Ferroresonance: TVA Experience & Mitigation Methods

Gary L. Kobet
Tennessee Valley Authority
Chattanooga, Tennessee, U.S.
glkobet@tva.gov

Abstract—**Ferroresonance is a phenomenon which can occur in part of a power system where capacitive reactance is in series with the nonlinear inductive reactance of a transformer. When the two values approach each other in magnitude, extremely high voltages can be applied to local equipment and insulation, sometimes resulting in damage and faults. In TVA transmission switchyards, ferroresonance has resulted from the series combination of the inductance of bus voltage transformers (VT) with grading capacitors across circuit breaker contacts. In distribution switchyards, the condition has occurred on 13kV buses fed from delta-connected power transformer windings, where the ferroresonant circuit included unbalanced stray bus capacitance again with bus potential transformers. This paper will describe some events in both categories and provides the mitigation solutions chosen for each. For transmission, the options include (among others) replacing circuit breakers or voltage transformers. For distribution, options include three-phase switching instead of single-phase and/or ensuring a grounding transformer is always connected to the bus during switching. Short-term solutions, in both cases, involved developing operating guidelines intended to minimize the risk.**

Keywords—Ferroresonance, grading capacitor, nonlinear inductance, grounding transformer, voltage transformer

I. INTRODUCTION

The Tennessee Valley Authority (TVA) is a federally owned, self-financed corporation with the mission to provide navigation, flood control, and electric power in the Tennessee Valley Region. TVA operates the Nation's largest public power system, with a service area covering parts of seven states and 80,000 square miles (over 200 km2) serving 10 million people. It is primarily a wholesaler of power to distributors, but it also sells power directly to larger industrial customers. The TVA transmission system consists of over 16,000 circuit miles (25,000 km) of transmission lines and 513 transmission substations, with transmission operating voltages primarily at 500kV and 161kV. TVA has over 50 power transformer banks with high-side windings rated 500kV and configured wye-grounded. TVA does serve a limited number of distribution switchyards rated 13kV either as the primary owner or in cooperation with a Local Power Company (LPC).

Over the past 50 years, the Tennessee Valley Authority (TVA) has experienced several ferroresonance events, both in transmission and distribution switchyards.

In transmission switchyards the ferroresonant circuit has been with grading capacitance of power circuit breakers in-series with conventional winding-type voltage transformers. In most cases, the condition has occurred during switching procedures, but in at least one case, it followed an automatic bus trip. In the more recent cases, it came as a surprise to some of us that even single contact circuit breakers can have "grading" capacitors which designers specify to increase the breaker fault interrupting rating. The mitigation for transmission switchyards has been to: (1) replace breakers with those not having grading capacitors, (2) adding bus capacitance (via coupling capacitor or high-capacitance CCVT), (3) adding secondary resistance loading to the PT secondaries, (4) remove grading capacitors (only if manufacturer approves AND breakers not overstressed), or (5) using PTs with gapped cores. Meanwhile, TVA has developed and communicated operating guidelines on how to minimize (not mitigate) the risk of ferroresonance during switching.

In distribution switchyards, the condition has occurred on 13kV buses fed from delta-connected power transformer windings. A grounding transformer is provided to provide a zero-sequence path for ground faults, but ferroresonance has occurred during switching procedures where the grounding transformer was intentionally disconnected. In most of these cases, three-phase gang-operated switches were used, but in the most recent case, single-phase switches were used. For three-phase switching, the mitigation for distribution switchyards has been to require the grounding transformer to be connected during the switching procedure. However, for single-phase switching, it has been proven by time-domain transient studies that having the grounding transformers connected is not effective. Note this is regardless of whether a neutral grounding switch (where applied) is open or closed. The most effective way to mitigate ferroresonance on 13kV delta tertiaries seems to be requiring three-phase switching (i.e., circuit breaker or gang-operated disconnect) with the grounding bank connected and its neutral grounded.

TVA has modeled some events using an electromagnetic transients program. This was done for two distribution events (Arab, Albertville), and for two transmission events (Franklin, Raccoon Mountain). It is our thinking that not every event requires a detailed study since the circuits are similar enough to recommend effective mitigations for each case. This is especially true since TVA has generally chosen not to implement secondary loading resistance as a mitigation, which certainly would require specific detailed studies.

II. Ferroresonance

Ferroresonance is a phenomenon whereby the non-linear magnetizing inductive reactance of an iron-core transformer interacts with system capacitance so that a series resonant circuit is formed, resulting in extreme high voltages on the bus to which the transformer is connected. See Figure 1, where the system capacitance cancels out all the transformer inductance, so that the only limiting impedance is from the source. The resulting voltage across the capacitor/inductor series combination is theoretically zero, but the voltage across the individual elements can be extremely high [1].

