Analysis of 115kV circuit switcher damage during a normal switching operation

Song Ji, Yujie Irene Lu, Dan Hasenwinkel, Joshua Joseph - National Grid USA

Keywords: 115kV line fault, Circuit Switcher Failure, Zero-sequence voltage protection, Harmonics, Ferroresonance

Introduction:

In modern society, electricity is indispensable to our daily life. A fault in the power system could result in power quality and stability issues, and even blackouts to a large area. Therefore, power system faults should be isolated properly by the protection system in a timely, effective, and selective manner.

Based on a disturbance investigation, this paper examines the damage to a 115kV circuit switcher, capacitor voltage transformer (CVT), and surge arresters on both sides of the transformer at a distribution substation following a 115kV system typical switching operation. Fault records from IEDs recorded 4.5 PU overvoltages on the 115kV bus. They provided invaluable information which gave insight into the nature of this ferroresonance overvoltage event. These records were used as inputs to PSCAD simulations to determine what happened, and the analog and digital data of fault records facilitate an efficient investigation and accurate analysis of these events.

Resonance in an alternating current (AC) circuit occurs where the reactive and capacitive elements are equal and opposite at a particular frequency (the resonant frequency). Ferroresonance is a special case of resonance involving non-linear inductances which can be present in the magnetizing impedances of a power transformer. Once it is initiated, the sustained overvoltage will exhibit distorted waveforms with high harmonic content. Equipment exposed to a long duration ferroresonance event will have irreversible damage. This paper will investigate the root cause of the equipment failures at station DM.

System Overview:

The simplified regional system one line is shown in Figure 1. 115kV lines L1 and L2 run parallel between source stations GD and DK located in western New York. The distribution station DM is tapped from line L1 & L2 through 115kV circuit switchers CS-1 and CS-2 respectively. Several other stations are tapped from these lines to supply normally closed sub-transmission loops or radial distribution stations.

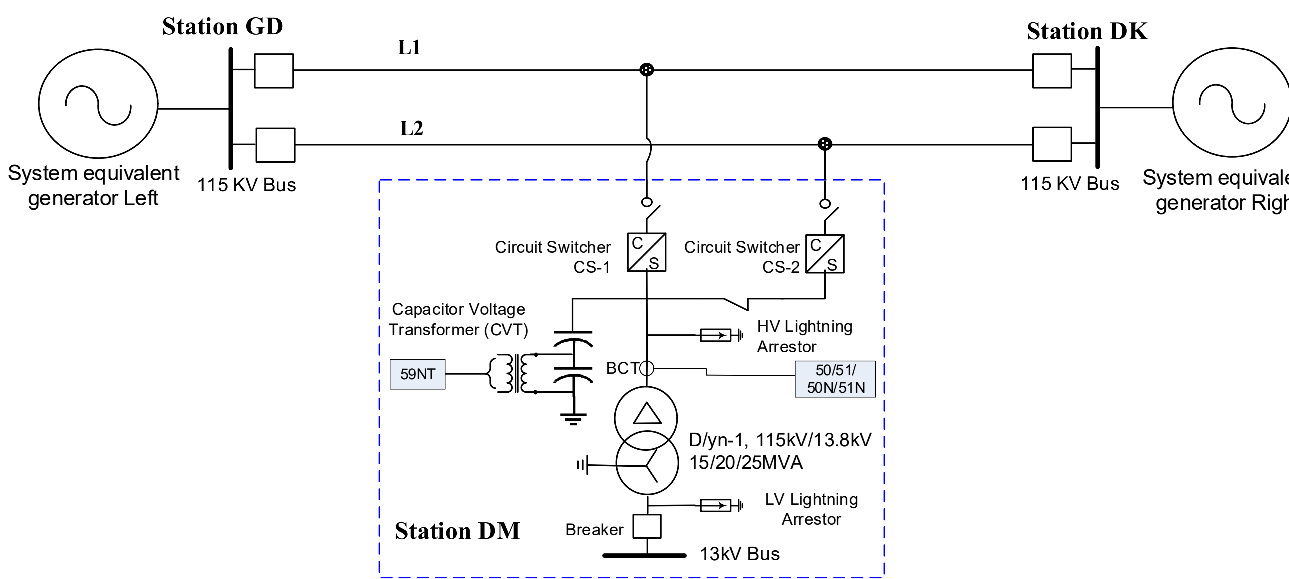

Figure 1: the simplified regional system one line

Under normal operation, the 115kV/13.8kV distribution step-down transformer at station DM is connected to line L1 through the normally closed circuit switcher CS-1. Circuit switcher CS-2 is normally open. If there is an outage of line L1, the station supply is interrupted. For a permanent L1 fault, automated opening of the transformer's low side main breaker and CS-1, followed by the closing of CS-2 restores the customers. When L1 is restored to service, a closed transition is used to restore DM to its regular supply. Line L1 and L2 will not be inter-connected at station DM except for closed transitions between the two lines to avoid customer outages.

