A Case Study of Voltage Transformer Failures in a Modern Data Center: Analysis, Mitigation, and Solution Implementation

Tamer Abdelazim
Senior Member, IEEE
Eaton Corporation
Power Systems Engineering
Calgary, AB T1Y7J7
Canada
abdelazim@ieee.org

Thomas J. Dionise
Senior Member, IEEE
Eaton Corporation
Power Systems Engineering
Warrendale, PA 15086
USA
ThomasJDionise@eaton.com

Robert Yanniello
Senior Member, IEEE
Eaton Corporation
VP of Engineering
Arden, NC 28704
USA
RobertYanniello@eaton.com

***Abstract* –While preparing a modern data center for startup, the commissioning process involved primary circuit switching that resulted in two voltage transformer (VT) failures. As a result of these failures, the authors conducted a comprehensive investigation of the VT failures. As the investigation proceeded, VT ferroresonance on circuit opening, and high frequency switching transients on closing, emerged as possible root causes of the VT failures. After incorporating extensive transient simulations and three rounds of field transient measurements, the authors designed and implemented a complete solution that included sizing of snubbers to overcome excessive switching transients, and the development of a saturable reactor to protect voltage transformers against the effects of ferroresonance. This paper describes root cause(s), simulations, field measurements, recommend solution(s), and solution implementation. The correlation between field measurements and simulation results show the effectiveness of modeling the implemented solutions.**

***Index Terms*-- switching transients, voltage transformers, ferroresonance, EMTP, saturable inductor, RC snubbers**

I. INTRODUCTION

A commonly performed operation during commissioning or normal facility operation is circuit switching. The switching operation causes transients [1]. These transients can result in equipment damage, and can be dangerous to personnel who are near damaged or affected equipment [2,3]. With the wide-spread application of vacuum breakers for transformer switching, this phenomenon is receiving renewed attention [4,5]. The severity of the switching transient voltage; i.e. high magnitude and high frequency, and the damage caused by the transient voltage, are determined by the following circuit characteristics [6,7]:

- Short bus or cable distance between circuit breaker and transformer
- BIL of the transformer (cast-coil, dry-type and some oil-filled)
- Inductance of the load being switched (transformer)
- Circuit breaker switching characteristics: non simultaneous operation of poles, current chop (vacuum or SF6) and restrike (vacuum)

An equally important problem is ferroresonance. ANSI/IEEE Std 100-1984 [8] defines ferroresonance as "A phenomenon usually characterized by overvoltages and very irregular wave shapes and associated with the excitation of one or more saturable inductors through a capacitance in series with the inductor." The key elements are saturable inductors in series with capacitance as shown in Figure 1. In the ferroresonant circuit, the capacitance (X_C) can be the capacitance of cable, overhead lines, or stray capacitance of transformer windings or bushings. Under normal operation, X_C is smaller than X_L. However, if some switching event causes the voltage to increase, then the transformer core may be pushed into saturation and X_L lowered. It is possible at some higher voltage this lower saturated value of X_L may equal X_C, forming a series resonant circuit called ferroresonance [9]. Ferroresonance phenomenon, as it relates to a VT, was explained in detail in [3].

On November 18 of 2013, this data center, experienced failure of two line-end VTs at 24.9 kV in newly installed switchgear. The damage to the line-end VT is shown in Figures 2 and 3. During the investigation, the bus VTs for the same gear failed on December 28, 2013. The 24.9 kV electrical distribution system for the data center is extensive, with some circuits as long as 800 m, as partially illustrated in Figure 4. A significant characteristic of the 24.8 kV system design is a primary selective system for the unit substations [10,11,12]. Figure 4 provides a simplified one line diagram illustrating this design and shows the line-end and bus connected VTs of interest. The UPM devices are manually operated fused padmounted switches. This one line is used for reference in reporting the results of the transient study, ferroresonance analysis, and onsite measurements in this paper.

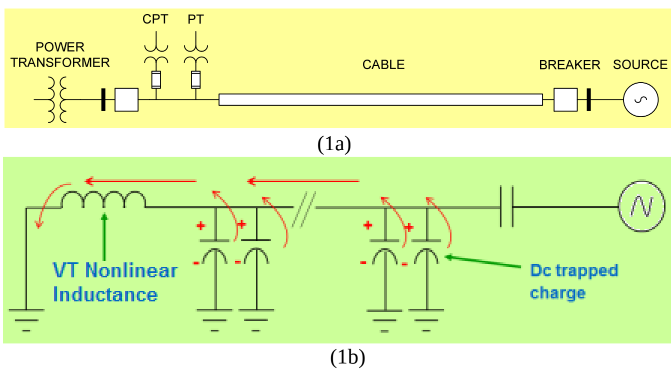

Fig. 1. Conceptual Explanation of VT Ferroresonance (a) oneline diagram, and (b) circuit parameters influencing ferroresonance

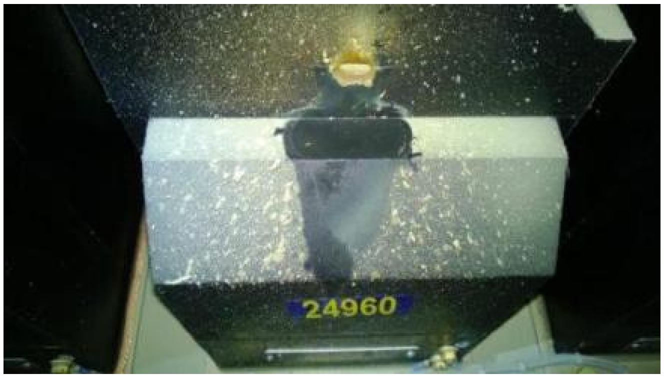

Fig. 2. Line-End VT Failure


Fig. 3. Cross Section of the Line-End VT Failure

The authors conducted a comprehensive investigation of the VT failures by modeling the data center power distribution system, including the switchgear and VTs on line and bus-side of the switchgear lineups, and performing a switching transient study to quantify the transient overvoltage produced by the 27 kV breakers at the UTS unit substations.

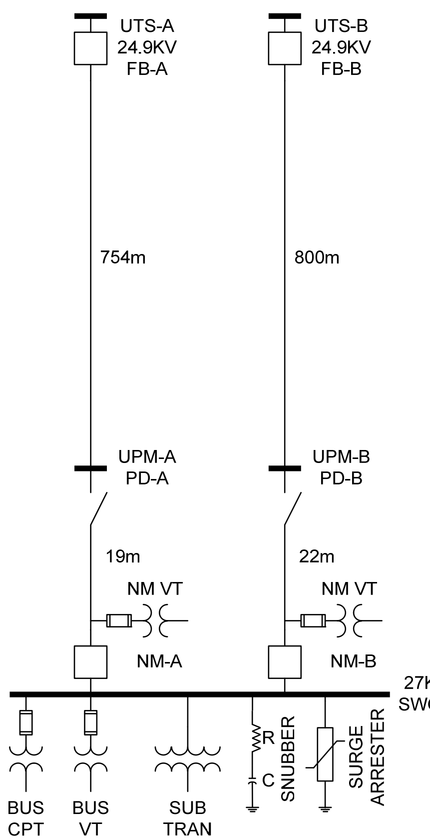

Fig. 4. Simplified One line of a Typical Cell at the Data Center

Using the Alternative Transients Program (ATP) version of the Electromagnetic Transients Program (EMTP) [13], the medium voltage distribution system was modelled for switching transient and ferroresonance analysis. Opening of the vacuum circuit breaker, stray capacitance of the cable and nonlinear inductance of the VTs being switched, i.e. VT saturation [14,15] were represented with sufficient detail.

