and an evaluation of mitigation measures that could also be applied to similar industrial power systems.

This study began with an investigation into ferroresonance in an industrial medium-voltage system. The problem came to light after VT primary fuses operated repeatedly during routine switching. To understand the underlying mechanisms, a detailed EMTDC model of the network was developed. The model closely matched the real substation setup and operating conditions, and its simulation results were compared with field observations.

The analysis showed that routine switching in the cable-fed GIS can lead to ferroresonance in the connected VTs. To investigate this further, the study examined several system parameters, including network loading, resistive damping in VT secondary circuits, and the grounding of the VT primary neutral. Each of these factors influenced both the start and duration of ferroresonant oscillations.

The study also explored potential mitigation strategies, with emphasis on solutions that do not require extensive modification of the existing installation. The findings indicate that relatively simple measures can substantially reduce the likelihood of VT fuse operations. Implementing these measures can enhance the operational reliability of comparable industrial power systems utilizing cable-fed GIS substations and VTs.

II. RELATED WORK

A. *Definition and Fundamental Characteristics*

Ferroresonance is a nonlinear oscillatory phenomenon that can occur when a saturable inductance interacts with system capacitance under certain operating conditions [1], [2]. Unlike linear resonance, the system response in ferroresonance is not unique; the network may settle into different operating states. These states are often accompanied by heavily distorted voltage and current waveforms. If the system provides insufficient damping, oscillations can persist, imposing significant electrical stress on equipment connected to the network.

B. *Conditions Favoring Ferroresonance in Power Systems*

Previous studies and IEEE guidance identify several factors that increase the likelihood of ferroresonance [2], [3]. These include saturable magnetic devices such as power or VTs, high system capacitance from underground cables, GIS, and breaker grading capacitors, and lightly loaded or unloaded systems. Switching actions, especially dead-bus energization or single-pole switching, often start the disturbances that lead to ferroresonant behavior.

VTs are especially vulnerable to ferroresonance because of their highly nonlinear magnetizing characteristics and the relatively low damping in their primary circuits. Under certain conditions, even small transient disturbances can drive the VT core into saturation. When this happens, the effective inductive reactance drops, allowing oscillatory currents to grow to relatively high levels. Since VT primary fuses are usually sized to carry only the normal excitation current under steady-state conditions, they may not tolerate the higher currents that can occur during ferroresonant events.

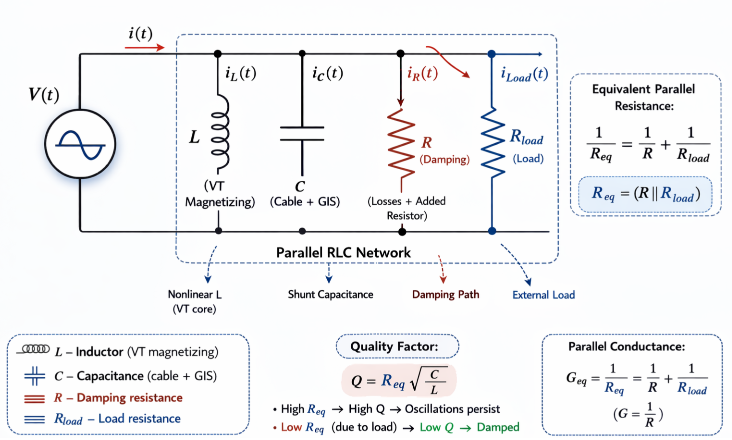


Fig. 1: Parallel RLC equivalent of ferroresonant network with load resistance.

