Proactive Study and Novel Mitigation of MV Power System Damage Due to Sub-Power-Frequency Ferro-Resonance for a Gas Plant

Tamer Abdelazim Mellik, *Senior Member, IEEE*, Frederick D Painter, *Member, IEEE*, David D. Shipp, *Life Fellow, IEEE*, and Thomas J. Dionise, *Senior Member, IEEE*

***Abstract*—As projects to expand the processing capacity of a gas plant located in west Texas were pursued, engineering staff observed that the planned incoming medium-voltage power feeder possessed many of the risk factors that have led to increasingly common control-power transformer (CPT) and voltage transformer (VT) failures in industry due to switching. Such failures could involve significant damage and down time. To address these concerns, a computer simulation study was undertaken. As part of initial data gathering, sweep frequency response analysis (SFRA) measurements were performed in an atypical context to establish resonant characteristics of these instrument transformers. When the remote source breaker was modeled to open, connected VTs/CPTs went into severe sub-power-frequency ferro-resonance with probable catastrophic failure. This was verified by Electromagnetic Transients Program (EMTP) simulations as well as by field measurements. The focus of this paper will be on the determination of this unique form of ferro-resonance, identification of risk factors, novel cost-effective solutions, implementation, and field measurement verification of the proposed mitigation solutions. Field measurements have shown high correlations with the EMTP simulations and have verified the effectiveness of the proposed novel mitigation solutions.**

***Index Terms*—Control power transformers (CPTs), electromagnetic transients program (EMTP), ferro-resonance, *RC* snubbers, switching transients, voltage transformers (VTs).**

I. Introduction

In early 2015, the end-user co-author of this paper attended a continuing education session sponsored by the Houston-area IEEE Section on the topic of sub-power-frequency ferro-resonance-related failures of voltage transformers (VTs) and control power transformers (CPTs). During this session, it became apparent that many of the risk factors associated with reported failures were common to a then-current activity to expand the power system at this gas plant located in west Texas. Risk factors highlighted at the time included the following:

1) long parallel runs of tape-shielded power cable;
2) VTs/CPTs at the cable terminus;
3) VTs/CPTs with negligible load;
4) use of VCBs as switching devices; and
5) a relatively high distribution voltage (21.6 kV).

Because of this, a study was initiated to investigate this specific gas plant configuration with the goal of identifying potential problems before the occurrence of a costly failure. If required, mitigating actions could be implemented prior to placing new power system equipment in service.

This gas plant is located in Reeves County, TX, USA, in the prolific shale-based hydrocarbon producing area known as the Delaware Basin. This gas plant is one of many that gather produced gas for the purposes of 1) removing impurities (such as carbon dioxide) and 2) extracting higher-value condensate and natural gas liquids. As part of a multiphase project to expand plant inlet capacity from 300 MMCFD to 900 MMCFD, the plant power supply system was being upgraded. This upgrade included construction of a new 8-mile 138-kV feeder circuit, new adjacent 138/21.6-kV power substation, and new 21.6-kV double-ended switchgear for in-plant power distribution. Completion of the last phase of the plant expansion is expected in the second half of 2017.

II. Technical Discussion

Various transformer failures have been reported during the last two decades associated with circuit breaker switching transients and ferro-resonance [1]–[4]. These failures have involved power transformers, VTs, control power transformers (CPTs), and reduced voltage autotransformers. The authors of this paper have investigated nearly 100 power transformer failures in the past several years switched by a variety of manufacturer's circuit breakers/switching devices. A majority of these transformer failures have been dry-type and cast coil, but some have been liquid-filled. Similar switching transient studies are being performed by others with similar experiences or conclusions.

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T. A. Mellik is with the Eaton Corporation, Calgary, AB T1Y 7J7, Canada (e-mail: abdelazim@ieee.org).

F. D. Painter is with the Anadarko Petroleum Corporation, The Woodlands, TX 77380 USA (e-mail: fredPainter@anadarko.com).

D. D. Shipp is with the Capstone Power Systems Engineering, Murrysville, PA 15668 USA (e-mail: daviddshipp@gmail.com).

T. J. Dionis is with the Eaton Corporation, Warrendale, PA 15086 USA (e-mail: thomasjdionise@eaton.com).

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Generally, the following conditions may increase transformer failure due to transient voltages caused from primary switching of power transformers and indicates a study is needed [2], [3], [5].

1) Length of cable from the primary switching device to the equipment is less than 100-ft resulting in small charging capacitance. A longer cable length does not mean that a failure will not happen, but it can be a key factor.
2) Dry-type transformers and some oil-filled transformers or transformers with low basic insulation level (BIL). Cases of failures on liquid-type transformers have been documented [2].
3) Breaker type: Current chop is a big factor with vacuum and SF6 breakers. Vacuum and high-voltage SF6 (transmission level above 75 kV) are also prone to restrike.
4) Highly Inductive load switching that involves transformer inrush or motor starting.
5) Frequent switching, both during startup/commissioning as well as regular testing of backup/redundant systems.

Ferro-resonance of VTs, CPTs, and power transformers has been known for decades [4]. When the long radial feed is remotely de-energized, a trapped charge is left on the cable capacitance. This produces the ferro-resonance of the VT or CPT, and may damage the VT or CPT primary windings. This will be further explained later in the paper. New design topologies needed to meet the demands of the power densities, which require higher voltages (especially mission critical loads) have led to an increase in ferro-resonance failures in Hundreds of VTs and CPTs. The characteristics of these system design topologies that contribute to ferro-resonance include.

1) Redundant long radial distribution feeders to critical loads requiring voltage sensing at the line-end—especially at 15-kV class and higher.
2) Primary CPTs fed by similar long radial feeders.
3) Primary selective switch/breaker lineups fed by similar long radials requiring voltage sensing to identify available sources.
4) When VTs are connected line-to-ground in a circuit that is normally ungrounded.

Per IEEE Standards Dictionary: Glossary of Terms and Definitions, Ferro-resonance is a phenomenon usually characterized by overvoltages and very irregular wave shapes associated with the excitation of one or more saturable inductors through capacitance in series with the inductor. This is the more traditional form of ferro-resonance.