Lines L1 and L2 are provided with dual high-speed protection systems at station GD and DK. Any fault on a 115kV line including the 115kV equipment at the tapped station DM will be detected by the line protection, then line breakers at source station GD & DK will trip and attempt to reclose. Digital fault recorders (DFR) are provided at both stations GD and DK. Triggers are set to capture system fault or abnormal operational conditions. At the tapped station DM, the step-down D/Yn-1 transformer is provided with electromechanical phase and residual instantaneous and time-inverse overcurrent protections (51 & 50N/51N) connected from HV bushing CTs. The operation of overcurrent protection will trip HV side circuit switcher and LV main breaker. The definite time ground overvoltage protection (59NT) measures the voltage from 115kV side CVTs and is used to detect a 115kV side ground fault, as the transformer HV winding is delta configured and won't supply fault current for a 115kV line side ground fault. The 59NT was recently added to the tap station due to large amounts of photovoltaic Distributed Generation (DG) connected to the station's feeders. The operation of 59NT protection will trip the LV main breaker to remove fault contributions from the 13kV feeders' DG.

The event and equipment damage:

On 8/17/2024, 115kV line L1 tripped and locked-out from both line end terminals GD and DK. Upon loss of power from line L1, circuit switcher CS-1 and LV bus incoming breaker at DM were opened by the auto transfer scheme. Circuit switcher CS-2 successfully closed, and then the low side main breaker closed. Thus, station DM was fully restored.

Approximately one hour later, 115kV line L1 was successfully re-energized from both line terminals. The configuration at DM was manually changed back to its normal configuration. The control center remotely closed CS-1 and opened circuit switcher CS-2 . A few seconds later, LV bus incoming breaker was tripped open, and control center was unable to close it back in. The traveling operator was notified to see what happened at station DM. The closing circuit had been problematic for the breaker.

Fifty (50) minutes later, the traveler arrived at station DM and found the 115kV circuit switcher CS-1 was on fire with severely damaged A & B phase interrupters as shown in Figure 2. The traveler managed to restore the station from line 2 through circuit switcher CS-2.

It should be noted that the 115kV lines L1 & L2 remained in service during the switching at DM. There were no triggered events from the line relays and DFRs at either source terminal station GD or DK.

Figure 2: the damaged 115kV circuit switcher CS-1 and cracked housing on B-phase interrupter

Detailed inspections were performed at station DM in the next few days. Burn marks and cracks were found on A-phase CVT external housing. Dielectric loss (loss tanδ) tests for CVTs indicated excessive losses on capacitor voltage dividers and are a sign of deterioration in the insulation.

In the next month there were two other events at the station resulting in customer outages. Transformer HV & LV side surge arrester associated faults occurred at station DM. The damaged equipment at the station was related to the switching operation and must have experienced overvoltage stress which caused irreversible damage to that equipment.

Now, it's necessary to review the available relay records at station DM and analyze the damage from the characteristics of different equipment.

Relay records and station equipment:

Zero sequence overvoltage protection:

After opening CS-2 and closing CS-1 at station DM, the zero sequence overvoltage 59N relay on the 115kV side was triggered(Figure 3).