C. *Damping Mechanisms and Quality Factor in Ferroresonant Networks*

Ferroresonance persistence is strongly governed by the effective damping of the nonlinear LC network formed by system capacitance and the saturable magnetizing inductance of VTs. In lightly loaded cable-fed systems, the dominant capacitance is typically the phase-to-ground capacitance of underground cables, while the inductive element is the nonlinear magnetizing branch of the VT operating in or near saturation. The dynamic behavior of such a network can be approximated by a parallel RLC equivalent, in which the quality factor (Q) provides a useful indicator of oscillatory persistence. The equivalent mathematical model for the Q factor is illustrated in equation 1, where R is the the equivalent shunt (parallel) resistance at the oscillating bus node, C is total effective phase-to-ground capacitance seen at the oscillating bus, and L is the effective magnetizing inductance of the VT primary winding.

$$Q = R\sqrt{\frac{C}{L}} \tag{1}$$

For a parallel configuration, demonstrating that Q increases with shunt resistance and decreases as damping increases. High values of R (e.g., under no-load conditions) result in large Q, meaning that only a small fraction of stored energy is dissipated per cycle, and oscillations may persist or evolve into sustained ferroresonant modes. Conversely, the presence of system loading or intentional resistive burdens significantly reduces the effective parallel resistance, thereby lowering Q and increasing energy dissipation per cycle. This reduction in Q suppresses oscillatory behavior before nonlinear energy exchange can be sustained. This damping process is illustrated in Figure 1. The critical role of damping and high-Q conditions in enabling ferroresonance has been widely documented in the classical transient analysis literature and in CIGRÉ technical guidance, particularly for cable-fed GIS substations under dead-bus switching conditions [4], [5].

D. Mitigation Techniques Reported in Literature

The technical literature describes several approaches to prevent ferroresonance from initiating or to mitigate its impact if it occurs [3], [6], [7]. One of the most commonly discussed methods is to introduce additional damping into the resonant circuit. In practice, this is often done by adding resistive loading to the secondary circuits of VTs. By placing burden resistors on the secondary side, extra losses are introduced into the oscillatory path. These losses help damp the oscillations and have been shown to reduce both the magnitude and the duration of ferroresonant overvoltages and currents [2], [8].

Another class of mitigation measures focuses on system configuration and grounding practices [3], [6]. Proper selection of VTs primary grounding, avoidance of unnecessary floating neutrals, and careful treatment of zero-sequence paths can materially influence ferroresonant behavior. Several studies note that changes in grounding configuration can shift resonant frequencies or increase damping sufficiently to prevent sustained oscillations under normal switching conditions.

The literature also points to operating practices as an important means of reducing the risk of ferroresonance [2], [7]. For instance, energizing a substation while some load is already connected can help provide natural damping. Similarly, avoiding single-pole switching where possible and minimizing dead-bus energization events can lower the chances of triggering ferroresonant conditions.

From a design standpoint, it has become increasingly common to recommend EMT studies during the planning stage, particularly for substations that are cable-fed or based on GIS technology. Carrying out these studies early in the project helps identify potential ferroresonance issues before the system is placed into service.

Finally, protection and monitoring enhancements such as VTs fuse failure detection logic, disturbance recorders, and high-resolution transient monitoring are identified as complementary measures. While these techniques do not eliminate ferroresonance, they improve situational awareness, reduce misoperations, and support faster diagnosis and corrective action when ferroresonant events occur.

III. METHODOLOGY

A. EMT Modeling Approach

A detailed three-phase electromagnetic transient model of the substation was developed using EMTDC. The model incorporated frequency-dependent representations of the underground cables, detailed saturation characteristics for both power transformers and VTs, and explicit modeling of the GIS and circuit-breaker stray capacitances. The actual switching sequences and protection logic were replicated to ensure an accurate representation of field conditions.

B. Simulation Scenarios

Several simulation scenarios were evaluated to assess system behavior under various operating conditions. These scenarios included dead-bus switching with no load, switching under partial load, adding VTs secondary phase-to-ground resistive loading, and varying VTs primary neutral grounding. For each scenario, bus voltage behavior, VTs primary current magnitude, and oscillation decay were analyzed.

IV. CASE STUDY

The investigated power system is a medium-voltage industrial substation operating at a nominal voltage level of 34.5 kV. The substation is supplied through two parallel 120/160 MVA, 230/34.5 kV power transformers connected to an upstream transmission network via approximately 2 km of underground cable, as depicted in Figure 2. The use of long, high-voltage cable feeders introduces substantial distributed phase-to-ground and phase-to-phase capacitance, which plays a critical role in the system's transient behavior during switching operations.