The two phenomena (i.e., overvoltages and irregular wave shape) described above are dangerous for the equipment.

If relatively small transformers are downstream, the irregular wave shapes consistent with conventional ferro-resonance at or near 60 Hz may occur and result in catastrophic failure. This traditional form of ferro-resonance is not the topic of this paper, although it was evaluated in the study. When the breaker is opened, high *dv*/*dt* may occur at the natural frequency of the circuit on the load side of the breaker, which is predominantly inductive and capacitive (*LC*). If small transformers are downstream of the breaker, for example, at the end of a cable run, they quickly dominate the downstream *LC* characteristics resulting in "subpower frequency" ferro-resonance—which is the primary topic of this paper.

This sub-power-frequency form of ferro-resonance is sometimes referred to as "20 Hertz" ferro-resonance since this is the middle of the range. However, the authors have observed frequency between 12 and 40 Hz. It occurs when the remote switching device opens leaving a trapped charge on the cable capacitance (C). The cable capacitance is in parallel with these small instrument transformer's iron circuits (L). Since these transformers are lightly loaded or unloaded (no damping), the result is high voltage with low frequency. This drives the iron circuits into severe saturation, drawing very high excitation current. Both system grounding and transformer grounding affect ferro-resonance. In general, an ungrounded system is more prone to ferro-resonance than a solidly grounded system—especially when the voltage source and ground reference is on the other side of the opening breaker than the transformer.

The switching transient issue has prompted transformer manufactures to actively seek solutions, including additional voltage withstand inherent in the transformer design. The switching transient issue is not unique to the USA, but also has been seen in Canada, Australia, South America, South Africa, Saudi Arabia, and other parts of the world. Manufacturers in Europe are also actively working on finding solutions [5].

A switching transient analysis was needed to evaluate the possible and worst case switching surge scenarios in modeling this medium voltage distribution system. For the switching transient analysis, it is important to accurately represent the opening of the breakers, stray capacitance of the cable and nonlinear inductance of the transformer being switched, i.e., VT/CPT saturation. These critical circuit components can be modeled [4], [6], [7]. The study reveals the associated voltage transients, which can then be compared to equipment insulation characteristics [3]. The optimum surge protection can be in the form of snubber circuits, surge arresters, and damping resistors or saturable reactors [2], [4]. Following surge equipment sizing, custom design snubbers are built and installed, specified surge arresters, and damping resistors are chosen (custom design is needed for or saturable reactors) [8]–[10]. Following these installations, field measurements may be needed to verify the effectiveness of surge equipment mitigation [3], [4].

The same switching transient analysis software can also be used to evaluate the "20 Hz" ferro-resonance issue as the cable capacitance and iron saturation characteristics are common to the model (opening).

III. System Description

This gas plant facility is supplied by its own substation 138-kV substation bus, which supplies three 30-MVA 138-kV/21.6-kV WYE-connected transformers. This Substation's three 21.6-kV buses are close coupled to the MV bushings of the 30-MVA transformers. Each 21.6-kV bus is feeding one or two remote switchgear assemblies. The longest cable length from one 21.6-kV bus to a switchgear is 450 ft (feeding switchgear EEC11). The 21.6-kV bus is feeding the switchgears by 25-kV 2000-A general purpose VCBs.

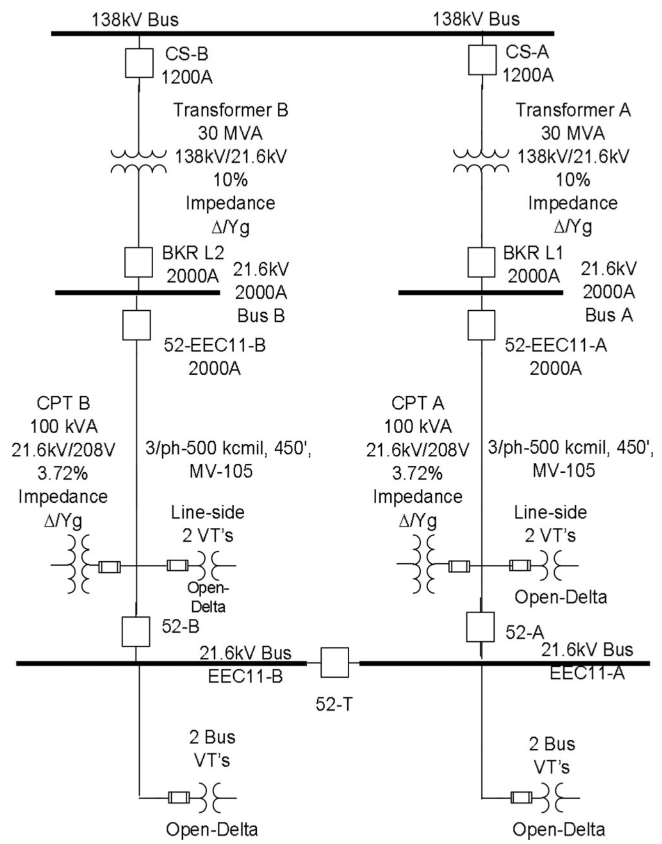

Fig. 1. Simplified one-line diagram for the substation and ec11 21.6 kV power distribution.

The switchgear EEC11 has two line-side open-delta VTs (VT-A and VT-B) 2000-VA 24 000/120-V 110-kV BIL, two bus op en-delta VTs (VT-11N and VT-11S) 2000-VA 24 000/120-V 110-kV BIL and two line-side CPTs (CPT-11A and CPT-11B) 100-kVA 21600:208/120-V 125-kV BIL. The source-side open-delta VT feeds only a relay and a panel voltmeter. The CPT's feed an automatic transfer switch (ATS) that, in turn, feeds auxiliary power (lights, battery charger, A/C, etc.)—or are completely unloaded depending on the position of the ATS. Fig. 1 shows a simplified one-line diagram for this Substation and EEC11 21.6-kV power distribution. Only the equipment that feeds EEC11 are shown, i.e., two of the three 30-MVA transformers and two of the three 21.6-kV busses.