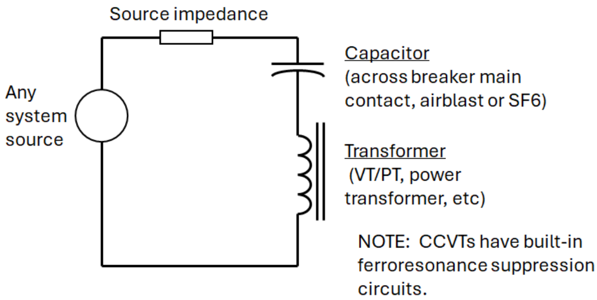

Figure 1. Ferroresonance

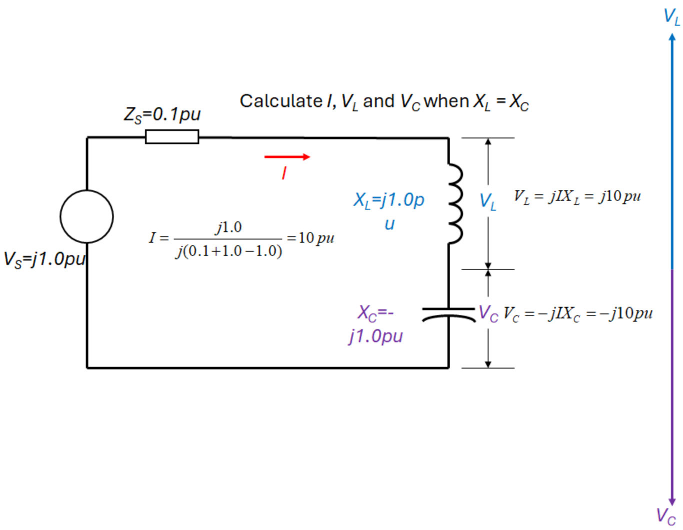

Figure 2. Simple ferroresonant circuit

Voltage transformers (VTs, instrument transformers) may be more at risk of such a phenomenon than power transformers, particularly VTs connected to transmission buses with circuit breakers having grading or TRV capacitors connected across the main contacts, or ungrounded distribution buses having unbalanced stray capacitance [2]. This has been TVA's experience, although it is certainly true ferroresonance can and does occur with power transformers as well.

Modes of ferroresonance include fundamental (at fundamental frequency), sub-harmonic, quasi-periodic, and chaotic. A sudden switching event such as opening a circuit breaker or opening a disconnect is typically required to drive a circuit into ferroresonance.

An excellent tutorial on ferroresonance is found in reference [1].

III. TVA Events

This section will describe the general circuits that have produced ferroresonance in each category (transmission, distribution), provide details for a few of those events, and include the chosen mitigation.

A. Transmission: Breaker grading capacitors and bus voltage transformers

Grading capacitors are used in power circuit breakers to equalize the voltage distribution across the series contacts in airblast breakers, where the number of interrupting breaks can be from two up to ten. However, capacitors can even be used across a single interrupting contact in some SF6 circuit breakers to increase the fault current interrupting ratings.

In TVA's experience, the ferroresonant circuit in the transmission case involves breaker grading capacitors in series with the non-linear inductance of winding-type voltage transformers. See Figure 3 where the breaker for line 1 has been opened; the source system at the end of line 1 keeps the circuit energized.

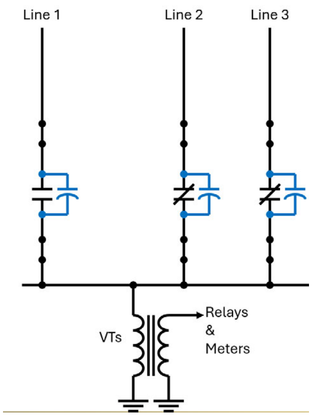

Figure 3. Circuit breaker grading capacitance in-series with bus VT

TVA has had several such ferroresonance events in transmission switchyards; the Franklin event of 2013 will be described in some detail here:

1) 2013 Franklin TN - during switching - sustained overvoltage (300kV phase-to-ground on 161kV bus)

In this case a 161kV bus section was cleared for certain maintenance and/or construction tasks. The bus was subsequently returned to service. The switching for bus clearing was uneventful and included opening circuit breakers 914, 904, 894, 1064 and their bus-side disconnects. Switch 850 was opened to deenergize the bus. It is important to note that while each breaker has disconnect switches on both sides, only the bus-side disconnects were opened to provide the working clearance.

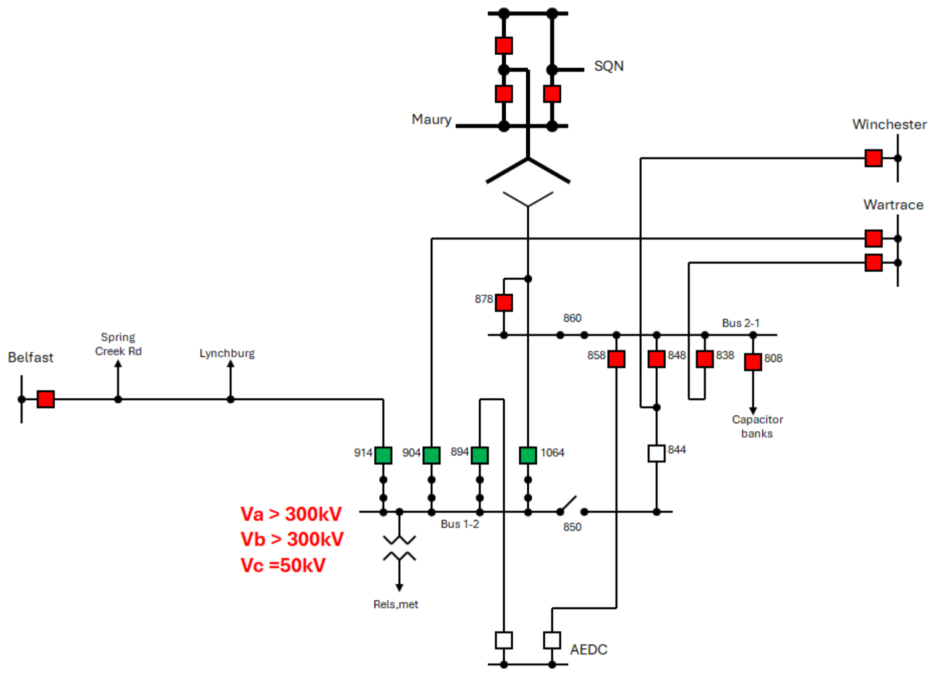

Figure 4. Ferroresonance at Franklin substation

On the return, ferroresonance occurred (see Figure 4). Following is the order of switching with observations from post-event analysis (the bus voltage readings were not noticed by operators in the control center nor in the field):

- Bus-side disconnect for 1064 closed. Bus voltage rose from zero to 27kV.
- Bus-side disconnect for 894 closed. Bus voltage rose from 27kV to 39kV.
- Bus-side disconnect for 904 closed. Bus voltage rose from 39kV to 46kV.
- Bus-side disconnect for 914 closed. Bus voltage rose from 46kV to 50kV.
- At this point the bus voltage was at 50kV with all four breakers open and switch 850 open.
- Next circuit breaker 914 was closed to test the bus (successfully, i.e., no fault).
- Shortly thereafter, breaker 914 was opened, and the phase-to-ground voltage on two phases exceeded 300kV. It can be seen from Figure 5 that it was fundamental mode (60Hz) ferroresonance.