On the 34.5 kV side, the substation uses GIS with vacuum circuit breakers for incoming feeders, bus-tie breakers, and outgoing loads. GIS systems have higher stray capacitance than air-insulated switchgear because their conductors are closer together, and grading capacitors are sometimes used across the breaker contacts. These features help with insulation coordination and reduce the equipment's footprint, but they also raise the network's total capacitance and can influence resonance during transient events.

Voltage measurement for protection, control, and metering is provided by a single-phase VT connected line-to-ground. The installed VTs are rated 100 VA with a primary voltage of approximately 20.8 kV and a secondary voltage of 69.3 V. Under normal operating conditions, the secondary circuits are lightly loaded, supplying only protection relays, meters, and control systems. This operating condition results in minimal inherent damping of the VT's magnetizing circuit, increasing susceptibility to non-linear oscillatory phenomena.

For several years, the substation had repeated VT and primary fuse failures. These issues did not happen during short-circuit faults, long overvoltages, or unusual steady-state loading. Instead, they always happened during routine switching, such as dead-bus energization, manual transfer between incomers, and isolating or restoring bus sections. Often, when a fuse operated, it caused loss of voltage readings, nuisance undervoltage alarms, and unexpected protection actions (e.g., 27 pickup), disrupting downstream processes.

Field data captured during selected switching events revealed pronounced voltage transients at the instant of breaker operation, followed by irregular oscillatory waveforms as in Figure 3. Although the RMS bus voltage typically remained within acceptable limits, the VTs' primary currents exhibited short-duration peaks and, in some cases, sustained oscillations of sufficient magnitude to operate the installed primary fuses. These observations indicated that the failures were driven by transient energy and waveform distortion rather than by steady-state thermal overload.

Long underground cable feeders, GIS-related stray capacitance, lightly loaded line-to-ground connected VTs, and specific switching sequences combined to create a system configuration prone to ferroresonance. The next Section