IV. Capacitance Measurements and Sweep Frequency Response Analysis (SFRA) Tests

The winding capacitances for the VT and CPT of interest were measured using a test set. The purpose of the capacitance measurements was to determine the transformer winding capacitances, i.e., high to ground (CH), low to ground (CL) and high to low (CHL). It was beneficial to have the results of these tests so the data could be incorporated into the model of the VT/CPT used in the switching transient analysis study.

Frequency scans of each transformer of interest were conducted using a SFRA. The purpose of this frequency scan was to determine the internal natural resonant frequencies of each transformer's primary high-voltage winding impedances and winding capacitances. The SFRA test allows the study to evaluate potential internal resonance induced failures in a cost-effective manner without knowing the specific internal transformer design parameters.

V. Original Design Simulation

For simulating switching transient cases, the study started by modeling the worst conditions and critical components in the electromagnetic transients program (EMTP). The critical parameters for modeling ferro-resonance and switching transients include the representation of the transformer saturation curve, i.e., core magnetizing characteristics and residual flux in the core, as well as winding capacitances, the modeling of cable inductance and stray capacitance-to-ground. The breaker opening and closing characteristics and the source impedance and the type of grounding of the source, if any. The worst case conditions involve evaluating various switching scenarios of VCB's to determine if ferro-resonance effects could damage the two line-side open-delta VTs (VT-A and VT-B), the two bus open-delta VTs (VT-11N and VT-11S), and the two CPTs (CPT-11A and CPT-11B) each at switchgear EEC11. Both opening and closing of the feeder breaker and EEC11 main breaker were simulated to evaluate the line side VTs/CPT and the bus VTs. As described below, the study determined that opening the breakers could produce harmful ferro-resonance effects and closing the breakers could produce harmful switching transient overvoltages. It should be noted that cases with different pole separation time was used as well as initial residual flux in the simulation. Pole separation or staggered pole openings results in more significant transient effects that opening all three poles simultaneously. The statistical Monte Carlo method was used to determine the pole opening time (staggered pole openings) that produced the worst case.

Residual flux is critical to the "20 Hz" ferro-resonance phenomenon. In cases where actual data was not available, and typical data for a parameter has been assumed, then sensitivity analysis was applied to that parameter.

A. Ferro-Resonance Cases

There are two line-side open-delta VTs, two bus open-delta VTs, two line-side connected three-phase CPTs in EEC11 switchgear (double-ended switchgear). Various scenarios were simulated for testing ferro-resonance. The worst simulated case will be shown.

In Fig. 1, BKR 52-EEC11-A (see Fig. 1) was opened. Figs. 2 and 3 represent the simulation results. The VTs severely saturate and the 20 Hz form of ferro-resonance occurs. The actual frequency settles out at near 14 Hz. Fig. 3 better illustrates this. Because there is no significant load connected at each VT secondary, very little damping occurs; which indicates the ferro-resonance persisted for the duration of the simulation time. The *y*-axis is voltage, and the *x*-axis is time in seconds for all graphs.

When instrument transformers are subject to the 20 Hz form of ferro-resonance, several different scenarios can occur. The excessive excitation current can result in unexplained blowing

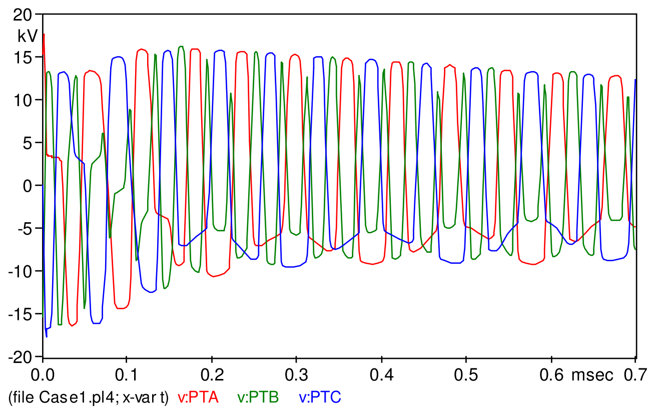

Fig. 2. Primary line-to-ground voltage after breaker opens; illustrates Ferro-resonance.

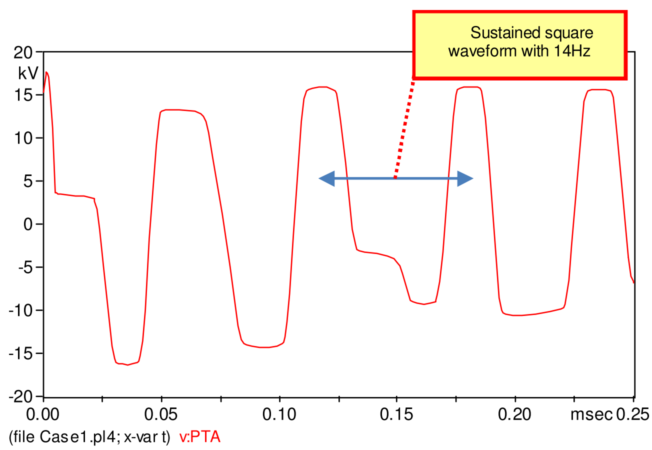

Fig. 3. Phase B line-to-ground from Fig. 2.

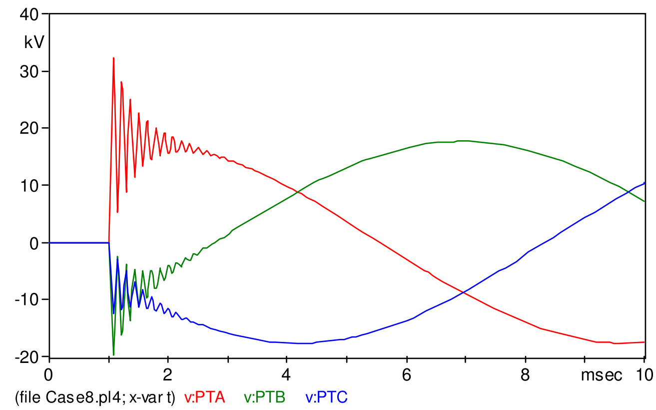

Fig. 4. Line-to-ground voltage after switch is closed; no Snubber.