The study indicated the system was subjected to two different switching phenomenon – high frequency overvoltages and VT ferroresonance. Each issue required its own unique mitigation technique. The high frequency overvoltages were addressed through the implementation of a custom resistor-capacitor (RC) snubber circuit at each vacuum circuit breaker. VT ferroresonance problems are traditionally addressed by the application of a loading resistor across the secondary of the VT to dampen the effects of switching transients. Due to the fact that the system utilized over 100 VTs, resistor losses over the life of the facility would have been excessive. As an alternative, the problem was addressed through the application of a custom saturable reactor across the secondary of each VT. These solutions are described in more detail in section III.

The performance of baseline testing, without remediation (baseline testing), was performed on 25th of February 2014. These results were compared to the snubber/saturable reactor performance testing that was conducted on 3rd of September 2014 (solution testing). Both tests were conducted by a third party at the facility. The baseline testing was used to characterize the system as found, and validate the model and resulting transient overvoltages (TOVs) at the line-end and bus VTs, i.e. no additional transient mitigation installed. The solution testing characterized the system after the installation of custom saturable reactors on the VT secondaries and resulting transient overvotlages at the line-end and bus VTs i.e. after mitigation was implemented.

II. Existing System Conditions (Baseline)

A group of sequence operations were performed to cover all operational scenarios of concern. These scenarios were opening and closing the UTS feeder breakers, switching between NM-A and NM-B, and UPM switching activities during various levels of power loading. A set of high-end portable power quality meters were connected to 1000:1 voltage dividers to monitor three medium-voltage points of interest: NM-A line VTs, NM-B line VTs and the common bus VTs. Another set of identical meters were installed on the secondary side of NM-A line VTs and NM-B line VTs. The resultant waveforms were compared for both baseline testing and solution testing. The waveforms of interest for selected transients are discussed in the following sections.

A. UTS Breaker Opening During Baseline Testing

During this scenario, a 5 kV square wave at 5-20 Hz was measured during baseline testing. This is very typical of most breaker opening cases as seen on the bus VT primary as shown in Figure 5.

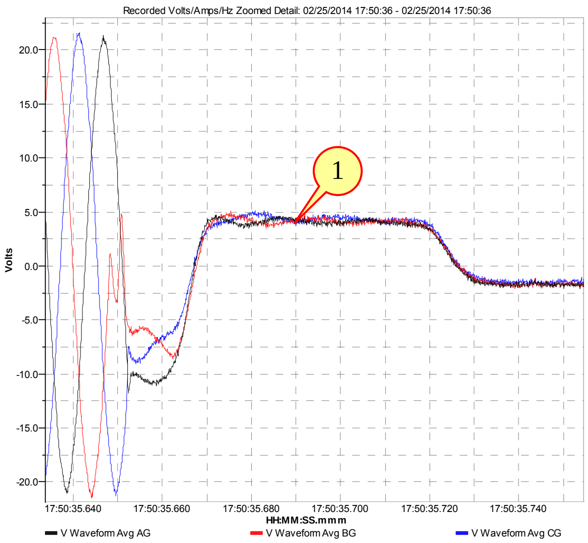

Fig. 5. Bus VT primary; Volts are in kV

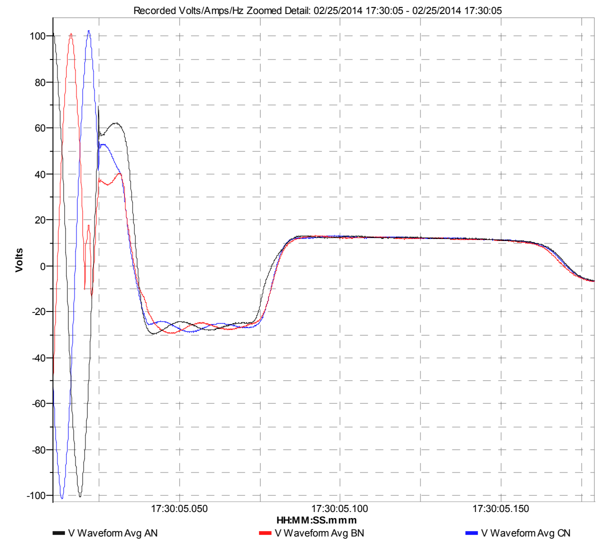

Fig. 7. Bus VT secondary

Similar results occur when any upstream 27 kV breaker is opened. This is the low frequency form of ferroresonance associated with VT saturation. Simulation illustrated the worst condition occurred by opening the 27 kV breaker FB-B in switchgear UTS-B with the cable length of 800 m. This case, shown in Figure 6, represents the existing system condition. This shows the most severe case with the breaker opening time chosen at the phase B maximum voltage.

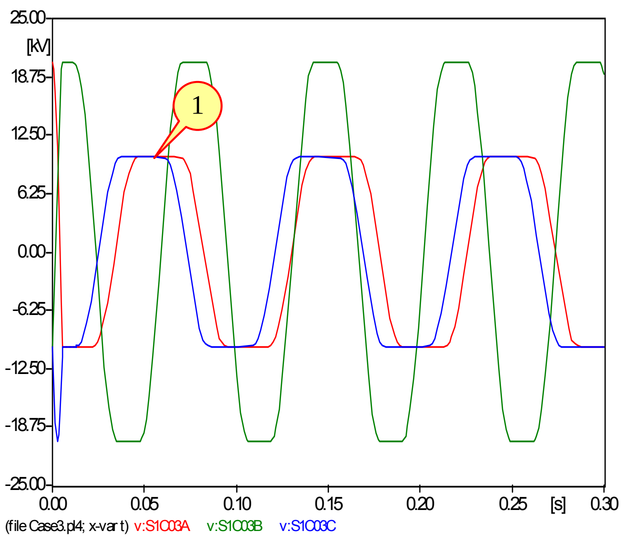

Fig. 6. Primary Line-to-Ground Voltage After Breaker is Opened; illustrates Ferroresonance on Phase B (from simulation)

Observations from Figure 5 & Figure 6:

1. Saturation form of ferroresonance, with 10 to 5 kV_{pk} square wave and estimated frequency of 17 Hz.
2. Magnitude is well below the normal peak value of 20 kV_{pk}.
3. However, it appears the square wave persists.

Another example of the saturation form of ferroresonance of 5-10Hz is shown for UTS breaker FB-A opening during baseline testing, as seen on the bus VT secondary in Figure 7.

Simulation illustrates the worst condition occurs by opening 27 kV breaker FB-B in switchgear UTS-B with the cable length of 800 m. This case, shown in Figure 8, represents the existing system condition and shows the VT secondary voltage. This shows the more severe case with the breaker opening time chosen at the phase B maximum voltage.