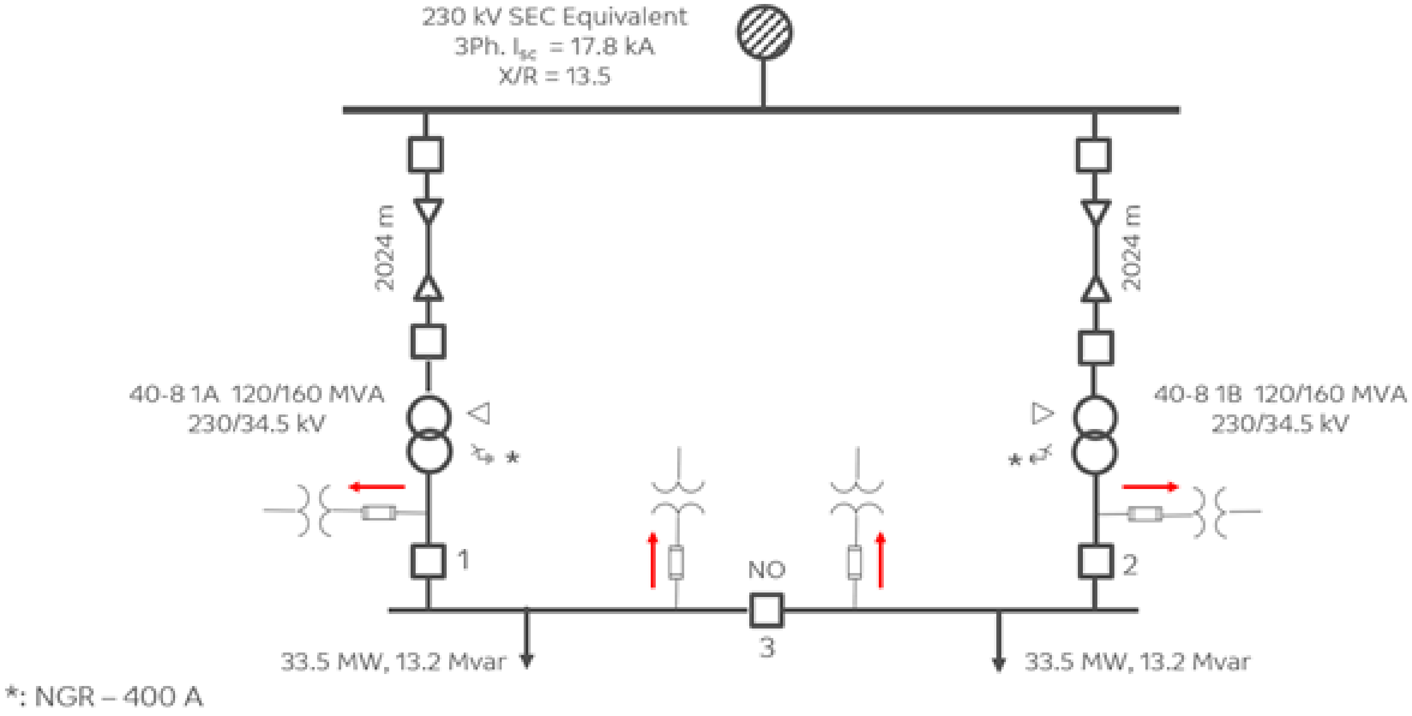


Fig. 2: Substation single-line diagram.

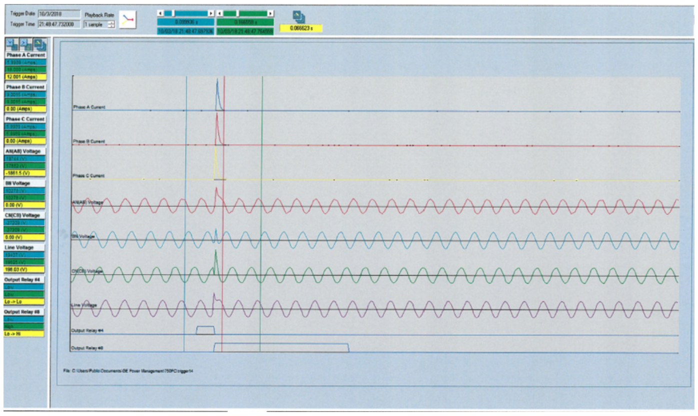


Fig. 3: Voltage surge during energization of 34.5KV GIS SWGR.

provides the physical and operational context for explaining why ferroresonance could recur in an otherwise normal industrial substation, thereby supporting the need for the detailed EMT analysis in the following sections.

V. RESULTS

A. *Ferroresonant Response Without Mitigation*

Simulating dead-bus switching without mitigation produced low-frequency, sustained oscillations characteristic of ferroresonance. Bus voltages displayed slowly decaying, irregular waveforms, and VT primary currents exceeded the 1 A fuse rating. These results closely matched field observations and confirmed that ferroresonance can cause fuse operation.

Figure 4a presents simulated bus voltage and VT primary current waveforms for the unmitigated dead-bus switching case, clearly showing sustained oscillations and excessive current levels.