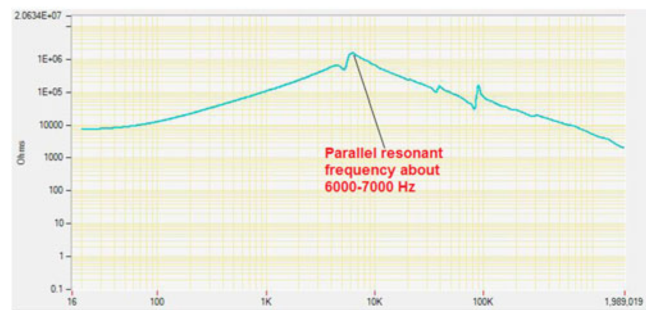

Fig. 5. SFRA frequency scan of the VT.

of fuses, iron burning after several switching events, as well as catastrophic failure. Many times, the excessive excitation current burns the primary winding open and results in a small series arc. At some time later, the VT/CPT failures can require transformer replacement as well as catastrophic failure. With catastrophic failure, the ionized gases build up pressure over-time until they eventually erupt out the side of the VT. If the failure engulfs the line side of the fuses and the fault is not cleared quickly, it may result in major switchgear damage as well. It is obvious that this ferro-resonance condition must be mitigated. A solution incorporating resistive load during switching is proposed and addressed in Section VI.

B. Switching Cases

There are two line-side open-delta VTs, two bus open-delta VTs, two line-side connected CPTs in EEC11 switchgear covering both sides. The component locations modeled were the same as in the ferro-resonance cases. The worst case simulated is shown below for switching transient.

Fig. 4 represents closing the BKR 52-EEC11-A in Fig. 1. It was noted that the VTs and the CPT were going to require resistive loading to mitigate ferro-resonance. Therefore, the VTs were simulated with 500-W space heater loading (see Section VI) with the hope that the resistive loading would be enough to mitigate the switching transient overvoltage condition. Fig. 4 shows EEC11 line-to-ground voltage. The transient overvoltage (TOV) is 32.17 kV with a frequency of 6500 Hz. Although the voltage magnitude of the TOV is within the VT BIL of 125 kV, the TOV frequency is above the recommended frequency of 1000 Hz (equivalent *dv*/*dt* consideration of the transformer winding). A snubber is recommended at this location to reduce TOV frequency.

Fig. 5 illustrates the SFRA frequency scan (ohms versus frequency) of the VT that shows one pronounced parallel resonant frequency between 6000 and 7000 Hz. Study results for the switching show that the oscillating frequency after closing the feeding VCB is 6500 Hz, which is close to the VTs first parallel resonant point and may excite internal resonance of the VTs. The snubber circuit (series *RC* circuit to ground) [2], [3], [9], [10], [11] is recommended for this location as it will shift this resonant frequency to something much less and alleviate the possibility of transformer internal resonance during the closing of the VCB.

The ring wave closely matches the internal resonance frequency of the instrument transformer. In these switching transient type conditions, the failures can now look the same as with the ferro-resonance type failures since both cause failures typically mid primary winding. For the case of substation EEC11, the 20 Hz form of ferro-resonance was present, excessive *dv*/*dt*

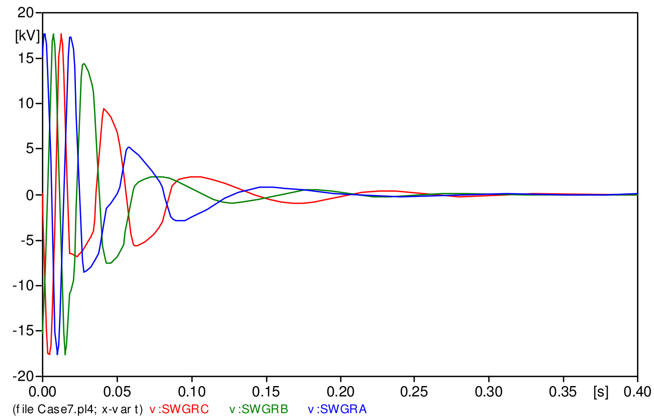

Fig. 6. Primary line-to-ground voltage after breaker opens; illustrates ferro-resonance on phases dampened (less than 0.2 s).

exists (greater than 1000-Hz ring wave) and the switching frequency was very close to the internal resonance of these instrument transformers. The study determined that snubbers would provide valuable equipment protection. Proper snubber design will solve both the *dv/dt* risk and the internal resonance risk.

The ferro-resonance and switching transient cases had confirmed the TOV produced by these VCBs, exceed prudent limitations at the primary windings of the line-side VTs, the bus VTs, and CPTs fed by their respective substation feeder breaker to switchgear EEC11. Mitigation recommendations for switchgear EEC11 in this gas plant were determined to be prudent. Mitigation solutions are described in Section VI below.

VI. Solution Simulation

A. Ferro-Resonance Cases

The general cost-effective solution for these type of ferro-resonance conditions, is to add resistive load damping (secondary loading resistors solve ferro-resonance problems; primary snubbers solve primary high-speed switching transient problems), with this in mind, the full system was modeled with 500-W per VT and 1000-W per phase for the CPTs. Prior to a disturbance, the system configuration that leads to the worst condition consists of one main breaker open and the entire EEC11 switchgear fed from the opposite main breaker through a closed tie breaker. For this system configuration, the disturbance consisted of opening BKR 52-EEC11-A upstream of the line-end and bus VTs (total of 4 VTs) and one CPT. As shown in Fig. 6, the added resistive loads quickly dampen the ferro-resonance to an acceptable level. This mitigation represents the solution to the ferro-resonance problem.

The waveform illustrates excellent dampening of all the VTs and CPT for the worst case switching condition. Complete elimination of ferro-resonance effects is not practical, since this would generally require resistive load at or greater than transformer VA ratings. This simulation proves that much smaller resistive loads are effective. Lesser values of damping resistance will not prevent ferro-resonance from occurring, but quickly dampens it sufficiently such that no damage occurs. The main drawback with the solution is the constant power consumption

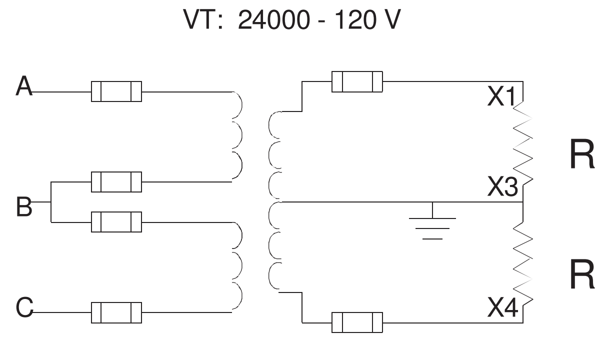

Fig. 7. VT load resistor.