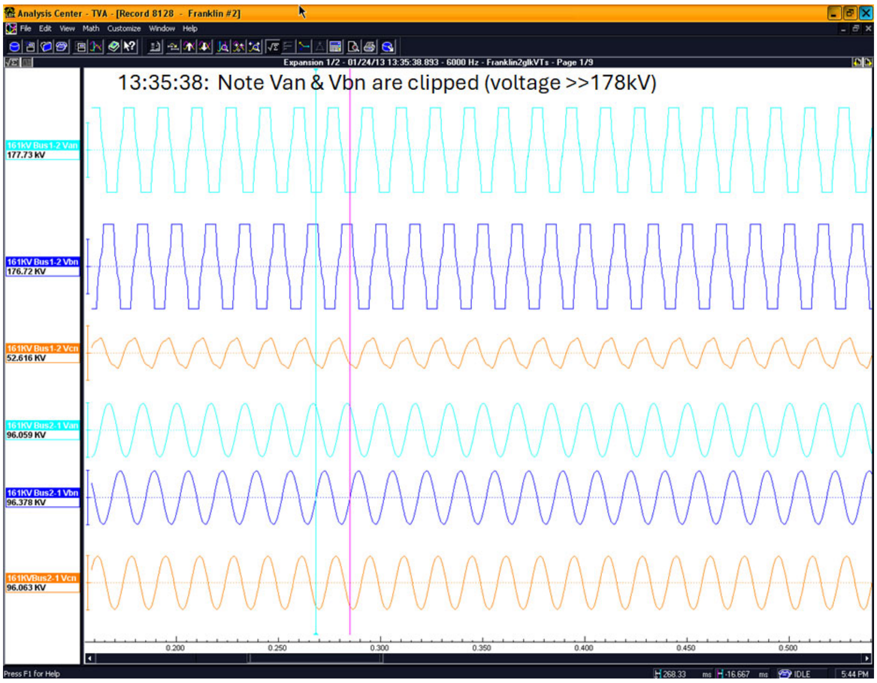

Figure 5. Fundamental mode ferroresonance at Franklin

As previously stated, it came as a surprise to some of us that the circuit breakers were SF6 single contact yet having a grading capacitor. After this was discovered and verified in the manufacturer's instruction manual for the breaker, the ferroresonant circuit was easily seen between the grading capacitors and the winding-type voltage transformers.

Following study using an electromagnetic transients program, the solution was to replace the conventional winding-type VTs with high-capacitance CCVTs, which successfully detune the circuit.

Other TVA transmission events are described in (IV.1) along with a discussion of possible mitigations and those chosen following each event.

B. Distribution: Ungrounded tertiary bus stray capacitance and bus voltage transformers

In distribution switchyards, the ferroresonance has been in the zero-sequence circuit due to unbalanced phase-to-ground capacitance. This is described in reference [1], see Figure 6. The series circuit is the unbalanced phase-to-ground capacitance with winding-type voltage transformers on the bus.

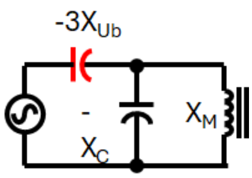

Figure 6. Ferroresonant circuit on ungrounded bus due to stray unbalanced phase-to-ground capacitance

TVA has had several such events on 13kV ungrounded buses; the 2023 Albertville event will be described here:

1) 2023 Albertville

The Albertville substation is jointly owned by TVA and two LPCs. Each LPC has their own 13kV switchyard served by the 13kV ungrounded tertiary winding of a different 161/46/13kV transformer bank. Each 13kV main bus has three wye-grounded/wye-grounded voltage transformers. TVA owns both transformer banks and provides switching/clearance services for the LPC 13kV switchyards. All 13kV disconnects are single-phase disconnects (non-gang-operated) which must be opened/closed one-at-a-time using a hot stick (aka "hook stick). See Figure 7.

The 13kV bus for one of the LPCs had been cleared a few days before the event, as follows:

- LPC transfers load off their 13kV bus to other stations.
- Two days later, customer opens all feeder breakers on their 13kV bus.
- TVA places a clearance (hold order) on the 13kV yard after opening single-phase disconnects between the bank and the yard.
- LPC clears zig-zig grounding transformer from their bus by opening isolating disconnect (suspected leaking bushing).
- A day later, TVA removes the clearance, and the LPC energizes their 13kV bus using single-phase disconnects, but without having returned the zig-zag grounding transformer. (No ferroresonance…. yet.)
- Two days later, TVA is requested to again deenergize the LPC 13kV bus for additional work. Again, this is done using single-phase disconnects. Ferroresonance is noticed post-event but no equipment failure (yet).
- Two hours later, the yard is reenergized using the single-phase disconnects, and the C-phase VT fails catastrophically, resulting in a fault and subsequent trip of the transformer bank.