B. *Impact of VT Secondary Loading*

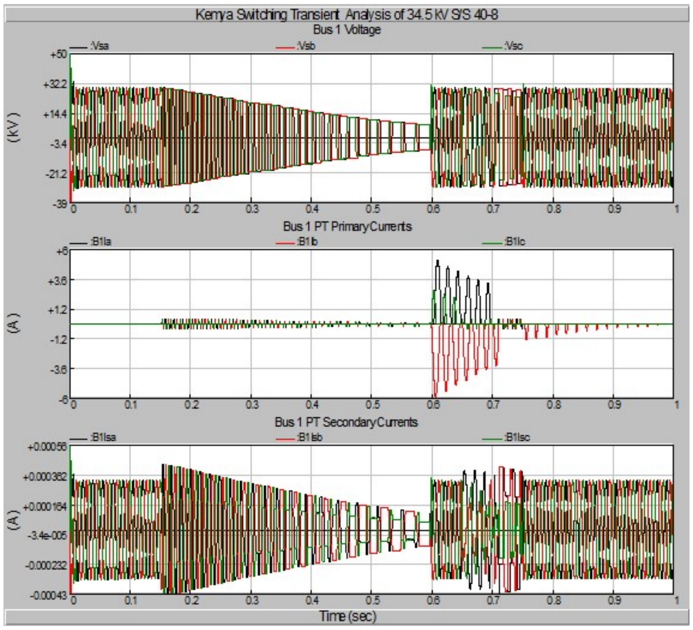
The addition of a 60 Ω phase-to-ground resistive load on the VT secondary significantly increased system damping. Simulation results showed rapid decay of ferroresonant oscillations and a substantial reduction in the VT primary current, thereby keeping the currents below the fuse-melting threshold. This behavior is consistent with established ferroresonance damping theory. The procedure of computing the resistance value is elaborated on Appendix A.

Figure 4b shows VT primary current waveforms the application of secondary resistive loading.

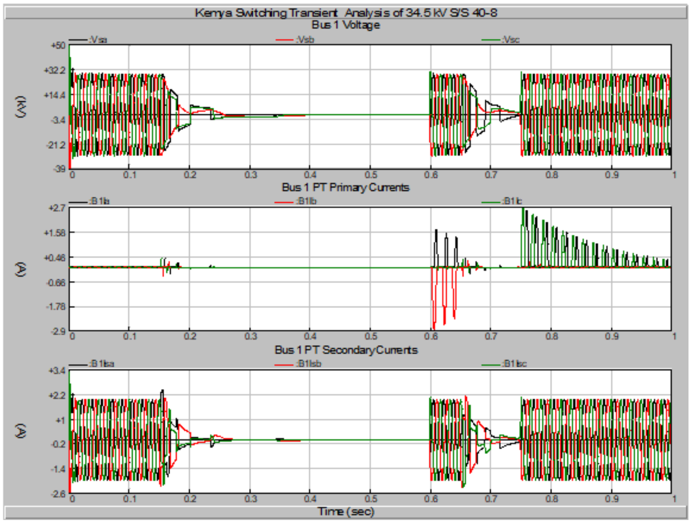
C. *Effect of System Load*

When system load was present, additional damping was introduced, reducing the magnitude of ferroresonant oscillations compared to the no-load case. However, VT primary currents still exceeded the 1 A fuse rating during certain switching events, indicating that load damping alone was insufficient (see Figure 5). Fuse uprating was therefore required in conjunction with other mitigation measures.

It is worth noting that under loaded conditions, inherent system damping introduced by the connected load impedance and transformer losses significantly reduces the Q-factor of the nonlinear LC network. Consequently, the additional damping provided by the 60 Ω VT secondary resistor represents



(a) Dead-bus switching with no load



(b) Dead-bus switching with resistor

Fig. 4: Dead-bus switching

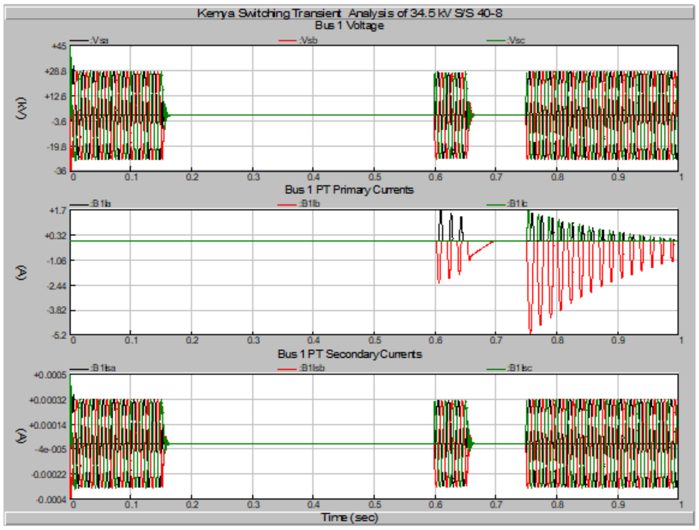


Fig. 5: Switching with load.