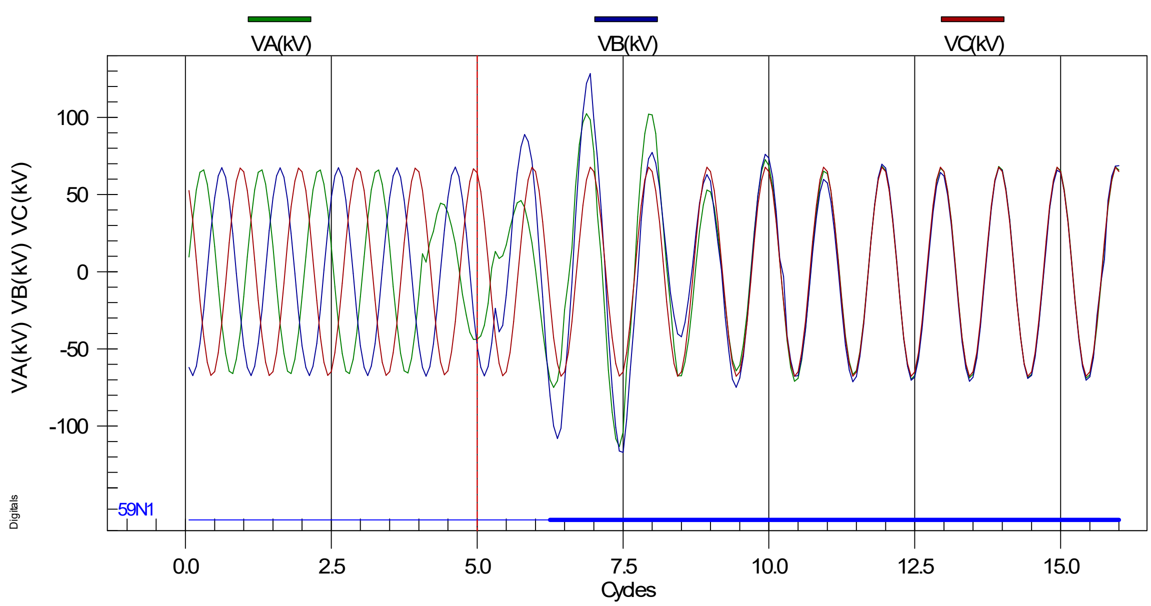

Figure 3: relay record of 115kV side 59NT relay

Per waveform, phase C voltage was normal, but A & B phase voltages were distorted with harmonic content and phase angles displacement was not normal right after CS-1 & CS-2 switching. The identical voltage waveforms were from single phase energization of the transformer as illustrated in Figure 4. It eventually changed to a condition for ferroresonance, which will be discussed later. The resultant 60Hz 3V0 exceeded the pickup value

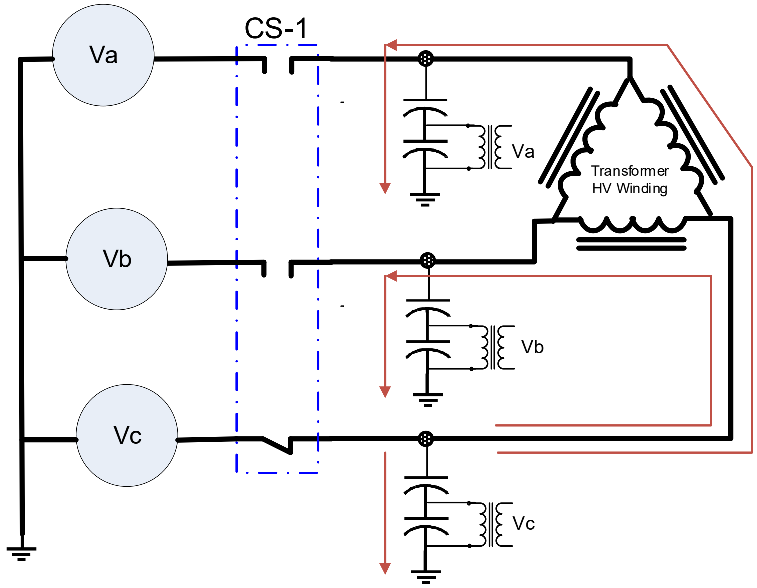

Figure 4: Voltage distributions over transformer HV winding and CVTs from single phase energization

After 59NT timeout, a trip command was sent to the transformer LV main breaker. However, by design the transformer winding was still energized from the 115kV system through circuit switcher CS-1. There were several sequential triggered records from the 59N relay. One of the records is shown in Figure 5.

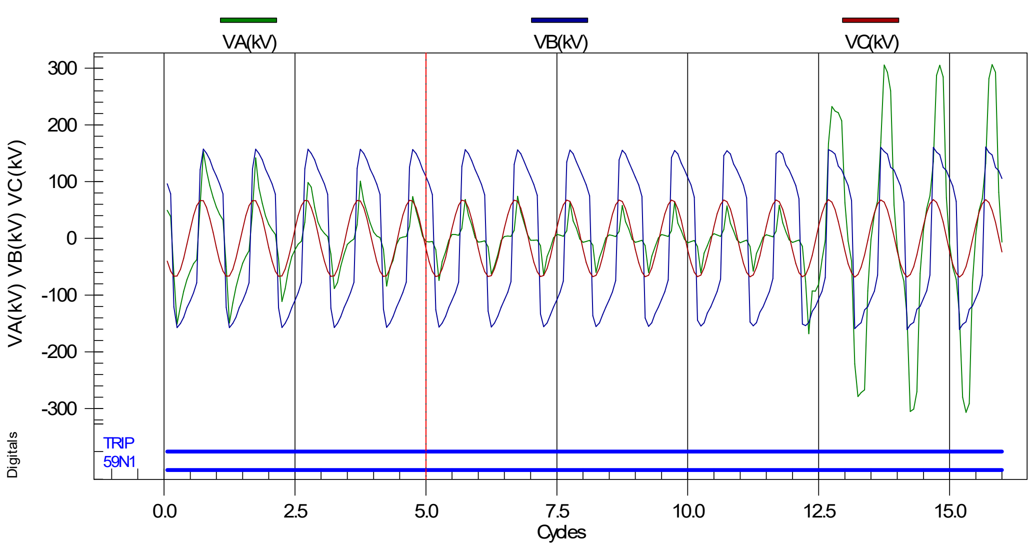

Figure 5: relay record of 115kV side 59NT relay standing trip signal after time-out

There were transient overvoltages on phases A & B, the secondary voltages were distorted, and the highest magnitude could be 4.5 times of rated voltage referenced to the ground. Since the voltage signals are from the secondary of CVTs, the actual primary temporary overvoltages could have been even higher. Based on voltage records, the station DM experienced long duration temporary overvoltage from ferroresonance following the switching. Due to the unusual nature of the disturbance, a detailed look at the failure and a model of the system's nonlinear response needed to be developed.