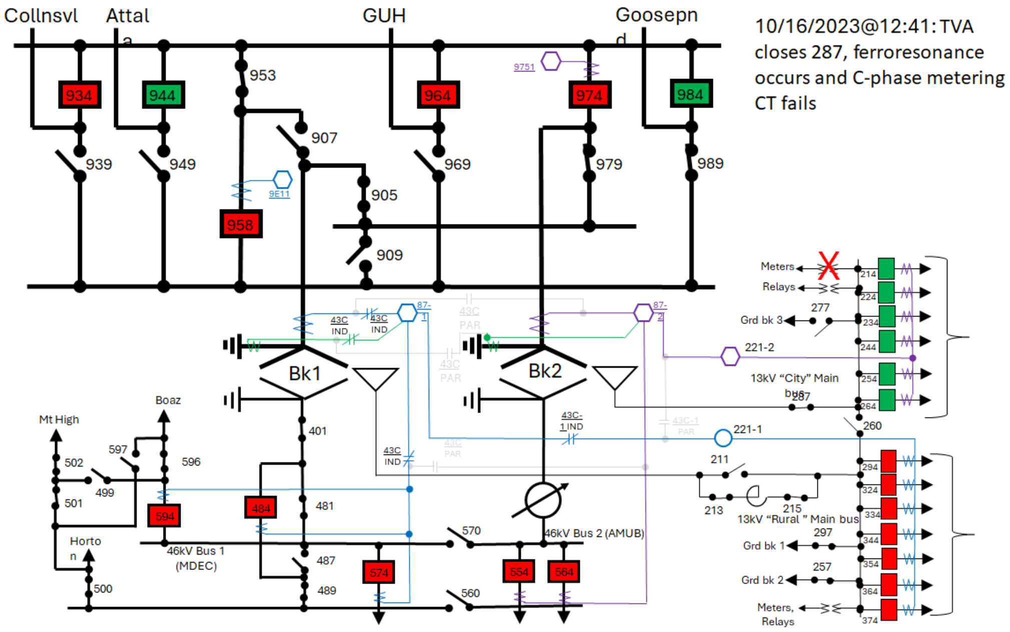

Figure 7. Ferroresonance at Albertville with single-phase switching and no grounding transformer

The waveforms for the bus deenergization two hours prior to the final energization & VT failure are shown in Figure 9. No such waveforms were available for the actual energization/failure event. These waveforms seem to indicate "chaotic" ferroresonance after the first phase was opened with a possible subharmonic mode after the second phase was opened [1]. The stress on the VT may have been such that subsequent failure on energization was likely.

The failed VT is shown in Figure 8.

Figure 8. Failed VT at Albertville

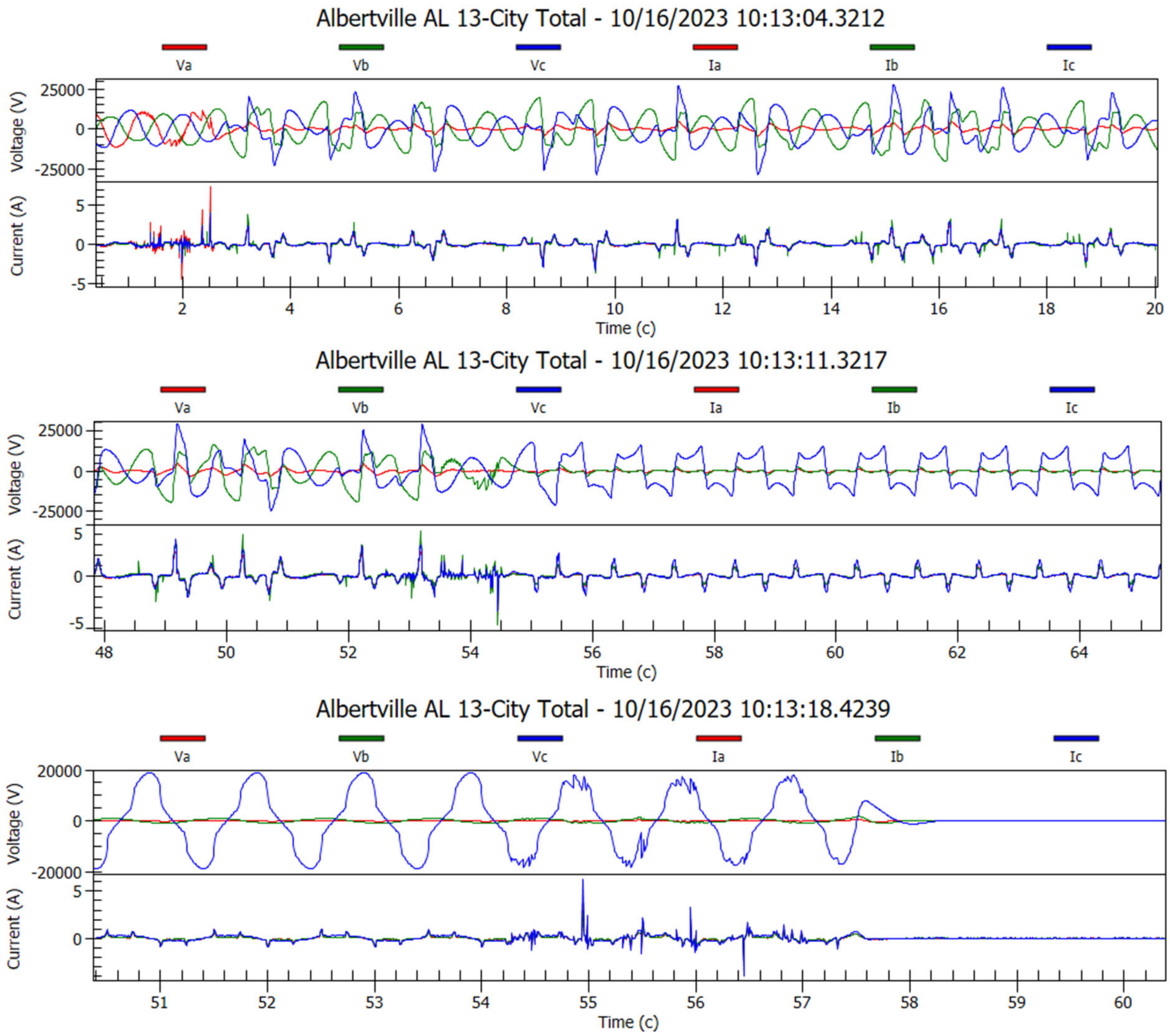

Figure 9. Ferroresonance waveforms at Albertville prior to catastrophic failure

IV. Mitigation Options

1) Transmission mitigating options

Mitigating options for the transmission events for TVA have included:

- Removal of grading capacitors across the breaker main contacts.
    - This is done only if the manufacturer approves AND the breaker will not be overstressed (i.e., available fault current does not exceed breaker interrupting capability without the grading capacitors).
- Replace breakers with those not having grading capacitors across the main contacts.
    - Some breakers have capacitors connected phase-to-ground on the line-side of the breaker contacts to smooth the transient recovery voltage (TRV) waveform; these capacitors are in parallel with the inductance of the bus voltage transformers and do not present a risk of ferroresonance.
- Add bus phase-to-ground bus capacitance.
    - This can be coupling capacitors only or coupling capacitor voltage transformers. Replacing conventional winding-type voltage transformers with CCVTs is included in this option. The CCVTs provide secondary voltage for the same purposes as the conventional VTs (i.e., relaying, metering, SCADA indication, etc.).[1]

TVA has attempted to develop operating guidelines as a preventive measure. But see the following events with a discussion of operating guidelines developed:

a) 1979 Watts Bar Nuclear Plant - during switching - catastrophic failure of 500kV bus VTs: The circuit breakers were 500kV airblast breakers having 6 breaks per phase with 3000pf across each break (500pf per phase). The mitigation solution was to install 5000pf coupling capacitors installed on 500kV buses, along with the issuance of two memos with operating guidelines.

b) 1992 Charleston TN - during switching - sustained overvoltage (345kV phase-to-ground on a 161kV bus): The circuit breakers were SF6 single contact with grading capacitor. The solution was to remove the grading capacitors prior to final commissioning of the station.

c) 1995 Loudon TN - during switching - sustained overvoltage (300kV phase-to-ground on 161kV bus): The circuit breakers were SF6 single contact with grading capacitor. The solution was to remove the grading capacitors prior to final commissioning of the station.

d) 1996 Sequoyah Nuclear Plant - during switching - catastrophic failure of 500kV bus VT. The mitigating solution was to reiterate previous operating guidelines

e) 2016 Raccoon Mountain - following automatic bus trip: The circuit breakers were 161kV airblast breakers with two interrupting breaks per phase having grading capacitors across each break. The solution was to replace the conventional winding-type VTs with high-capacitance CCVTs.

f) 2024 Marshall - during switching - sustained overvoltage: The circuit breakers were SF6 single contact with grading capacitor. The short term solution was to again reiterate previous operating guidelines. The long term solution will be to replace the two circuit breakers with ones not having grading capacitor, after which no operating guidelines will be required.

It is interesting to note that following the 1979 Watts Bar event, operating guidelines were issued to avoid ferroresonance. And again, following the events of 1992, 1995 and 1996, similar guidelines were issued. Still again, similar guidelines were issued in 2013 following the Franklin event, and TVA has experienced two additional transmission ferroresonance events. What does this say about the effectiveness of operating guidelines?

2) Description of operating guidelines and their "effectiveness"

Before moving on, a discussion of the operating guidelines is in order.

These are quotes from the memos TVA issued to operators. Note the date/year of each.

- 1979 memo: "*...it is very important that when energizing or deenergizing a piece of equipment with an air circuit breaker (acb) using grading capacitors that the amount of time during which the breaker isolating disconnects are closed but the breaker itself is open should be minimized. In preparation for closing the breakers to energize a bus, the breaker isolating disconnects should not be closed on more than one breaker with the breakers open while preparing to energize a bus. Likewise, when deenergizing a bus or a line, the isolating mod's should be opened immediately after opening the breaker.*"

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[1] TRV capacitors are connected on the line-side of circuit breakers do not help mitigate ferroresonance because they are not connected directly to the bus.

- 1980 memo: "*…while energizing a bus with only the pt's connected to it, close the isolating switches for only one breaker then immediately close the associated breaker before proceeding to the next breaker or inspecting the switches for proper operation. While deenergizing a bus, open one breaker then open its isolating switches before proceeding to the next breaker…. In the event of a bus tripoff (bus differential), immediately open the isolating switches for all breakers before proceeding to inspect the bus.*"

- 1996 memo: "*…any time switching is being performed to deenergize or energize a switchyard bus with a potential transformer, if possible, deenergize the bus and potential transformer with a sectionalizing MOD [motor operated disconnect] or disconnect or from a remote terminal…. If the air blast or SF6 breaker at the station has to be used, open isolating disconnects immediately. In the event of a bus differential or relay operation, the isolating disconnects on air blast or SF6 breakers should be opened immediately.*"

- 2013 memo: This was a one-page document intended to provide step-by-step instructions when clearing/returning a bus section. See Figure 10.

The effectiveness of each set of guidelines may be judged by the number of ferroresonance events occurring following their issuance.

This seems to point to the need for engineering solutions rather than operational ones. As excellent as our operators are, planners/designers may unintentionally set traps for them by providing a system with the opportunity for ferroresonance.

The engineering solutions described above (adding bus capacitance, replacing bus VTs, removing grading capacitors or replacing circuit breakers) seem superior to hoping the switching procedure has been written according to a memo.