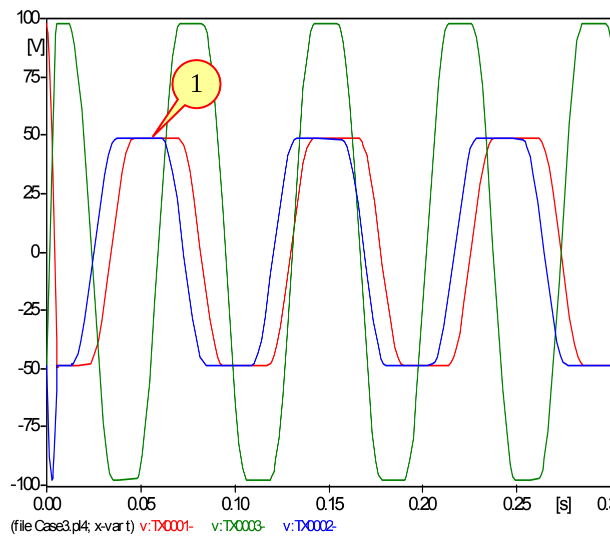

Fig. 8. VT Secondary Voltage After Breaker Opens, Ferroresonance Demonstrated (from simulation)

Observations from Figure 7 & Figure 8:

1. Saturation form of ferroresonance, with a 30 to 10 V_{pk} square wave and estimated frequency of 5 to 10 Hz.
2. Magnitude is well below the normal peak value of 100 V_{pk}.

Another example of the saturation form of ferroresonance, during UTS breaker opening is shown in Figure 9, a saturation 5 kV square wave followed by a “saw tooth” with 6 peaks.

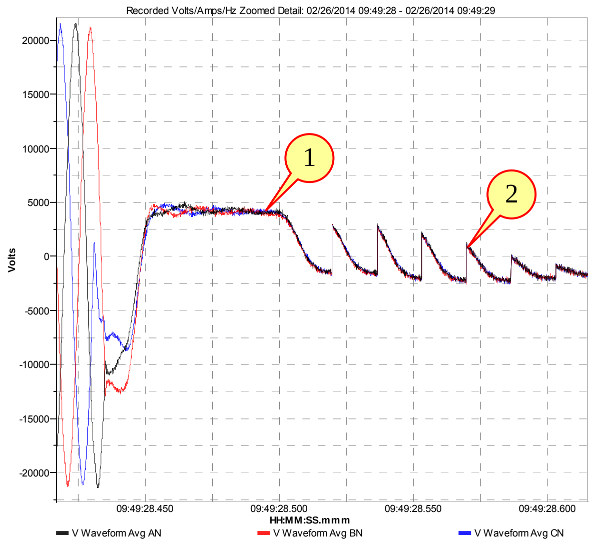

Fig. 9. From Transients, NM-A VT Primary

Observations from Figure 9:

1. Saturation form of ferroresonance with a 125 to 5 kV_{pk} square wave.
2. A “saw tooth” with 6 peaks.
3. This is the line-to-ground voltage coupled through the voltage dividers.
4. Magnitude is well below the normal peak of 20 kVpk.

B. UPM Switch Closing During Baseline Testing

During UPM switch closing, pre-strike was captured on the NM-B VT primary transients as shown in Figure 10.

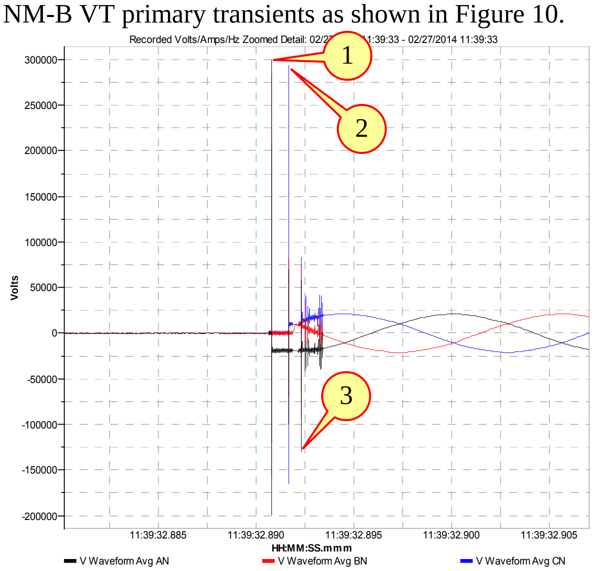

Fig. 10. From UPM Transients, NM-B VT primary

Observations from Figure 10:

1. Pre-strike during breaker closing on all three phases, highest magnitude of 510 kV_{pk} on phase-c.
2. Pre-strike on phase-b with a magnitude of 440 kV_{pk}.
3. This is the line-to-ground voltage coupled through the voltage dividers.

During UPM switch closing, pre-strike was captured as seen on the bus VT primary transients as shown in Figure 11.

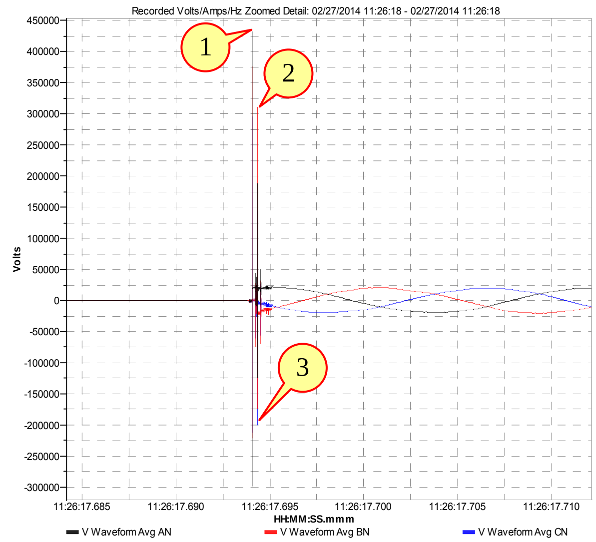

Fig. 11. From Baseline Testing, Bus VT Primary

Observations from Figure 11:

1. Pre-strike during breaker closing on all three phases, highest magnitude of 435 kV_{pk}.
2. Pre-strike on phase-b with magnitude of 305 kV_{pk}.
3. Pre-strike on phase-c with magnitude of 190 kV_{pk}

During UPM switch closing, pre-strike was captured as seen on NM-A VT secondary as shown in Figure 12.

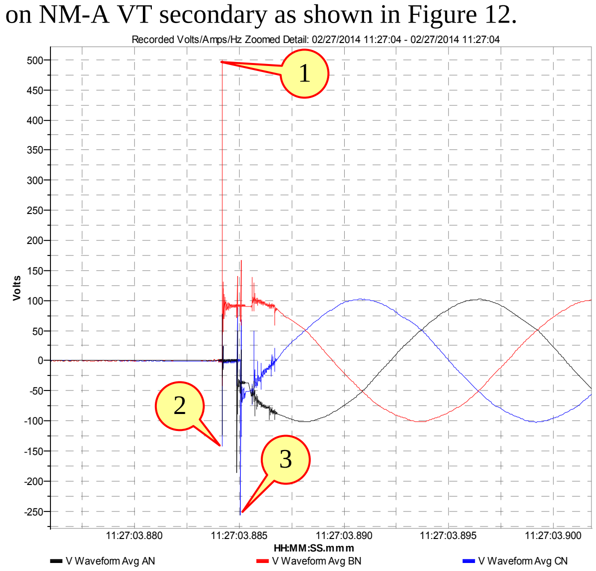

Fig. 12. From UPM Transients, UPM VT secondary

Observations from Figure 12:

1. Pre-strike during switch closing on all three phases, highest magnitude of 500 V_{pk} on phase-a.
2. Pre-strike on phase-c with magnitude of 135 V_{pk}.
3. Pre-strike on phase-b with magnitude of 260 V_{pk}.
4. This is the line-to-ground voltage capacitively coupled from primary to secondary of the VT.