HV Circuit Switcher:

115kV circuit switchers, CS-1 & CS-2, are provided on the transformer HV side as the fault interruption and isolating device. Circuit switchers, with the combination of a ganged disconnect switch and fault interrupter, are less costly than conventional circuit breakers and can be applied in less space than a circuit breaker and its disconnect switch. The typical circuit switcher has only one trip coil and has limited interrupting capability than comparable breakers.

The circuit switchers at station DM have a horizontal interrupter design configuration with an integral vertical break disconnect switch.

Figure 6: Horizontal interrupter circuit switcher with integral vertical disconnect switch

The SF6 filled interrupters are installed on vertical post insulators, therefore the housing of interrupters cannot be maintained at ground potential and window CTs can't be installed around the interrupter housing. In the event of a circuit fault, the interrupter is instructed to clear the circuit, the disconnect opens to establish visible air gap. On a closing operation, the disconnect closes before the interrupter does.

The damaged circuit switcher CS-1 was manufactured in 1974 with 2000A continuous current rating. As shown in Figure 2, the outmost phase interrupter (A-phase) exploded and the middle phase (B-phase) interrupter insulating housing has a large crack. This implied that the huge internal gas pressure must be present inside of the interrupter and the pressure was caused by the heat. As the current rating of CS-1 is 2000A, to generate such heat, the magnitude of the flowing current through CS-1 would be much more than 2000A if the damage was caused by the current. However, there was no triggered events & records on line L1 relays and DFRs at source station GD & DK. The damage must be due to other reason.

When the primary voltages are applied to the circuit switcher, there are two kinds of voltage stress, the longitudinal and transverse voltage difference, as shown in Figure 7.