In addition, the deficiency in such guidelines is seen in the word "immediately", as in "immediately close the breaker" or "immediately open the isolating disconnects". Given that it takes several minutes for an operator to travel between the control house (where the breaker control handle is located) and the switchyard (where the isolating disconnects are located), a ferroresonance condition may last for those several minutes before an operator and "immediately" perform the required action.

The other problem with these edicts using the term "immediately" is with automatic bus tripping. Because transmission substations are generally unattended, and because many isolating disconnects may be manual only (no motor operators with no remote-control capability from the dispatch center), it can be many minutes or even hours before an operator can be (1) contacted, (2) reach the station, and (3) perform the required action (i.e., "immediately" open the isolating disconnects).

For these reasons, engineering solutions seem superior to operating guidelines.

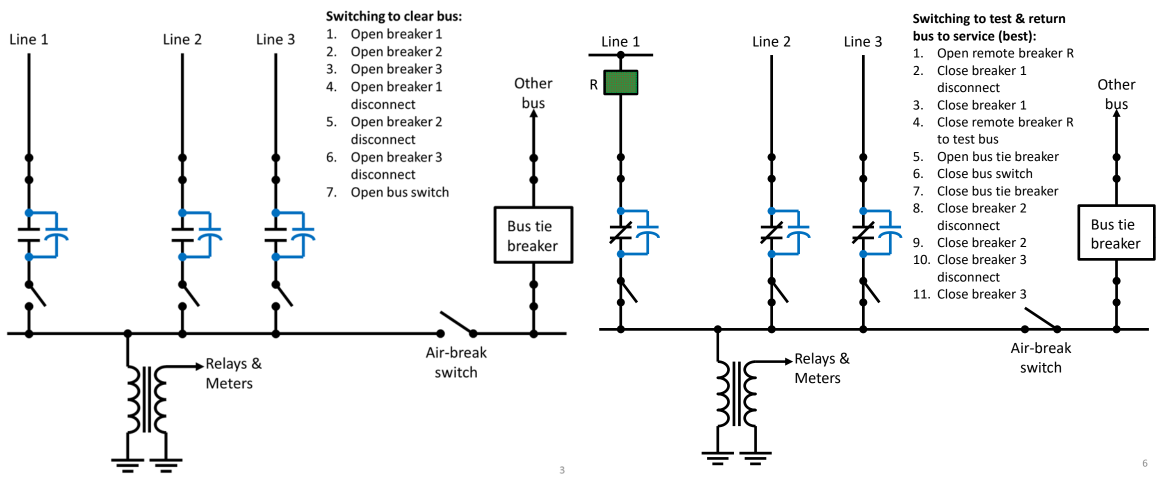

Figure 10. 2013 Operating Guideline - Clear/return bus

3) Distribution mitigating options

Mitigating options for distribution events have included:

- Three-phase switching instead of single-phase switching [1].
- Ensuring a grounding transformer is always connected to the bus during switching.
- Replace the three wye-grounded/wye-grounded voltage transformers with two VTs connected open-delta.
- Add phase-to-ground capacitance to the bus.
- Add secondary loading resistance to the VTs.[2]
    - This solution must be checked to make sure the thermal rating of the VTs is not exceeded.

Reference [2] describes three events besides the 2023 Albertville event, including:

a) 1995 White Pine - during switching - a 13kV ungrounded bus with three Ygrd/Ygrd metering VTs was being energized using single-phase disconnects one phase at a time, with the grounding transformer isolated (disconnects open). Ferroresonance occurred resulting in damage to three metering VTs. The switching procedure was changed to ensure the grounding bank was connected prior to bus switching.

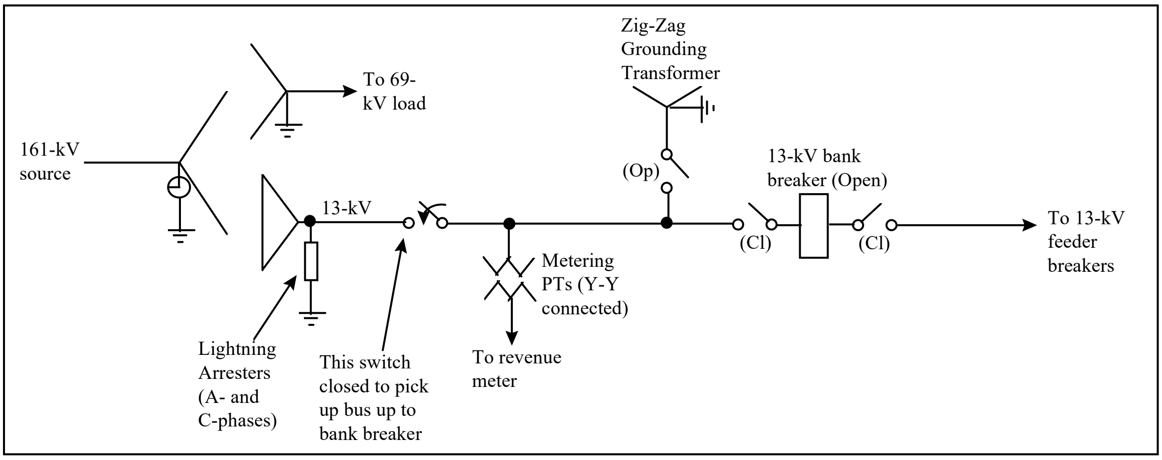

Figure 11. White Pine 13-kV switchyard

b) 1995 Morristown - during switching - single-phase disconnects were being used to energize a 13kV bus section with three Ygrd/Ygrd metering VTs up to an open bank breaker; the grounding transformer was on the load side of the open bank breaker. Ferroresonance occurred resulting in damage to the revenue meter connected to the metering VTs. The solution chosen was to move the metering VTs to the same bus as the grounding transformer. The same potential for ferroresonance exists, however, if the grounding transformer is for some reason left disconnected.