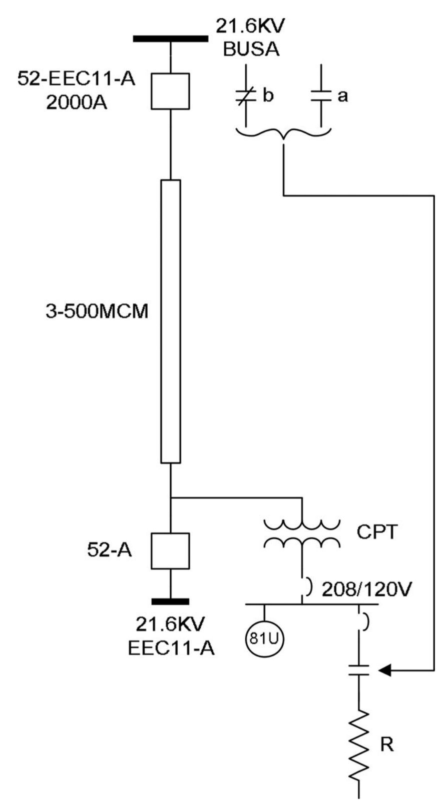

Fig. 8. CPT switched resistor conceptual control diagram.

used by the damping resistors. If this is a concern, a special switching circuit is needed to allow the resistors to be switched ON only during ferro-resonance and switching OFF during normal operation. Fig. 6 shows the basic connection to the open-delta VTs.

Another circuit was developed for switching the damping resistors installed at CPTs' secondaries and is shown in Fig. 8. In this scheme, it works well in principle. When the remote breaker opens, one of its auxiliary contacts typically is used to cause a contactor to close thereby energizing the 3-kW resistive load bank during the risk period. The controls then drop the load out after a few seconds. The intent is to only have the watts loss during the risk period of a few seconds. A drawback is that the control wires need to connect between the two substations with

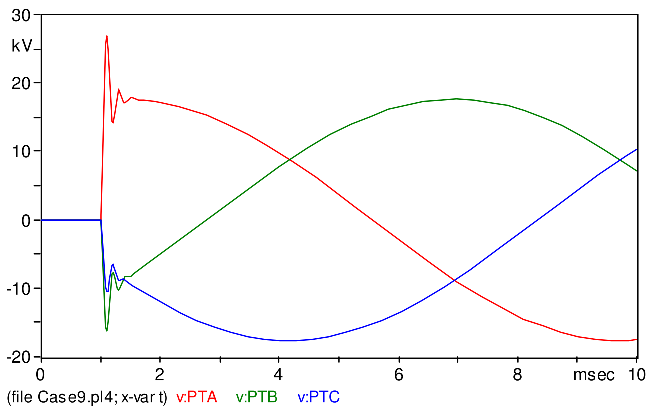

Fig. 9. Line-to-Ground Voltage After Switch is Closed; with custom snubber.

Fig. 10. CPT switched resistor control cabinet.

length, costs, reliability, and transferred earth potentials being significant factors.

B. Switching Cases

The installation of a custom line-side snubber (120 Ω and 0.125 μF) to protect the line side VTs and CPT in EEC11, were selected (series *R*–*C* circuit). The approach used by the authors in selecting the snubber parameters is given in [2] and [9]. The calculation of surge impedance of transformers and cables is considered in this approach. The choice of snubber parameters also depends on the desired transient response, i.e., damped, overdamped, and critically damped response. Frequently such calculations are augmented with trial and error techniques, or rather sensitivity analysis, using simulations in EMTP to find the optimal snubber parameters.

Fig. 9 shows the line-to-ground voltage with snubbers (compare to Fig. 4). The TOV is 26.84 kV with an overdamped frequency response. The snubber circuit is recommended for this location as it will alleviate the possibility of transformer internal resonance during the closing of the VCB and lowers the natural frequency to well under 1000 Hz.

VII. Equipment Design/Hardware

The novel mitigation techniques employed involve physical location connection selection, use of existing equipment and a unique way to eliminate control wiring between the substation and EEC11 switchgear. These novel approaches allowed simple but very cost effective and reliable mitigation.

A. VT and CPT Ferro-Resonance Mitigation

The ferro-resonance condition for the VTs was solved in the following manner. The VT damping resistors shown in Fig. 7 are comprised of multiple space heaters. Since these space heaters are very reliable, simple, and must be energized all the time, simply reconnecting these existing components to the VTs provided another novel and cost-effective solution.

The CPT load of 3 kW (1000 W/phase) would cause excessive localized heating and wasted energy. It was determined that this resistive load should be switched on but only when the remote breaker was switched open. It was also decided that running control wiring between substations was a solution of last choice. Note that an underfrequency relay (81U) is indicated in Fig. 8 and housed in a control cabinet of Fig. 10. The novel approach here was to sense frequency at the CPT as the ferro-resonance condition quickly decays to 14 Hz. An 81U relay was selected over other types of relays because frequency is unique to this ferro-resonance condition where all other available electrical parameters could be caused by multiple phenomenon and could result in nuisance operations. The 81U relay was set to cause the resistive load contactor to close any time the frequency decayed to less than 50 Hz and open about 10 s later. The 10 s active time for the resistive load is more than adequate because the resistive load provides damping in 200 ms. Other controls assured excessive cycling did not occur (not shown). In this manner, control wiring between substations was not required—along with all the related concerns being eliminated.

B. VT and CPT Transient Mitigation

The EEC-11 building houses double-high switchgear with 16 vertical sections. The main breaker is in the bottom of a vertical section. The bottom breaker is also congested with three 500MCM cables per phase plus a fourth cable circuit to the CPT as well as taps to the VTs. Additionally, the three incoming cables will have cable terminations/stress cones. For these reasons, installing the snubbers in the switchgear main breaker compartment was immediately ruled out, and alternatives for snubbers housed in an external enclosure were proposed.