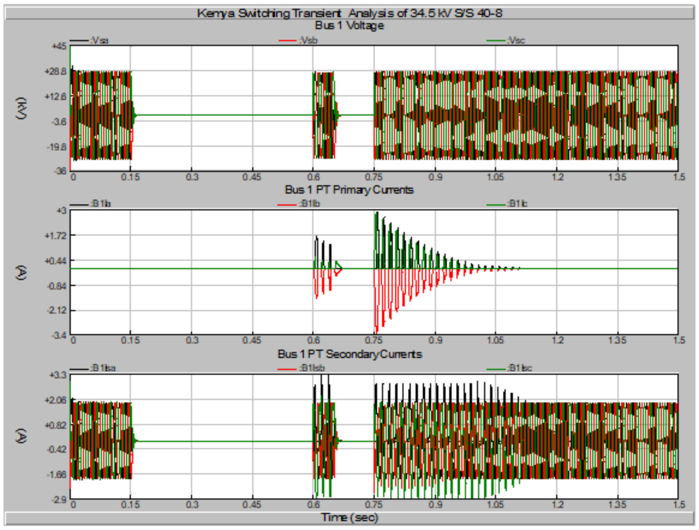


Fig. 6: Switching with PT primary neutral isolated.

a comparatively small increment, resulting in a negligible change in oscillatory response relative to the no-load case.

D. Neutral Grounding Sensitivity

Isolating the VT primary neutral further reduced zero-sequence energy circulation and improved system stability. Simulation results showed reduced current magnitude and faster decay of oscillations, even under unfavorable switching conditions.

Figure 6 illustrates the effect of VT primary neutral grounding versus isolation on ferroresonant current behavior.

VI. DISCUSSION

The investigation found that repeated VT fuse operations were caused by ferroresonance. This happened during switching events, when system transients triggered an interaction between the network capacitance and the magnetizing inductance of the VTs. As this interaction began, oscillatory voltages appeared, and the VT core became saturated. When the core is saturated, the effective inductance drops, and energy starts to circulate between the inductive and capacitive parts of the circuit.

Under these conditions, the currents rose far above the normal excitation level of the VT. The fuse operations were not due to faulty equipment or incorrect fuse ratings. Instead, they occurred due to oscillatory currents arising from the ferroresonant condition. Earlier studies on instrument transformers in cable-fed substations have described similar situations in which oscillations can persist even when the steady-state system voltage remains within acceptable limits [2], [7].

While increasing fuse ratings improved tolerance to transient currents, they did not eliminate the underlying resonance, consistent with published guidance indicating that protective device uprating alone cannot suppress ferroresonant behavior without additional damping [2], [6]. Effective mitigation, therefore, required intentional dissipation of oscillatory energy through resistive loading and grounding optimization.

The effectiveness of secondary resistive loading and grounding configuration adjustments observed in this study aligns with recommendations reported in both IEEE and CIGRÉ literature, which emphasize damping enhancement and careful management of zero-sequence paths as primary means of controlling ferroresonance in medium-voltage systems [3], [9].

Following the study, several mitigation measures were implemented. Phase-to-ground resistive loading was added to all VT secondaries for consistent damping. VT primary fuse ratings were increased from 1 A to 2.5 A to handle residual transient currents.

In low-resistance grounded systems, the zero-sequence network is constrained by the grounding resistor rather than a solid ground reference. Consequently, the grounding treatment of line-to-ground-connected VTs can materially influence the susceptibility to ferroresonance. Depending on the resulting zero-sequence damping and neutral displacement, isolating the VT primary neutral alters both the system's zero-sequence energy path and its voltage reference. On the one hand, removing the grounded neutral reduces the circulating zero-sequence current through the VT magnetizing branch, thereby decreasing the magnitude of the ferroresonant current and the associated thermal stress on the VT. On the other hand, the absence of a defined ground reference allows neutral displacement and increases the system's degrees of freedom, which can promote sustained or unstable ferroresonant oscillations, particularly in cable-fed and lightly loaded networks. As a result, the impact of neutral isolation is not unidirectional; it may reduce device-level stress while simultaneously increasing the system's susceptibility to persistent oscillatory behavior. Therefore, its effectiveness must be evaluated for the specific system configuration using EMT analysis.