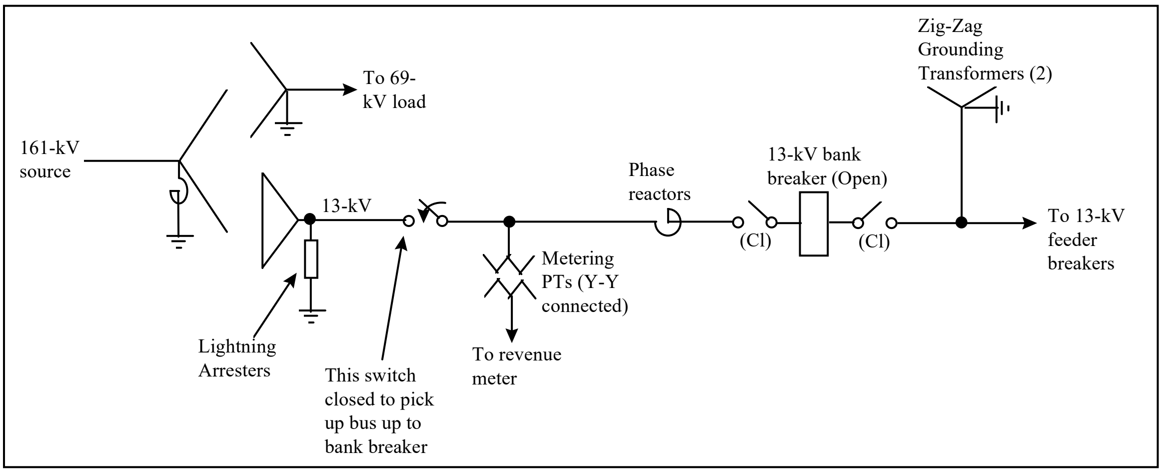

Figure 12. Morristown 13-kV switchyard

[2] The retirement of electromechanical relays has significantly reduced the burden on VTs, which reduces available damping resistance.

c) 1997 Arab - during switching - a 13kV ungrounded bus with three Ygrd/Ygrd metering VTs was being energizned using three-phase disconnects up to an open bank breaker; the grounding transformer was on the load side of the open bank breaker. Ferroresonance occurred resulting in failure of two gapped lightning arresters on the 13kV bus near the power transformer bushings. The proposed solution was to replace the Y-Y metering VTs with two open-delta VTs. Unfortunately this was not done. Instead the VTs were moved to the 13-kV transformer bus (ahead of the 247 switches), leaving the same risk. An operating instruction has only recently (late 2024) been added to the operating diagram that requires the grounding transformer to be connected prior to any bus switching.

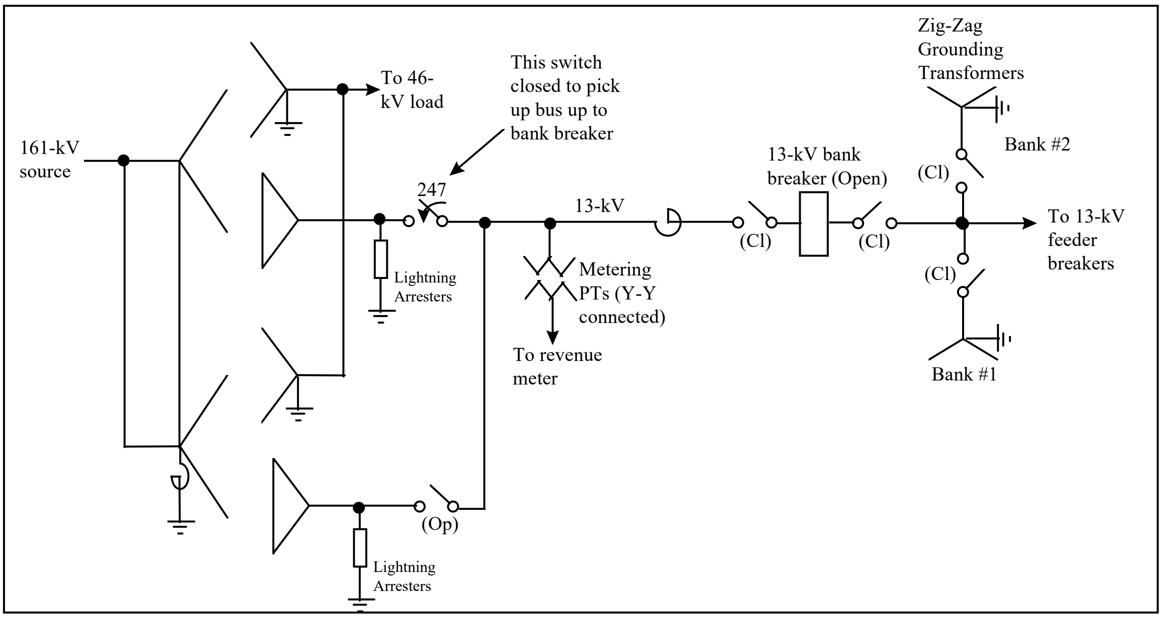

Figure 13. Arab 13-kV switchyard

Following the 1997 Arab event, back in 1998 electromagnetic transient studies indicated three-phase switching (via gang-operated disconnect or circuit breaker) with the grounding bank connected prevented ferroresonance.

Those same studies predicted that adding phase-to-ground capacitance to the bus may also be an adequate solution. But as [2] points out the following disadvantages of this solution:

- It adds another element in the circuit subject to failure.
- If one of these capacitors failed to ground, station load would be tripped.
- If one failed open, ferroresonance protection would be lost. This failure mode may or may not be noticed visually.
- The VT magnetizing branch may still be saturated.