C. Options for Snubber Locations

One option was to mount the enclosure beneath the EEC-11 building directly on the C-channels spaced at 18 in intervals that form the building substructure. As shown in Fig. 11, the incoming cables to the main breaker are in cable tray under the floor and penetrate the floor plate directly below the line-side stabs for the main breaker which is in the bottom cell of the switchgear. The snubber cables would also penetrate the floor plate at this same location and terminate on the line-side stabs

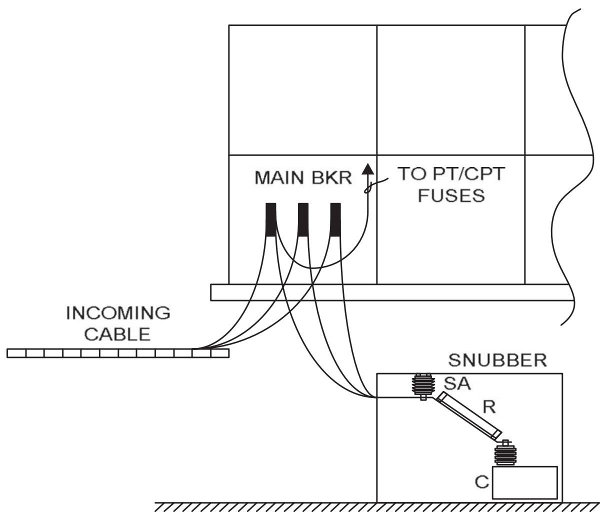

Fig. 11. Proposed arrangement of snubber for EEC-11 (where SA = surge arrester, R = resistor, and C = capacitor).

of the main breaker. This option had limited space for cable bending and only access thru the bottom panel for maintenance.

Another option was placing the snubber enclosure on a concrete slab under the EEC-11 building rather than suspending it from the undercarriage. As shown in Fig. 11, again the snubber would be directly below the main breaker. The bottom of the EEC-11 building substructure is elevated 6 ft above grade, and a short run of cable tray to support cables could be installed. This option afforded sufficient space for cable bending and access for maintenance thru sides and top. For these reasons, this second option was selected. Fig. 11 shows the proposed arrangement of the snubber for EEC-11. By connecting the snubber here, one snubber protects both VTs and CPT—another novel concept employed by its judicious location.

D. Environmental Concerns

At this west Texas location, blowing dust and sand is a common problem. Water ingress will typically not be an issue since the assembly is beneath the EEC-11 building. A gasketed enclosure for the snubber that is dust tight, not water tight, is the primary concern. Dust tight hinged doors are preferred. For these reasons, a NEMA 4/12 enclosure was selected instead of a NEMA 3R. Both painted and stainless enclosures were considered. Although the stainless enclosure cost about three times the painted enclosure, stainless was selected because of its resistance to corrosion in this harsh outdoor environment.

E. Snubber Cable Pigtails

For the installation of the snubber enclosure on a slab, this will require about 15 ft of cable (pigtails) from exit of the snubber enclosure to the line-side stabs of the main breaker in Section 15. There is an open airgap of approximately 6 ft., and cable tray was selected to provide support in this gap. The cable will not be run in conduit. Cable glands were proposed for where the pigtails exit the snubber enclosure. For the plant cabling, 25 kV 133% 105 °C tape-shielded cables were used and readily available. For the pigtails to the snubber, this same 25 kV individual single conductor cable was used. Pig tails of 18 ft in length exterior to the snubber enclosure were selected. The plant staff cut the cables to the exact length required and installed termination kits.

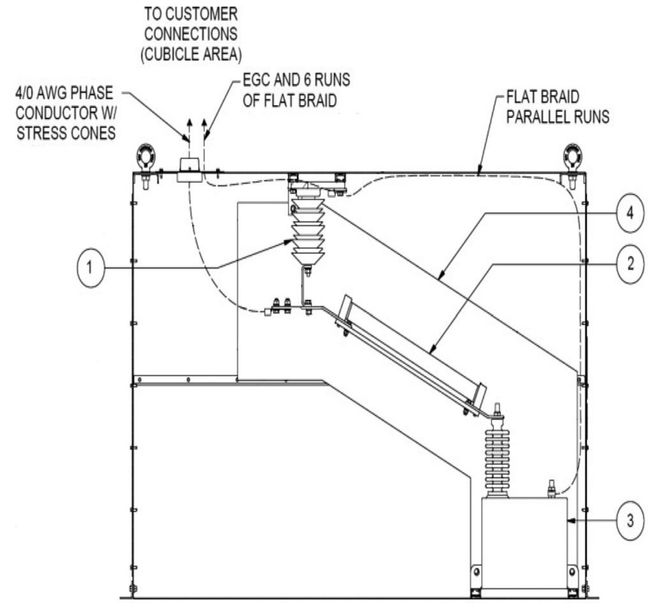

Fig. 12. Conceptual design of the snubber for EEC-11. (1) Surge arrester. (2) Resistor. (3) Surge capacitor. (4) Phase barrier.

F. Snubber Cable Terminations

Since shielded cables were selected, these cables can now run adjacent to the grounded snubber enclosure, giving flexibility in routing the cables internal to the snubber enclosure. Stress cones will be required on both ends, so space inside the snubber enclosure was allowed for stress cones in open air. These shielded cables are very short runs, so the shields are grounded in the cubicle end and ungrounded in the snubber enclosure end. However, stress cones at both ends are required. Cable shields need to be grounded anytime the shield to ground voltage exceeds about 25 V (consult cable manufacturer application data). This translates to grounding both ends of the shields anytime the cable length exceeds about 50 ft. For a short cable of 10 ft., if both ends of the shields are grounded, the induced current could be very high, because the series shield impedance will be very low, which will melt the shields.