Switch closing case was simulated by closing UPM switch PD-B upstream of NM-A VT with a cable length of 19 m and a pole disagreement of 0.4 msec. Similar to UPM transient testing, no load was connected at the VT secondary (existing system configuration). Figure 13 shows the line-to-ground TOV is 22.91 kV, with a frequency of 33 kHz.

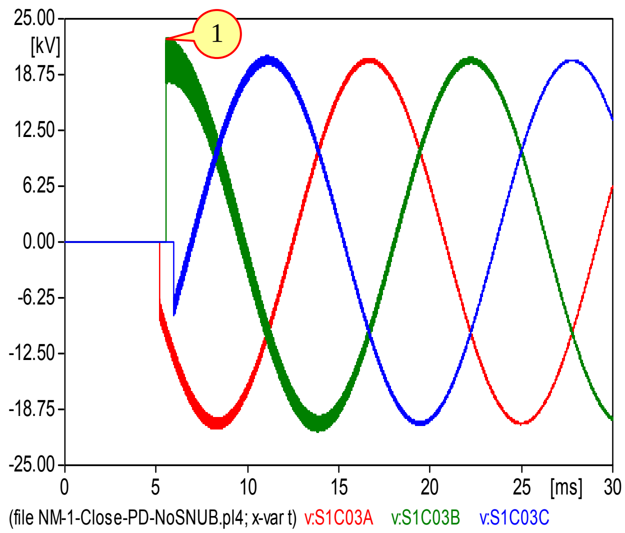

Fig. 13. Primary Line-to-Ground Voltage After Switch is Closed (from simulation)

A similar waveform was captured during the energization of a feeder with the NM breaker open. This was typical of all transients observed during the testing, as shown in Figure 14 and Figure 15.

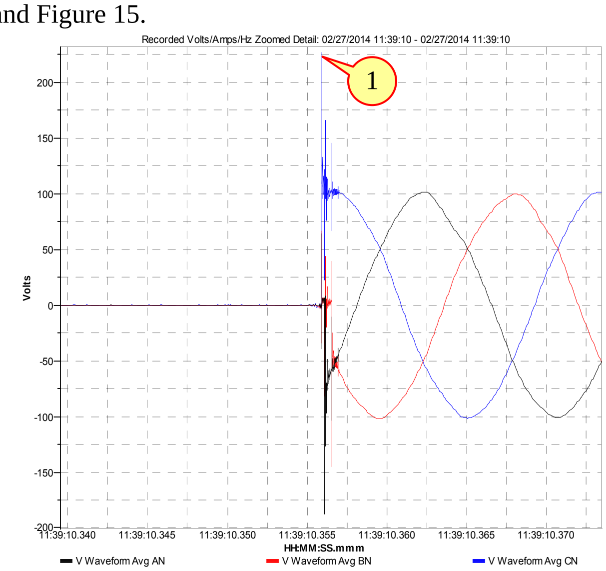

Fig. 14. Bus VT Secondary; From UPM Transients

III. Solution

The data center's medium-voltage distribution system was simulated. The following main components were modeled for the switching transient and the ferroresonance analysis:

- The utility system maximum and minimum fault values
- The utility transformers
- Cable circuits
- Equivalent stray capacitance at the switchgear and VTs
- VTs (voltage transformer parameters that include saturation characteristics)

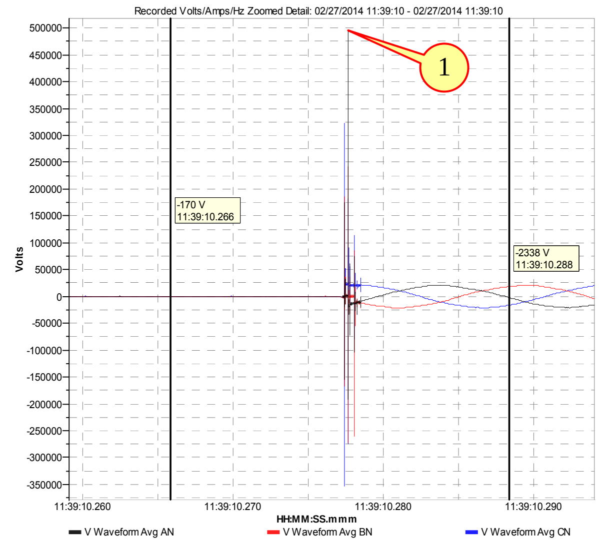

Fig. 15. shows a similar scenario but with a higher voltage transient.

- Equivalent stray capacitance across circuit breaker contacts
- Existing Surge arrestors
- Vacuum circuit breaker switching characteristics including chop current and pole disagreement.

The simulation results in Section II show the ferroresonance phenomena occurred for the VTs on the line-side of circuit breakers within the worst ferroresonance locations. As described earlier, the proposed and most effective solution for mitigating the ferroresonance is a saturable reactor, as shown modeled in Figure 16.

After the upstream circuit breaker opens, there will be a dc trapped voltage on the open line. With the VT on line side of the downstream breaker, the trapped voltage can be large enough to saturate the VT magnetizing impedance, setting-up a resonance condition, which causes the current to oscillate as a "square" wave. The oscillation can last for an extended period of time until eventual failure of the VT occurs. It should be noted that the failure may not necessarily occur based upon just one switching event but can occur over time based upon a number of switching events and where the circuit breaker opens on the voltage waveform. [3].

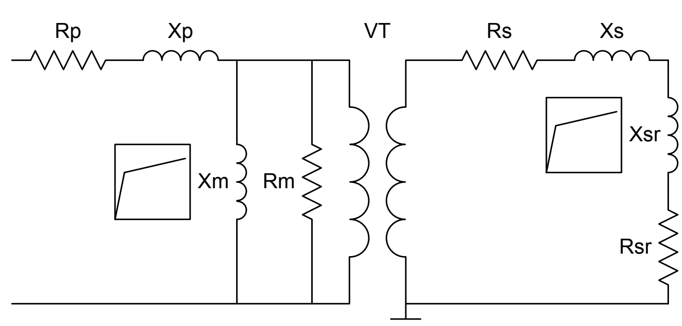

Fig. 16. Proposed Saturable Reactor for Mitigating VT Ferroresonance

Modeling and site measurements have shown that vacuum circuit breaker (VCB) induced voltage transients can cause damage to the bus and line VTs because of the short cables length. The results of the study indicated that one (1) snubber on the line-side of each VT would dramatically reduce the magnitude of the voltage transient, as well as its dc offset. The snubber was shown to reduce the frequency of the transient oscillation below the recommended 1000 Hz . The snubbers were sized per IEEE Std. C57.142-2010 [15], [2] [16] and [17] as shown in Figure 17.