Again, those studies included investigating adding secondary loading resistance to the VTs. In the Arab case, the required resistance did mitigate ferroresonance but was disqualified because the ANSI metering accuracy limit was exceeded [2].

However, studies performed after the 2023 Albertville event revealed that having a grounding bank connected does not prevent ferroresonance if single-phase switching is used[3] (see Figure 14). According to the studies, the only way to mitigate ferroresonance on 13kV delta tertiaries is three-phase switching (i.e., circuit breaker or gang-operated disconnect) with the grounding bank connected and its neutral grounded.

TVA has a project under development to replace three sets of single-phase disconnects at the Albertville station with a three-phase load break interrupter or power circuit breaker. Until that is done, the operating instruction is: "*Before energizing/deenergizing a 13kV main bus, ensure the grounding transformer is connected (disconnects closed). To avoid ferroresonance, it is best to energize/deenergize the 13kV bus by energizing/deenergizing the main power transformer bank (161/46/13kV. Ferroresonance can occur when using single-phase disconnects even if the grounding transformer is connected."*

As in the transmission case, operating guidelines are not considered a satisfactory solution.

[3] This is regardless of whether the neutral grounding switch is open or closed.

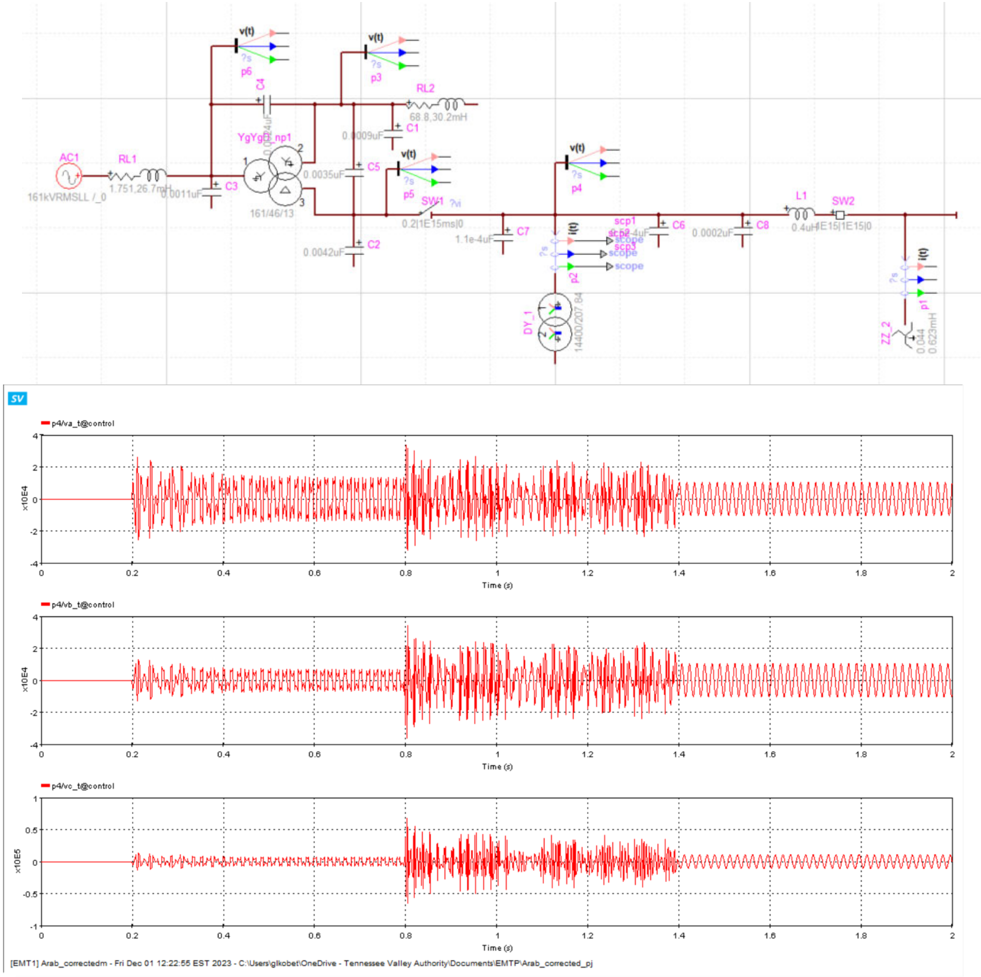

Figure 14. VTs on main bus, grounding bank connected/grounded, single-phase switching (energize main bus)

V. Conclusion

This paper has described TVA experience with ferroresonance in transmission and distribution switchyards with events dating back nearly 50 years. The attempt to mitigate such events using operating guidelines has proven ineffective. A valid conclusion appears to be the best solutions are actual engineering solutions that mitigate the risk of ferroresonance regardless of switching procedure or automatic bus tripping. Other utilities are advised to carefully consider whether operating guidelines can effectively mitigate this risk on their own systems.

References

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Biography

Gary Kobet is an Electrical Engineer for the Tennessee Valley Authority (TVA) in Chattanooga, Tennessee. His responsibilities include developing and maintaining operating guides and advising operators on system and equipment protection issues. He has performed stability studies and post-event disturbance analysis and provided oversight of TVA's Phasor Measurement system and applications. He has also worked in the System Protection department scoping relaying schemes for transmission and generation projects, as well as developing relay set point calculations and performing electromagnetic transient studies. Previously he worked as a field engineer and as power quality specialist. Mr. Kobet earned the B.S.E. (electrical) from the University of Alabama in Huntsville in 1989 and the M.S.E.E. from Mississippi State University in 1996. He is a member of the IEEE/PES Power System Relaying and Control Committee and is a registered Professional Engineer in the state of Alabama.