G. Conceptual Design of the Snubber

The conceptual design of the snubber is shown in Fig. 12. The highly noninductive resistor and surge capacitor comprise the snubber. The snubber combined with the surge arrester provides total surge protection for the downstream VT and CPT. For reliability reasons, a single-phase capacitor rated 24 kV was selected and applied to this system with nominal voltage of 12.47 kV line-to-ground. The surge arrester serves as a stand-off to support the resistor, resulting is saving of space. Because of the compact design, phase-to-phase and phase-to-ground clearances in air for 23 kV, 125 kV BIL per NEC Table 490.24 were not possible, so thermoset fiberglass-reinforced polyester insulating board barriers were installed to achieve the same BIL. 4/0, 25 kV shielded cable with stress cones comprise pigtails, which run to the line-side of the main breaker in EEC-11. The snubber and surge arrester are grounded with an equipment grounding conductor (EGC) for 60-Hz faults, and highly-stranded flat-braid conductor for transients.

H. Sizing Phase and Ground Conductors

The snubbers do not have any local fusing and are connected to the source side of the EEC-11 main breaker and rely on the feeder breaker in the upstream substation for protection. Per the NEC Article 250, it is permissible to size the phase conductors for the snubber to 1/6 of the ampacity of the phase conductors in the feeder based on the upstream feeder breaker protection setting. As the feeder cable ampacity is just 1350 A, this gives 225 A for the rating of the phase conductors of the snubber cable. In this case 4/0 cable will be suitable for the phase conductors of the jumper cable. The 4/0 cable was also chosen for the EGC. As mentioned earlier, 25 kV 133% 105 °C tape-shielded cable was used for both the phase and EGC snubber cables.

I. Snubber Protection

In high reliability applications, monitoring of the snubber circuit is often recommended to ensure the integrity of the snubber components. A variety of options are available to protect the snubber and detect if the snubbers are functional. They range from nothing (oversized but treated like a lightning arrester) to fuse protection to very sophisticated loss of circuit detection: glow tubes, high- and low-current sensors, blown fuse indicators and remote monitoring. However, in this application the choice was made to keep it simple, and treat the snubber like a lightning arrester, and not install any protective functions. Furthermore, the site plans to do preventative maintenance every year and test the resistors and capacitors in the snubber, visually inspect wiring and grounding, and perform other checks. Robust ratings for the snubber components combined with regular preventative maintenance were considered adequate.

J. Completed Snubber Installation

The completed snubber installation is shown in Fig. 13. The dimensions of the enclosure are 48 in H × 36 in D × 72 in L. The front-doors and removable side panel are visible on the NEMA412 stainless steel enclosure. Notice the gradual bend in the 4/0 AWG phase and ground cables as they exit the snubber and enter the cable tray, which is the minimum bending radius of this 4/0 cable. The supplemental ground of the enclosure to the ground grid is visible at the lower left corner of the enclosure.

VIII. Measurements

Measurements were performed after installation and commissioning. The following discussion shows energization and

Fig. 13. Completed snubber installation at EEC-11.

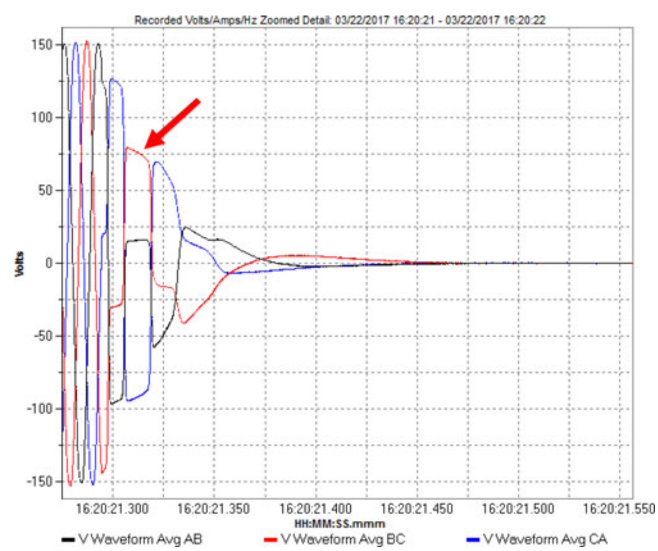

Fig. 14. CPT opening measurements.

de-energization of the source breaker to EEC-11 with its main breaker open. The only components in the measurements are the line side CPT, VTs, and cable. Measurements were only permissible from the CPT and VT secondaries. These results show the action of the snubbers, CPT and VT damping resistor ferro-resonance mitigation.

In Fig. 14, the measurement of the CPT show the 20-Hz ferro-resonance is very pronounced. The arrow shows when the underfrequency sensing controls switch in the secondary damping resistors. Note how dramatically the ferro-resonance condition is then damped out.

In Fig. 15, the VT secondary voltages are shown. The 20-Hz ferro-resonance condition is quickly damped out. The VTs have fixed space heaters connected all the time. Compare Figs. 14 and 15 with Fig. 6. The measurements confirm the presence of 20-Hz ferro-resonance and how effective the damping resistors

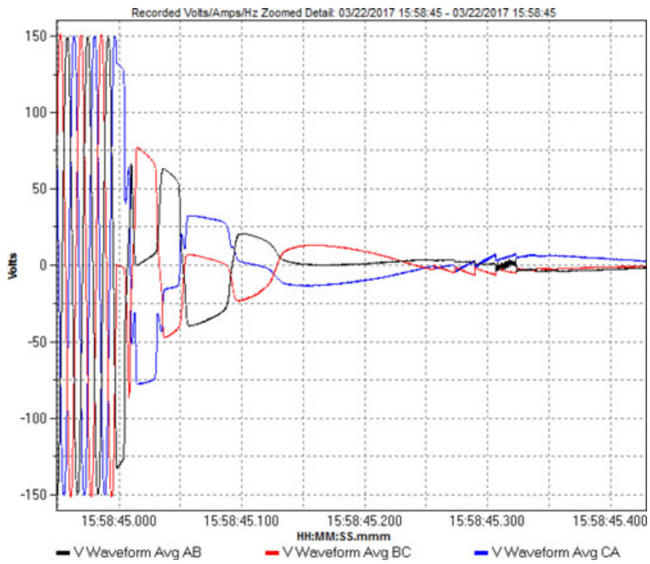

Fig. 15. VT opening measurements.