For mitigating the ferroresonance, a custom saturable reactor was designed based on the VT saturation curve, as shown in Figure 18. The saturable reactor should be designed to saturate above the VT it is protecting, otherwise it creates a high impedance load on the VT. When the VT sees an over-voltage that goes beyond its thermal rating, which was around 125% of rated voltage, then the reactor kicks in – but not before. During site testing, the initial reactor design was saturating before the VT. In order to shift the curve to the right of the VT's saturation curve, an air gap of about 0.020" was added. This technique is incorporated in many CTs used for transient performance to reduce remnant (residual magnetism) effects.

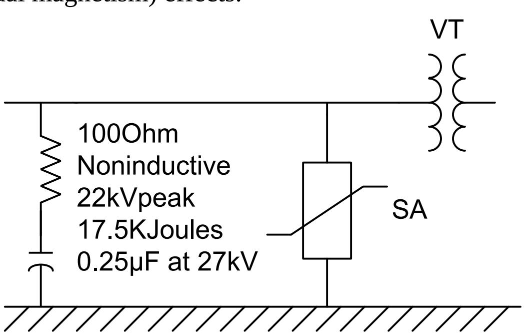

Fig. 17. Snubber Solution for Mitigating Transient Overvoltage at VT

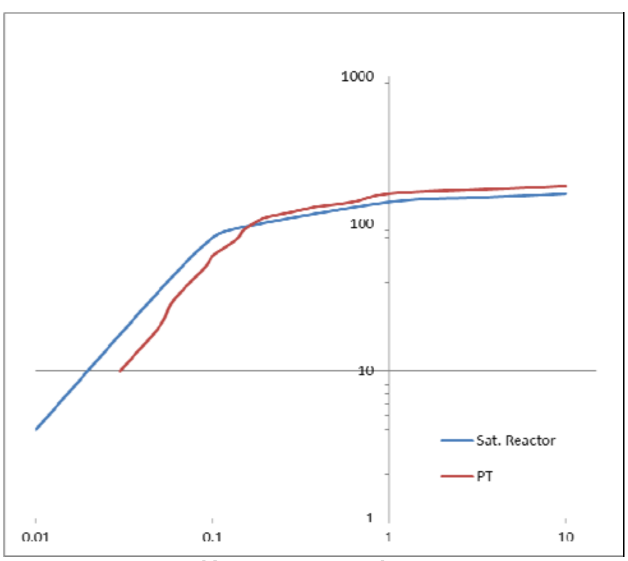

Fig. 18. Custom Saturable Reactor Designed to Mitigate Ferroresonance

The air gap shifted the curve about a decade to the right, which is what was needed from the basic design. It also changed the slope of the linear portion of the curve, which has no bearing on its performance. By adjusting the core size and area, as well as the number of turns, no dc component can pass thru the VT secondary circuit. The coil resistance was increased by reducing the secondary winding copper area to yield 1 ohm. By adding a bifilar winding, an added 5 ohms was achieved, but had zero net effect on flux, inductance, and voltage in the reactor winding. This winding was in series with the main coil to give a net resistance of 6 ohms.

IV. Solution Testing

This section shows selected waveforms that prove the effectiveness of the solution. In section II, tests were performed that show the two problems in the present system configuration. The same testing scenarios will be repeated, but after installing/simulating the proposed mitigation i.e. VTs are loaded with the saturable reactors and custom snubbers are applied.

A. UTS Breaker Opening During Solution Testing

The same testing scenarios as in Section II are repeated. As shown in Figure 19, the saturable reactor "VT load", quickly dampens the ferroresonance to an acceptable level. The simulation results in Figure 20 show similarities to the measured results in Figure 21, and although the simulation case was performed on the most severe case i.e. opening breaker time at phase B maximum voltage, both cases show damping of ferroresonance in less than 250 ms with the saturation reactor installed. This shows the effectiveness of the saturable reactor. Similar waveforms are shown in Figures 21 and 22 for the same switching event of opening the upstream UTS breaker.

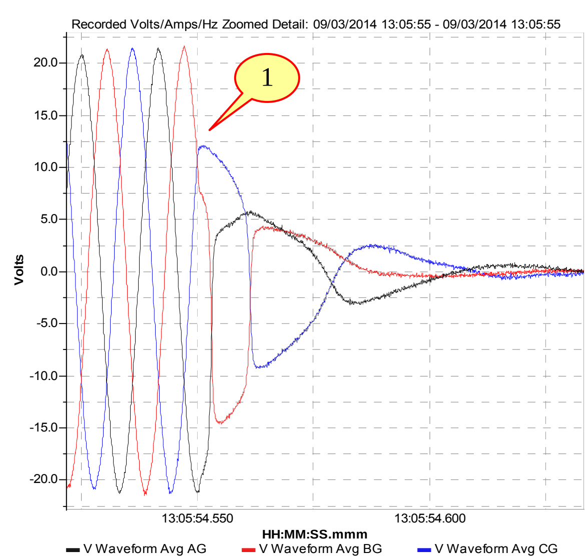

Fig. 19. NM-A incoming feeder UTS opening; Volts are in KV.

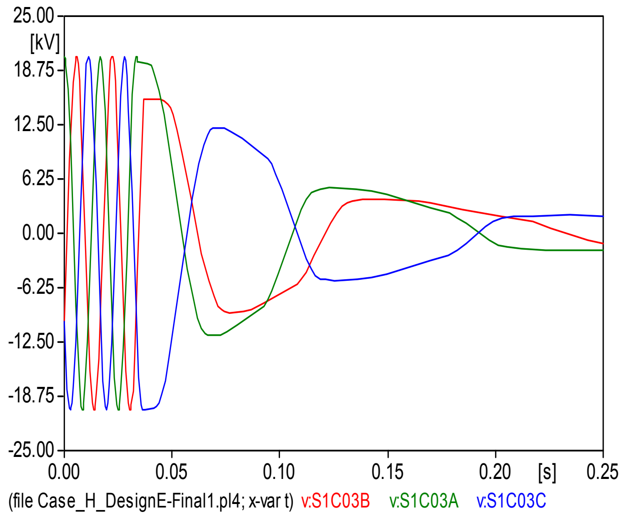

Fig. 20. NM-A incoming feeder UTS opening (from simulation)

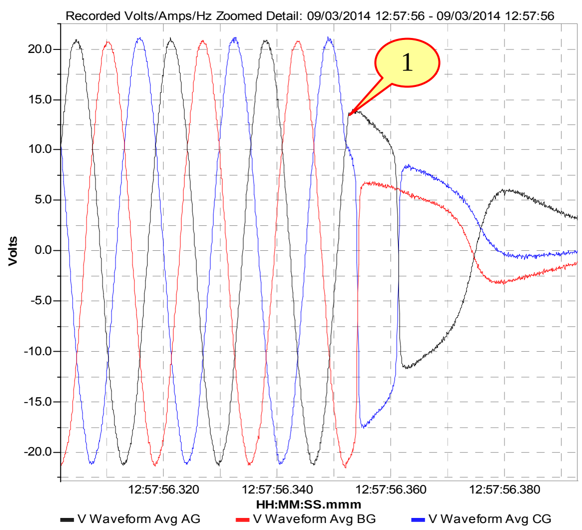

Fig. 21. NM-B Primary Switchgear Voltage; Volts are in kV

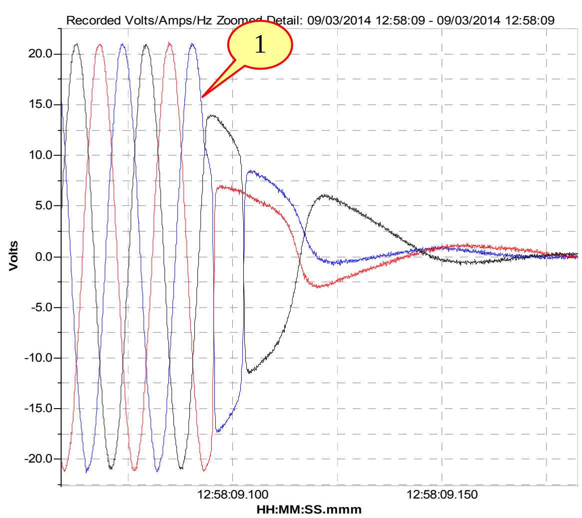

Fig. 22. Bus Primary Voltage After UTS opening; Volts are in kV

Observations from Figures 20-22:

1. The system is damped quickly after opening the upstream breaker
2. Damping time is less than 100 ms
3. Voltage magnitude is in the normal peak value of 20 kV.

In Figures 23 and 24, after opening breaker FB-A, secondary

VT waveforms are shown. Figure 23 shows NM-A secondary voltage and Figure 24 shows simulated VT secondary voltage. The simulated case shows the worst case, but both show damping in less than 250 ms.

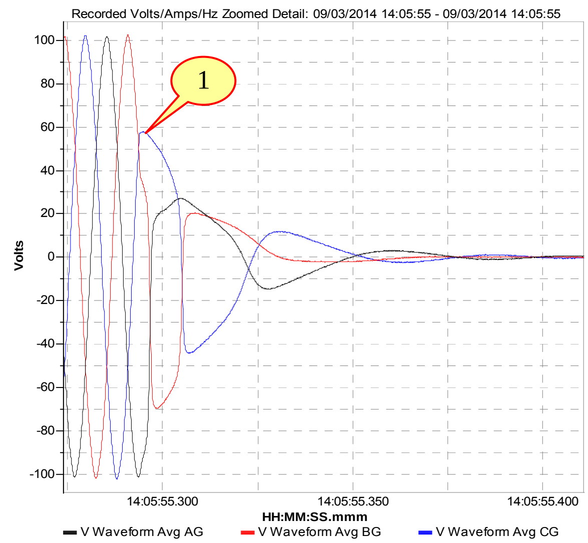

Fig. 23. NM-A secondary voltage - UTS opening

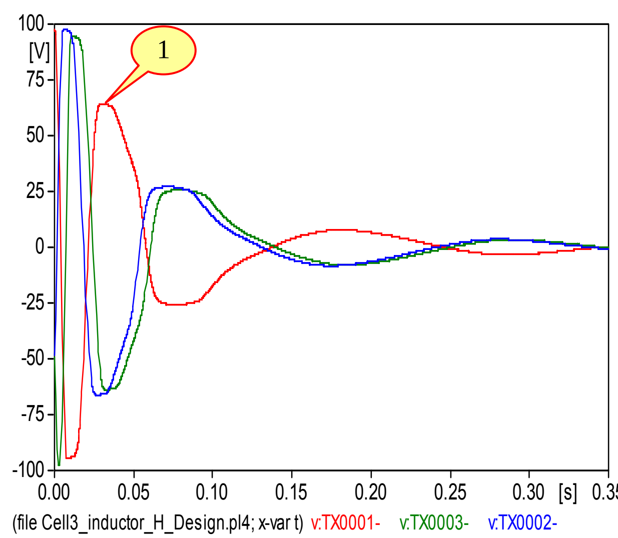

Fig. 24. NM-A secondary voltage - UTS opening (from simulation)

B. UPM Switch Closing During Solution Testing

This section has similar testing conditions to the previous except custom snubbers are installed at the primary of the VTs. During closing, as performed in Section II (closing the UPM switch PD-A upstream), pre-strike was captured as seen on NM-A and NM-B VT primaries and in Figures 25 & 26.

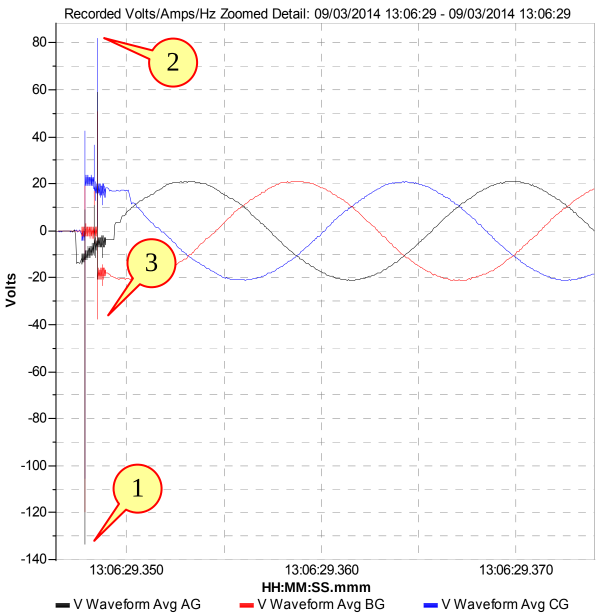

Fig. 25. NM-A Primary VT Voltage; Volts are in kV

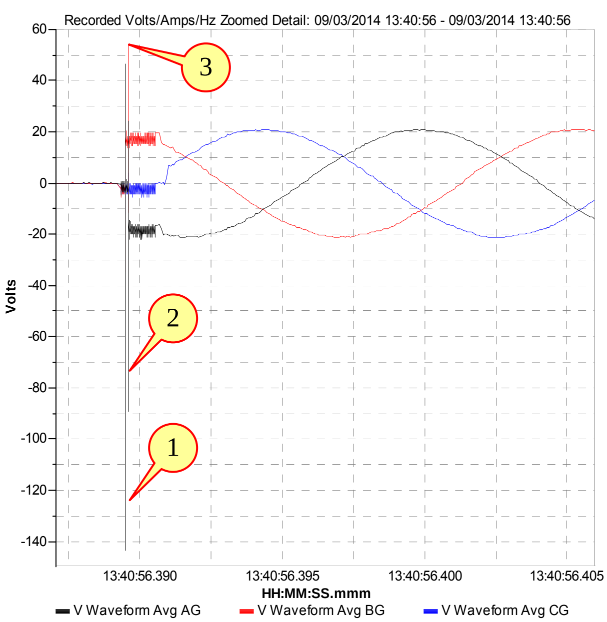

Fig. 26. NM-B Primary Voltage; Volts are in kV

Observations from Figures 25 & 26:

1. The TOV is damped quickly after closing the upstream switch
2. Voltage magnitude is in the normal peak value of 140 kV.

This case was again simulated by closing the upstream UPM switch PD-A. The TOV magnitude is 24.67 kV with a frequency of 3300 Hz, as shown in Figure 27. Note that the case was initially simulated in EMTP with a 30 ohm resistor and 0.125 uF capacitor. The case was repeated, but using a fine-tuned snubber (100 Ohms and 0.25uF)., This showed a reduced TOV of 26.14 kV, with a frequency of 2500 Hz, as shown in Figure 28.