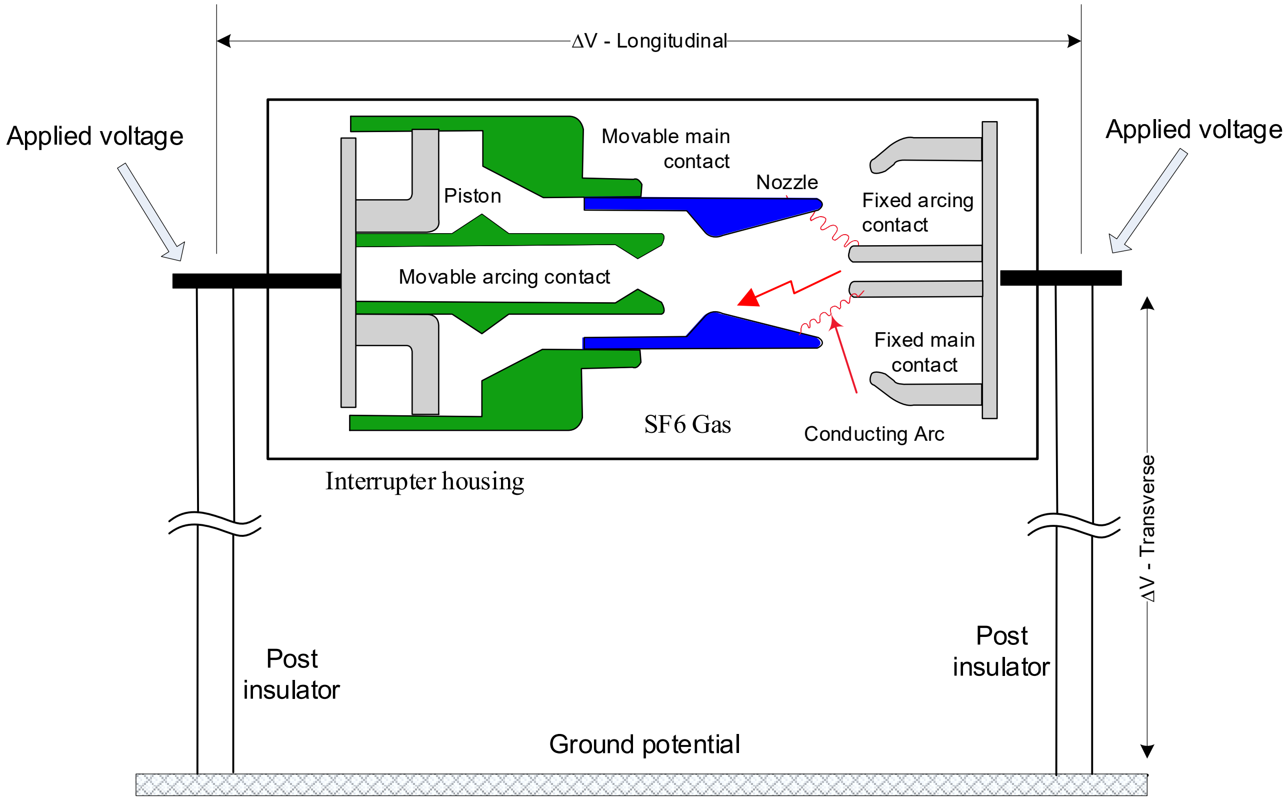

Figure 7: voltage stress on the interrupter of circuit switcher

The transverse voltage is the difference between the applied voltage and the ground while longitudinal voltage is the difference between the fixed and movable main contacts. The longitudinal voltage difference is zero when the interrupter is in closed position. If the interrupter is not at fully closed position, the small gap would be formed between the fixed and movable main contacts. When the longitudinal voltage exceeds the dielectric strength, the discharge arcing would be developed across the contacts. The arcing and the heat would increase gas pressure in the interrupter and finally damage the external housing.

Based on the damage pictures in Figure 2, it was most likely that circuit switcher CS-1 was not fully engaged in the closed position, which was also the trigger of ferroresonance and will be discussed later. The discharge arcing from the longitudinal voltage across phase A & B interrupter was the cause of the damage.

Metal-oxide arrester:

At station DM, gapless metal oxide arresters are mounted next to each phase bushing of the transformer HV and LV windings. Surge arresters are the basic protective devices against system transient overvoltage. The maximum continuous operating voltage (MCOV) rating defines the maximum continuous voltage at which an arrester is designed to operate. The rating of the MCOV of HV and LV side surge arresters are 98kV rms and 10.2kV rms respectively.

As a voltage sensitive device, the operation and status of the surge arrester are directly correlated with the voltage presence. When the applied voltage exceeds the MCOV rating, the arrester exhibits a very non-linear behavior. However, metal-oxide arresters can operate for limited periods of time when applied voltages exceeds the MCOV rating. This capability is called temporary overvoltage (TOV) capability. The system temporary overvoltage is defined in IEEE Std. C62.22 as "an oscillatory overvoltage associated with switching or faults (for example, load rejection, single-phase faults) and/or nonlinearities (ferroresonance effects, harmonics) of relatively long duration, which is undamped or slightly damped". Surge arrester manufacturer can provide a time curve showing the temporary power-frequency overvoltage without damages. The typical overvoltage capability curve is shown in Figure 8:

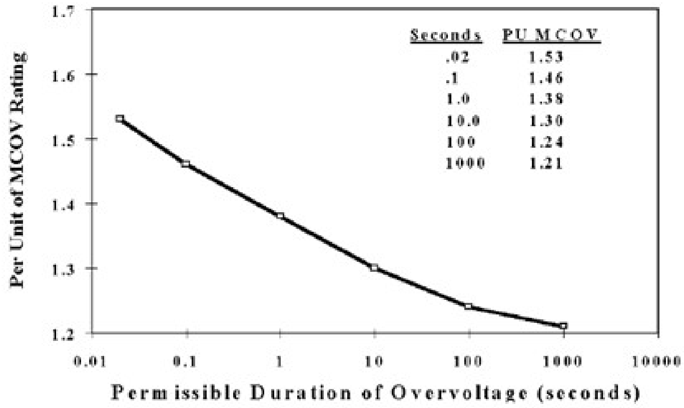

Figure 8: Typical 60-Hz Temporary Overvoltage Capability for Metal Oxide Arresters [1]

If TOV exists and exceeds the withstand curve, the large amount of heat would be generated in the housing and the surge arrester is susceptible to thermal damage. The reported surge arrester failures at station DM were most likely caused by the long duration of overvoltage from ferroresonance presence following the switching.

Transformer equivalent circuit:

A transformer usually consists of two or more coupled windings on a magnetic core which is constructed predominantly from laminated iron with the addition of small amounts of silicon and other elements to improve the magnetic properties and lower losses. For the practical power transformer energized by sinusoidal voltage, the relationship between the induced voltage (E) and the peak magnetic flux (Φ_{max}) is:

E(t)= $4.44 \times f \times N \times \Phi max = 4.44 \times f \times N \times A \times B$
Where:
f = frequency in Hz,
N = Number of turns of the winding,
A= cross-sectional area of the core,
B= Magnetic flux density.

The excitation characteristics of a transformer is determined by its core construction. As the ferromagnetic core can't support infinite magnetic flux density and will saturate at a certain level. The typical transformer magnetic flux-field density [B-H] curve and flux-excitation current are illustrated in Figure 9a & 9b respectively.