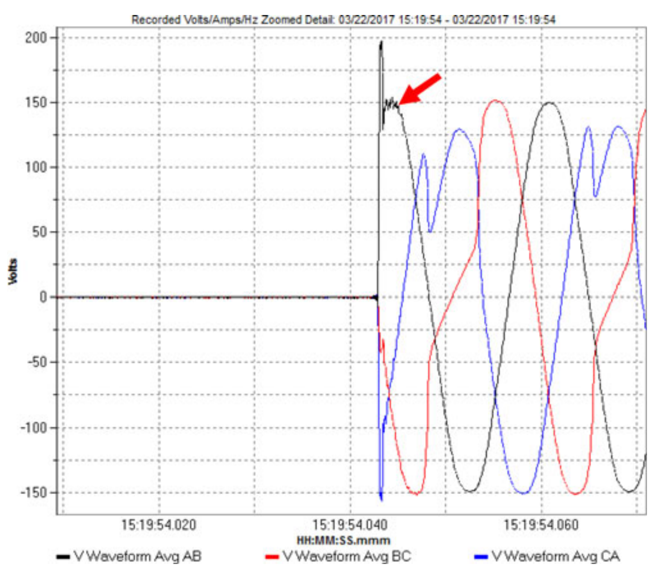

Fig. 16. CPT energization measurements.

perform with a consistent match to the computerized predicted outcome.

In Fig. 16, the prestrike/reignition closing transient shows dramatic reduction and almost complete elimination of the ring wave as predicted in Fig. 4 (see arrow). Note how closely it matches the simulated wave form in Fig. 9. This shows very good snubber action as well.

The field measurements have verified the effectiveness of the proposed mitigation solutions as well as proving the EMTP model accuracy.

IX. Conclusion

This paper shows an in-depth analysis of switching breaker transients. The analysis has shown the ferro-resonance phenomenon occurs for the bus and line-side VTs and the CPTs on the line-side of EEC11 main circuit breakers. The authors have confirmed by simulations and measurements, that the proposed ferro-resonance mitigation at EEC11 switchgear is working very well. After the upstream circuit breaker opens, there will be a dc trapped voltage on the open line. With the VT in-service, the trapped voltage can be large enough to saturate the VT magnetizing impedance and starts to oscillate with a "square" waveform for the VT. The oscillation will last for a long period of time, until eventual failure of the VT occurs overtime. It should be noted that the failure may not necessarily occur based on just one switching event but will occur overtime based on a number of switching events and is dependent on where the circuit breaker opens on the voltage waveform. The analysis has also shown the substation feeder VCB induced voltage transients will cause damage to the bus and line-end VTs and the CPTs at the EEC11 switchgear unless mitigation is applied. The results of the analysis in this part of the study also indicate that one snubber each is required on the line-side of each 21.6 kV main breaker. Based on simulation results, the application of the snubber will dramatically reduce the magnitude of the voltage transient below 50% of BIL, as well as reduce the dc offset of the voltage transients. The frequency of the transient oscillation is reduced below the recommended 1000 Hz or less with the application of the snubber. A special control circuit is implemented to allow the damping resistors in the circuit when needed. This will save energy due to noncontinuous power consumption.

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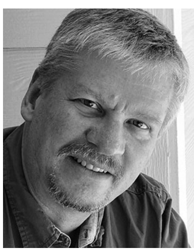
Tamer Abdelazim Mellik (S'02–M'06–SM'14) received the B.Sc. degree in electrical and computer engineering from Suez Canal University, Ismailia, Egypt, in 1995, and the Ph.D. degree in electrical and computer engineering from the University of Calgary, Calgary, AB, Canada, in 2005.

He has more than 20 years of power system experience involving modeling, simulation, and R&D/algorithm design of industrial and utility power systems. He has authored or co-authored 35 papers in international journals and conferences. He is interested in transient and steady-state studies, and utility and renewable energy studies.

Dr. Mellik is a Registered Professional Engineer in the provinces of Alberta and Manitoba.



Frederick D. Painter II (S'81–M'82) received the B.S. degree in electrical engineering from West Virginia University, Morgantown, WV, USA, in 1982.

Since graduation, he has been an Electrical Engineer with Marathon Oil Company (31 years) and Anadarko Petroleum Corporation (more than three years). During his career, he has performed a variety of engineering duties associated with onshore and offshore oil and gas production/processing operations throughout the world. He currently serves as a Senior Facilities Engineering Advisor within Anadarko's midstream engineering group, with a focus on power systems design and construction for gas processing facilities.

Mr. Painter is a licensed Professional Engineer in the State of Texas.

David D. Shipp (LF'11) received the B.S.E.E. degree in electrical engineering from The Oregon State University, Corvallis, OR, USA, in 1972.

He has spent many years performing the engineering work associated with his present-day responsibilities, which include a wide range of services covering consulting, design, power quality, arc flash, grounding, and power systems analysis topics. He has written more than 90 technical papers on power system analysis topics and another ten for the Society of Petroleum Engineers. More than 15 technical papers have been published in IEEE/IAS international magazines and two in EC&M.

Mr. Shipp is a past Chair for the IEEE I&CPS-sponsored Working Group on generator grounding. He is very active in IEEE at the national level and helps write the IEEE Color Book series standards.

Thomas J. Dionise (S'79–M'82) received the B.S.E.E. degree in electrical engineering from The Pennsylvania State University, University Park, PA, USA, in 1982, and the M.S.E.E. degree in electrical engineering with the Power Option from Carnegie Mellon University, Pittsburgh, PA, USA, in 1984.

He is currently a Power Quality Advisory Engineer with the Power System Engineering Department, with Eaton Corporation, Warrendale. He has more than 34 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 has coauthored 30 papers.

Mr. Dionise was the recipient of the Metal Industry Committee Prize Paper Award in 2006 and 2010. In 2011, he was the recipient of harmonic filter design for an electric arc furnace received second Place, IAS Transactions Prize Paper Award, and in 2014 another on issues that affect data center reliability received the IEEE Industry Applications Magazine second Place Prize Paper Award. He is the Chair of the IEEE Metal Industry Committee and member of the Generator Grounding Working Group. He is a licensed Professional Engineer in Pennsylvania.