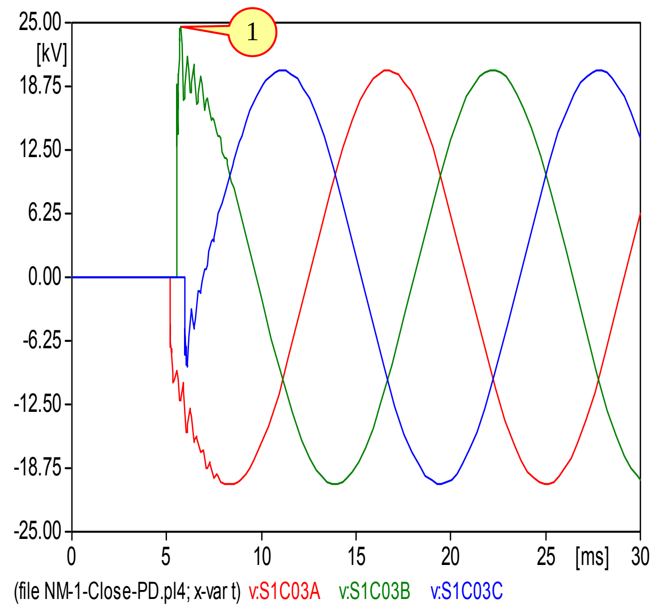

Fig. 27. NM-A Primary VT Voltage after closing UPM Switch using a Protec-Z snubber (from simulation)

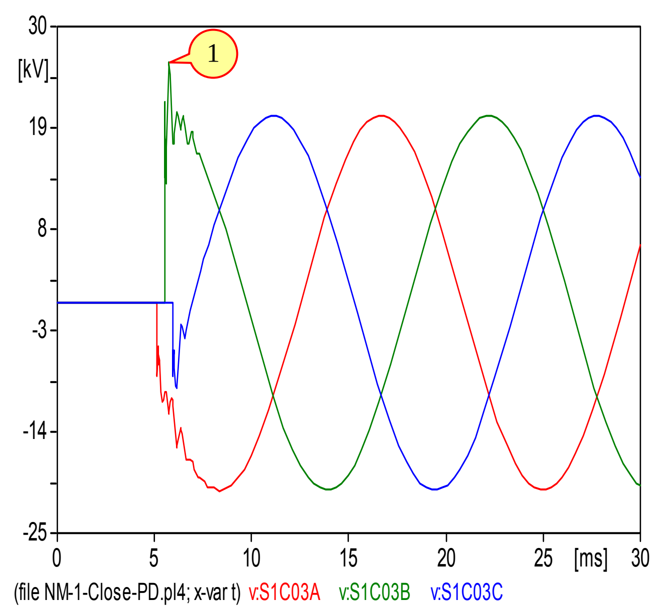

Fig. 28. NM-A Primary VT Voltage after closing UPM Switch (from simulation)

Figures 29 and 30 show the VT secondary voltage when closing the UPM PD-B switch. In Figure 30, notice that phase A closes first, followed by very little delay when phase-B closes, then a much longer delay until phase C closers. This pole separation or pole disagreement can initiate transients in the other phases for which the pole has not yet opened. In both phase A and phase B, there is a significant TOV followed by a damped oscillation The peak as well as the rate of change of voltage can damage the VT primary winding insulation.

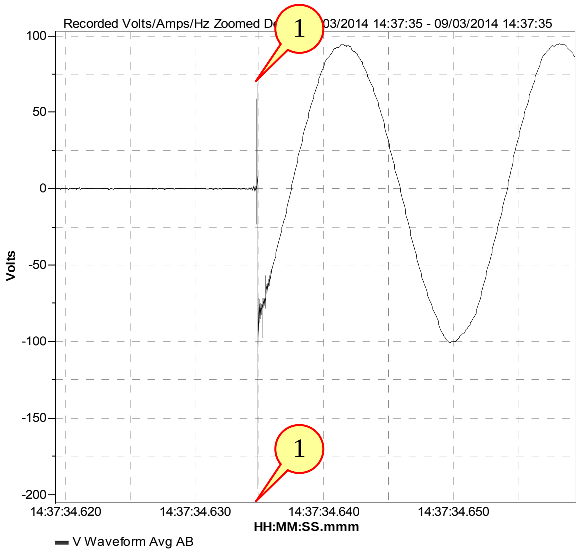

Fig. 29. Bus VT secondary voltage after UPM Switching

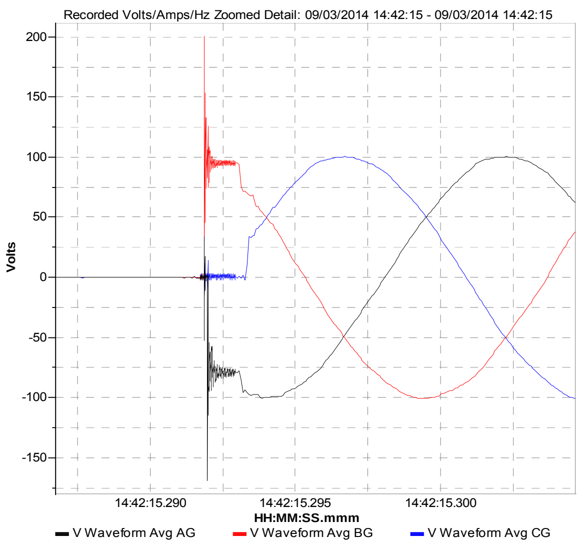

Fig. 30. Secondary bus voltage – Closing NM-B

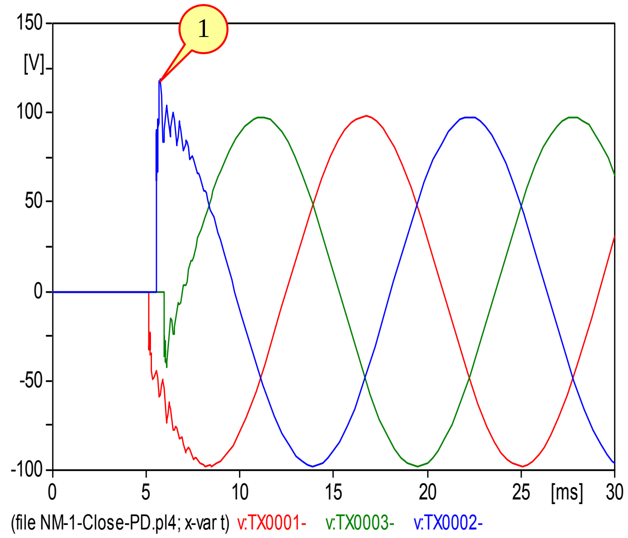

Fig. 31. NM-A Secondary VT Voltage after closing the UPM switch using Protec-Z snubber (from simulation)