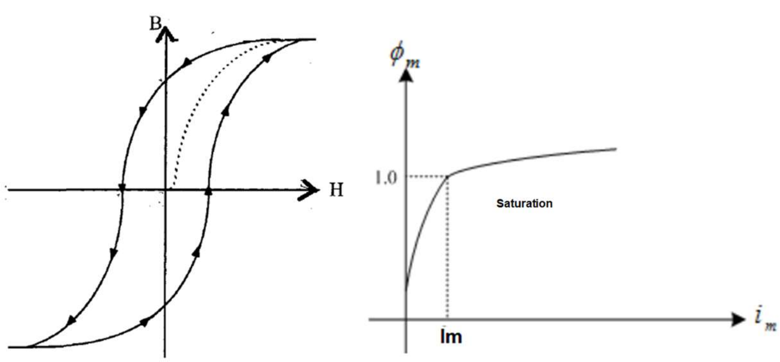

Figure 9a & 9b: the typical transformer B-H (left) and flux - excitation current curve (right)

Considering the winding ohmic losses, hysteresis and eddy current losses in the core, the transformer circuit can be represented in a classical T-model shown in Figure 10.

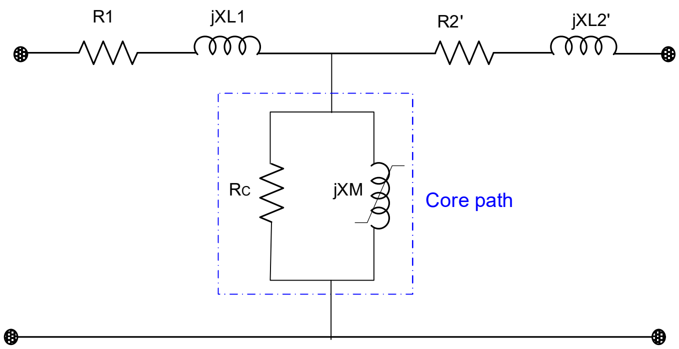

Figure 10: the classical T-model of two-winding transformer

The magnetic flux density B in the transformer iron core initially rises linearly when the magnetic field intensity H increases. However, beyond the saturation point, the flux density ceases to increase linearly with the field intensity and begins to saturate. Thus, the magnetizing inductance, Xm, exhibits non-linear behavior due to magnetic saturation effects.

Ferroresonance circuit:

If the capacitance, inductance and resistance are present in an electrical circuit, the series or parallel resonant circuit can be formed. The impedance of simple series resonant circuit shown in Figure 11 is calculated as follows:

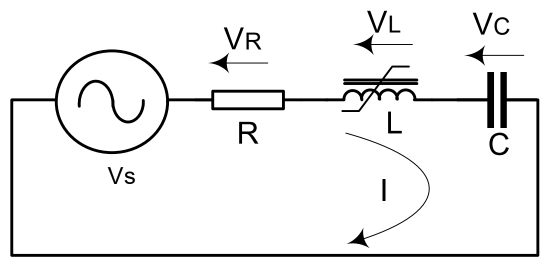

Figure 11: a simple series resonant circuit

$Z=r+j\omega L-j/[\omega C]$

Where:

r = resistance,

L = non-linear inductance,

C= capacitance,

Resonance is present if the imaginary part of the impedance Z becomes zero. This will happen when the resonant circuit frequency equals to $1/\sqrt{LC}$. At resonant frequency the impedance of the series resonant circuit is very small, and is determined only by the value of the resistance R.

To form a ferroresonance circuit, the nonlinear saturable inductance (transformer), the capacitor and low loss in the circuit are required. Ferroresonance is normally initiated following a switching operation.

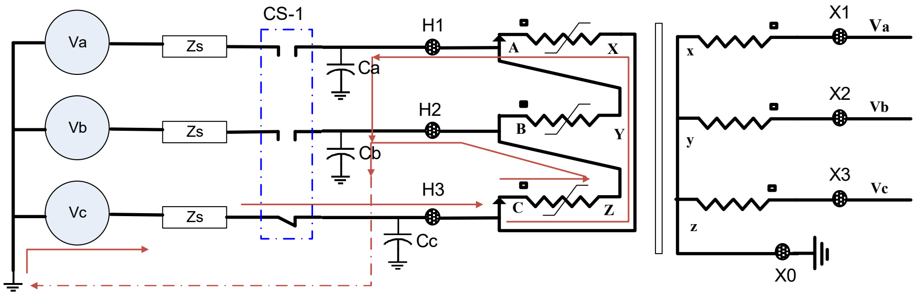

Figure 12a: Non-load transformer with single C-phase energization at station DM

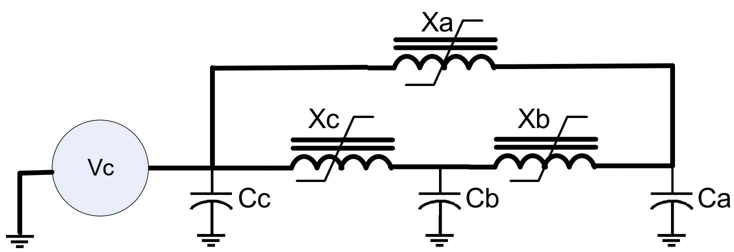

Figure 12b: Simplified ferroresonance circuit at station DM

As shown in Figure 12a & 12b, when phase A & B main contacts of CS-1 were not closed and the transformer had no load, a complex resonance circuit was formed between the transformer HV side magnetizing impedances and the capacitance of the CVTs, bus, and transformer bushings.