Operational practices were also adjusted to enable transfer switching under load when feasible, and digital fault recorders were recommended to improve future event analysis.

Although EMT simulation results indicated that isolation of the VT primary neutral reduced zero-sequence energy circulation and improved damping of ferroresonant oscillations, this mitigation approach was not selected as the primary solution for implementation. The decision was driven by protection and operational considerations rather than purely transient performance.

In the investigated substation, the VT circuits are used for protection functions that rely on a stable phase-to-ground voltage reference, including undervoltage protection and system monitoring. Removing the VT primary neutral grounding introduces a floating reference, which can lead to neutral displacement and reduced measurement reliability under certain system conditions, particularly in a low-resistance grounded network. This may adversely affect protection sensitivity and coordination.

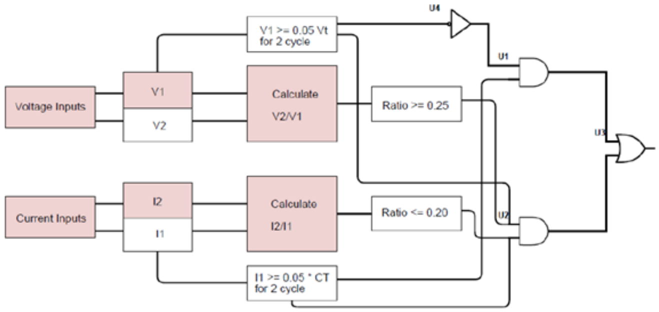


Fig. 7: PT fuse-failure Logic Diagram.

Furthermore, modification of VT primary grounding requires changes to the protection philosophy, potential re-validation of relay settings, and coordination with switchgear and protection vendors. Compared to secondary resistive loading, which can be implemented without affecting primary system configuration or protection schemes, neutral isolation was considered a higher-risk modification.

Therefore, although neutral isolation demonstrated beneficial effects in simulation, it was treated as a conditional or secondary mitigation measure. The selected solution prioritized methods that provide effective damping while preserving existing protection functionality and system grounding practices.

The VT/PT fuse-failure program was implemented as a supervised sequence-component plausibility check to prevent nuisance undervoltage tripping during loss-of-voltage measurements. The logic asserts a VT$_{FAIL}$ condition when negative-sequence voltage indicates an apparent unbalance while negative-sequence current remains below a security threshold, which is inconsistent with true phase-loss conditions and is indicative of VT fuse loss or VT removal. A secondary detection path asserts VT$_{FAIL}$ when positive-sequence current is present but the positive-sequence voltage is negligible, indicating loss of all VT channels. Upon assertion, VT$_{FAIL}$ blocks the undervoltage trip output while generating a dedicated alarm and event record; short pickup and dropout delays are applied to maintain security during switching transients. This logic is in Figure 7.

The recommended actions to mitigate the ferroresonance are:

- To install phase-to-ground loading resistors at the secondary side (69.3 V) of all PT's (bus & line PT's).
- To replace the existing 1 A PT primary fuses with 2.5 A fuse rating.
- To verify with the switchgear OEM the necessity of bus PT's primary neutral grounding. If zero-sequence measurements are necessary, then the grounding of the neutral shall be maintained. Otherwise, the neutral

grounding can be eliminated to ensure faster damping of the system Ferroresonance condition.

- To conduct the manual transfer switching under load conditions.

VII. CONCLUSIONS

This paper investigates repeated VT fuse failures at a 34.5 kV industrial substation. EMT simulations and field data identified ferroresonance as the primary cause. Contributing factors included long cable capacitance, saturable VT cores, and lightly loaded switching. Implementing simple, cost-effective solutions eliminated ferroresonance and prevented further failures. These findings support similar medium-voltage installations and underscore the importance of transient studies in system design.