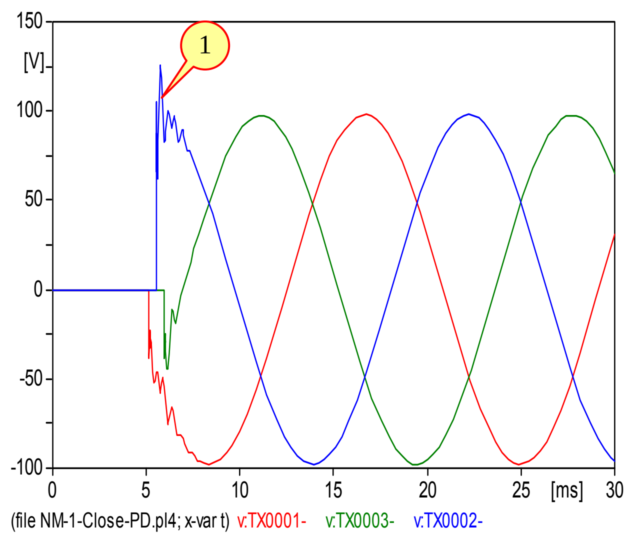

Fig. 32. NM-A Secondary VT Voltage after closing the UPM switch

<u>Observations from Figures 29 & 30</u>:

1. The TOV is damped quickly after closing the upstream switch
2. Voltage magnitude is in the normal peak value of 150 kV.
3. In some cases during both baseline testing and solution testing, the breaker closing transients are in excess of 500 kV_{pk} as measured through voltage dividers. It appears these high magnitude transients are a result of the scaling/calibration issue, and not actual values.

This case was simulated by closing UPM switch PD-B upstream. The TOV magnitude is 120.01 V with a frequency of 3300 Hz, as shown in Figure 31. Note that the case was initially simulated with a 30 ohm resistor and 0.125 uF capacitor but repeated using a fine-tuned snubber (100 Ohms and 0.25 uF). This analysis shows a reduced TOV of 125.52 V, with a frequency of 2500 Hz, as shown in Figure 32. There is a reduction in TOV by using the fine-tuned snubber, but still damped to an acceptable level.

V. Conclusions & Observations

Sections II and IV have shown the resultant waveforms during UTS breaker opening and closing with and without the saturable reactor as a solution to the ferroresonance problem, and with and without custom snubbers as a solution to the switching transient problem. The effectiveness of the implemented solution has been verified through field testing and simulation. Below are the significant observations noted during the simulations, analysis and testing:

1. During baseline testing, the measured waves showed significant 5 to 20 Hz ferroresonance at the VT on opening, and even worse pre-strike /re-ignition transients on closing. After the installation of saturable reactors, the system settles quickly for the same tests, i.e. in less than 100 ms. It has been clearly shown that the saturable reactors provide the necessary damping to mitigate the ferroresonance problem at this data center.

2. On breaker closing during both baseline and solution testing, the transients on the primary of the VTs showed significant magnitude on the order of 500 kV with pole disagreement of about 1 msec. The corresponding transient on the VT secondary was on the order of 500 V. The transients are capacitively coupled from primary to secondary of the VT, not thru the turns ratio, so the voltage divider scaling/calibration is not a concern.

3. For the breaker closing during both baseline and solution testing, there were many pre-strike events. Similar pre-strike events have been observed for a VCB closing into an arc furnace transformer. In that case, the pre-strike was aggravated when the operators opened and closed the VCB about 5 times within as many minutes. For the testing at this data center, the "iterations" of breaker close/open of up to 6 times may not have allowed the VI to fully recover, resulting in pre-strike on the next close operation.

4. On breaker opening during baseline testing, there is evidence of a saturation form of ferroresonance. After the breaker opens, there is a pronounced "square wave" of 5kV, with frequency of 5 to 20 Hz as seen at the VT primary. This response is very typical of the breaker opening cases. The square wave persists for a few cycles at 5-10 Hz before damping out. However, during solution testing, the system shows a fast damping of oscillations within 100 ms.

5. However, in at least one case during baseline testing, the saturation form of ferroresonance "square wave" had a much higher magnitude of 75 V at 4 Hz, as seen at the VT secondary. This higher magnitude was preceded by re-ignition during breaker opening on all three phases. The re-ignition may have trapped additional charge, increasing the voltage on the secondary of the VT.

6. During opening of NM-B breaker (baseline testing), transients were noted at the NM-A VT on the order of 475 kVpk. This is significant because NM-A breaker was already open when the NM-B breaker was opened. The transient was coupled from NM-B up through the 24.5 kV UTS feeder and back down through the adjacent UTS feeder to NM-A.

7. The magnitude of the transient overvoltages during baseline and solution testing on the order of 500 kVpk and rate-of-rise reported on the primary of the VTs would be expected to cause the surge arrester to operate, but it did not. It is possible there was a scaling/calibration issue between the voltage dividers and the power quality meter. The voltage dividers have a ratio of 1000:1, which gives 20 Vrms line-to-ground input to the power quality meter. The power quality meter has a minimum input voltage of 60 V. The transient response of the power quality meter in the 20 V range is not known. Normally the power quality meter is applied at 120/208 V or 277/480 V, which results in input voltages well above the minimum of 60 V.

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VII. Bibliographies

Tamer Abdelazim Mellik, P.Eng., Ph.D., (S'02-M'06-SM'14) received the BSc. degree from Suez Canal University, in 1995, and the Ph.D. degree from the University of Calgary, Calgary, AB, in 2005. He has over 20 years of power system experience involving modeling, simulation, and R&D/algorithm design of industrial and utility power systems. He is a registered Professional Engineer in the provinces of Alberta and Manitoba. He has authored or co-authored thirty papers in international journals and conferences. He is interested in transient and steady state studies, utility studies, renewable energy and special filtering techniques for ESPs applications.

Thomas J. Dionise, PE, (S ’79-M ’82-SM ’87) received the B.S.E.E. degree from The Pennsylvania State University, University Park, in 1982, and the M.S.E.E. degree with the Power Option from Carnegie Mellon University, Pittsburgh, PA, in 1984. He is currently a Power Quality Engineering Specialist in the Power System Engineering Department, with Eaton Corporation, Warrendale. He has over 30 years of power system experience involving analytical studies and power quality investigations of industrial and commercial power systems. In the metals industry, he has specialized in power quality investigations, harmonic analysis and harmonic filter design for electric arc furnaces, rectifiers and VFD applications. He co-authored papers which received the Metal Industry Committee Prize Paper Award in 2006 and 2010. In 2011, a paper he co-authored on harmonic filter design for an electric arc furnace received 2nd Place, IAS Transactions Prize Paper Award. Mr. Dionise is the Chair of the Metal Industry Committee and member of the Generator Grounding Working Group. Tom has served in local IEEE positions and had an active role on the committee that planned the IAS 2002 Annual Meeting in Pittsburgh. He is a licensed Professional Engineer in Pennsylvania.

Robert Yanniello (S’78–M’80–SM’05) received the B.S. degree in electrical engineering from The University of Akron, Akron, OH, in 1980. He started his career with the medium-voltage switchgear customer order design group, Westinghouse Electric, East Pittsburgh, PA. He has since held positions in medium-voltage switchgear sales and engineering, has served as a field application engineer and a low-voltage switchgear customer order engineering manager. Since 1994, he has been with Eaton, where he has had design responsibility for the various product lines that make up Eaton’s Electrical Systems and Services Group, which includes MV switchgear. He is the holder of twenty patents. Mr. Yanniello is a member of the IEEE Industry Applications Society and an author of three previous IEEE papers. He is a registered professional engineer in North Carolina and South Carolina.