Once ferroresonance circuits were formed, the temporary overvoltage was present on transformer terminals and resulted in equipment damage at station DM.

Ferroresonance simulations in PSCAD:

To verify the above analysis, an electrical simulation circuit was built in PSCAD/EMTDC environment. The snapshot of simulation circuit is shown in Figure 13.

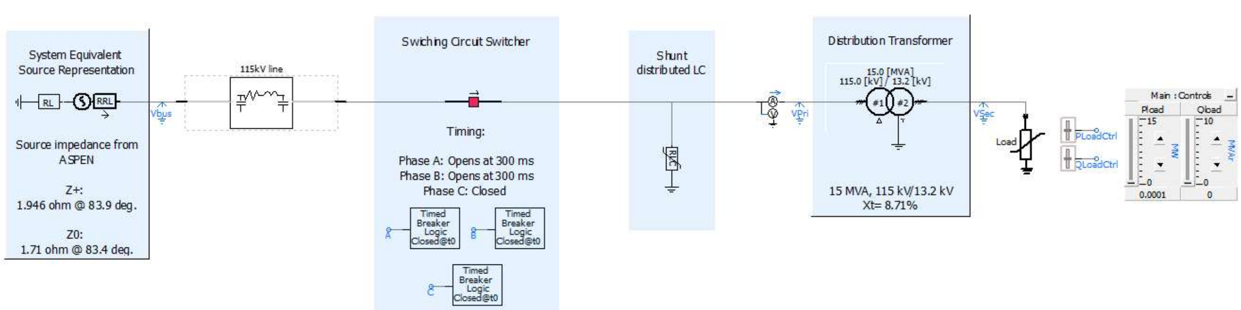

Figure 13: Ferroresonance simulation circuit in PSCAD

In the simulation circuit, source impedance and line models were from Thevenin equivalent circuit from ASPEN short circuit tool. The poles of the circuit switcher are independently controlled; A & B phase poles were opened during the simulation. The transformer load can be adjusted. In the simulation, no load was applied. On transformer HV terminals, the lumped shunt LC circuit was used to represent parameters of CVTs, surge arresters and the stray capacitance. Based on the real event scenario, the following constraints are required:

1) the bus voltages at the source stations were not affected during ferroresonance event,

2) the crest magnitude of overvoltage at the DM transformer HV terminal was 4.5 P.U,

3) The longitudinal voltage difference across the opened interrupter main contacts was 7.0 P.U in the simulation. This would ensure the dielectric breakdown and arcing discharge across the opened contacts.

The above constraints were the objective of finding the lumped shunt LC parameters by using multiple-run component in PSCAD. In the beginning, the user would define a range for LC, then the optimal values of L & C parameters were selected through a number of simulations by error and try of variable input signals. The snapshot of finding LC parameters is shown in Figure 14.

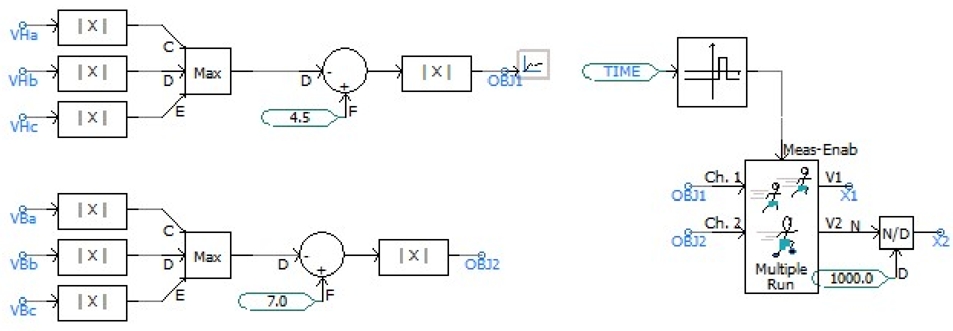

Figure 14: selection of shunt LC parameters

The objective variables (OBJ1 & OBJ2) were the magnitude of temporary overvoltage and sent to the input channels of the tool. The output variables V1 & V2 were optimized capacitance and inductance value.

The ferroresonance simulations were performed with and without transformer LV side loading. The no loading simulation results are shown in Figure 15 & 16.