APPENDIX

A. A.1 Objective

This appendix presents the procedure for determining the value of the resistive burden connected to the VT secondary for ferroresonance damping. The selected resistance must:

- Provide sufficient damping to reduce the quality factor of the nonlinear LC network;
- Remain within the thermal and accuracy limits of the VT-rated burden.

B. A.2 Governing Relationship

For a purely resistive burden connected to the VT secondary, the power dissipated in the resistor is:

$$P_R = \frac{U_s^2}{R} \tag{2}$$

where:

- U_s = rated VT secondary voltage (V),
- R = secondary resistance (Ω),
- P_R = power absorbed by the resistor (VA).

To ensure the VT rated output is not exceeded, the following constraint must be satisfied:

$$P_m + P_R \leq kP_t \tag{3}$$

where:

- P_t = rated VT output (VA),
- P_m = existing measurement/protection burden (VA),
- k = permissible loading factor ($0.25 \leq k \leq 1.0$).

Rearranging yields the minimum allowable resistance:

$$R = \frac{U_s^2}{kP_t - P_m} \tag{4}$$

C. A.3 Example Calculation (34.5 kV System VT)

For the investigated substation:

- $U_s = 69.3$ V,
- $P_t = 100$ VA,
- $P_m = 10$ VA (existing burden),
- $k = 0.8$ (80% loading limit).

Allowable resistor power:

$$P_R = kP_t - P_m = (0.8)(100) - 10 = 70 \text{ VA} \tag{5}$$

Therefore:

$$R = \frac{69.3^2}{70} \tag{6}$$

$$R = \frac{4802}{70} \approx 68.6\ \Omega \tag{7}$$

A standard resistor value of 60 Ω was selected, resulting in:

$$P_R = \frac{69.3^2}{60} \approx 80 \text{ VA} \tag{8}$$

which remains within the VT rated output of 100 VA.

D. A.4 Primary-Side Equivalent Resistance

The damping effect may be examined on the primary side using the turns ratio:

$$n = \frac{V_{primary}}{V_{secondary}} \tag{9}$$

For a 20.8 kV / 69.3 V VT:

$$n \approx 300 \tag{10}$$

The resistance reflected to the primary is:

$$R_{primary} = n^2 R_{secondary} \tag{11}$$

For $R_{secondary} = 60\ \Omega$:

$$R_{primary} = (300)^2 \times 60 \approx 5.4\ \text{M}\Omega \tag{12}$$

This reflected resistance increases damping of the nonlinear parallel LC network formed by cable capacitance and VT magnetizing inductance.

E. A.5 Practical Considerations

- The resistor should be non-inductive construction.
- Continuous power rating should be at least twice the calculated dissipation.
- Final adequacy of the selected value must be validated by EMT simulation.

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VITA

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Prof. M. R. Qader is a Professor of Electrical Engineering at the University of Bahrain. He has held several senior academic leadership roles at the University, including Vice President for Academic Programs and Graduate Studies, Dean of Postgraduate Studies and Scientific Research, and Director of the Engineering Program. He earned his B.Sc. (Hons) in Electrical Engineering from the University of Bahrain in 1991, and subsequently received his M.Sc. (1993) and Ph.D. (1997) in Electrical Engineering from the University of Manchester Institute of Science and Technology (UMIST), United Kingdom. Prof. Qader's research addresses power quality, voltage sags, and electric power systems, with contributions spanning power quality enhancement, strategic control systems, and fuzzy control methodologies. He has also supported institutional initiatives aligned with the Sustainable Development Goals (SDGs) and green energy programs. In addition, he has chaired numerous international conferences and led multiple research initiatives. A strong advocate for academic quality and research-led education, Prof. Qader has made major contributions to curriculum and program development at the University of Bahrain. He has developed more than 50 undergraduate and postgraduate programs and has led the development and review of approximately 112 academic programs across the University. He has authored over 100 publications in reputable peer-reviewed journals.

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