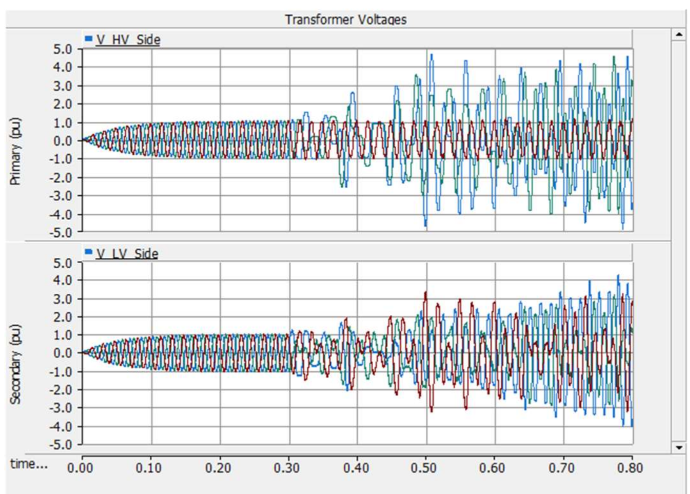

Figure 15: Transformer HV & LV terminal voltages during ferroresonance event

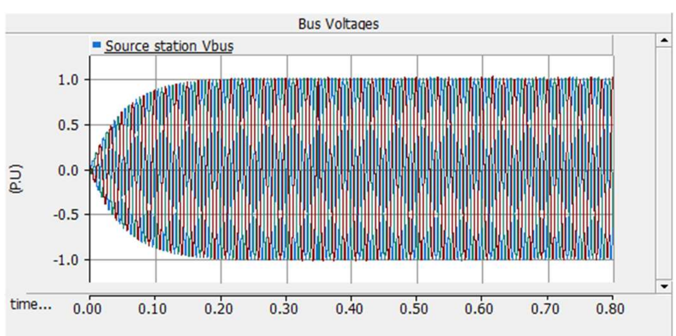

Figure 16: Source station bus voltages

The transformer did experience temporary overvoltage from ferroresonance. The long duration exposure to such overvoltage is detrimental to the insulation of electrical equipment and would adversely impact the lifespan and performance of the affected equipment. The localized ferroresonance may not have any influence at the remote source station. The same simulation was performed with loadings added to the transformer and no ferroresonance appeared.

Conclusion:

Inadvertently energizing the unloaded transformer in none 3-phase could result in the ferroresonance. The inductive and capacitive equipment under ferroresonance may experience excessive temporary overvoltage which would affect the life span and performance of the equipment. Therefore, the power supply for the ferroresonance circuit needs to be opened in a timely manner.

Future AI/ML methods focusing on short time intervals and high frequency component localization show promising results to enable the detection of ferroresonant waveform characteristics. These stem from using the Fourier analysis technique, evolving into both time and frequency domains.

References:

1. IEEE Std C62.22 – 2009, IEEE Guide for the Application of Metal-Oxide Surge Arresters for AC Systems

2. PSCAD/EMTDC Technical manual

Authors:

Song Ji has been with Department of Protection Policy and Support of National Grid since 2009. Song has 30 years' experience in the power industry.

Yujie Irene Lu received a BSEE degree in Power Systems Engineering from Huazhong University of Science & Technology in China, and a MSEE in Electrical Engineering from Virginia Polytechnic Institute in Blacksburg, VA. She is a senior member of IEEE and a registered professional engineer in the Commonwealth of Massachusetts. She received the 2010 Annual Outstanding Engineer Award from the Boston Chapter of the IEEE Power and Energy Society in November 2010. Irene has been employed in Protection Engineering at National Grid since 1990. She is a consulting engineer in the Department of Protection Policy and Support, where she analyzes system disturbances, performs system analysis for short circuit conditions, develops protection and control system standards, designs protection systems and determines protection settings and logics.

Dan Hasenwinkel received a BSEE degree in Electrical Engineering from Rose-Hulman Inst. of Technology, and a MSEE from Clemson University. He is a member of the IEEE and a registered professional engineer in the State of New York. From 1999 onward he has been employed at National Grid and its predecessor companies. He has been a Principal Engineer in the New York Protection Policy and Support group for one year. He was previously in the protection engineering department for seven years, providing support for station and line protection for transmission, sub-transmission, and distribution projects. Dan also has experience in substation engineering, energy management system projects and support, as well as IT portfolio and project management.

Josh Joseph received his BS and MS degrees in Electrical Engineering from University at Buffalo, The State University of New York. He is a member of the IEEE and a registered profession engineer in the State of New York. He has been employed by National Grid since 2018 where's served as Senior Commissioning Engineer and Senior Protection Operations Supervisor. Josh is currently a Lead Engineer in PTO O&M Services where he develops standard test templates, creates and maintains procedures and standards, and provides technical expertise to support National Grid operations from an engineering perspective.