TRANSFORMER FAILURE DUE TO CIRCUIT BREAKER INDUCED SWITCHING TRANSIENTS APPPLICABLE TO THE CEMENT INDUSTRY

By:
David D. Shipp, PE, Fellow IEEE, Eaton Corp., daviddshipp@eaton.com
Thomas J. Dionise, PE, Senior Member IEEE, Eaton Corp., thomasjdionise@eaton.com
Visuth Lorch, Member IEEE, Eaton Corp., visuthlorch@eaton.com

ABSTRACT

Switching transients associated with circuit breakers have been observed for many years. Recently this phenomenon has been attributed to a significant number of transformer failures involving primary circuit breaker switching. These transformer failures had common contributing factors such as 1) primary vacuum or SF-6 breaker, 2) short cable or bus connection to transformer, and 3) application involving dry-type or cast coil transformers and some liquid filled. This paper will review these recent transformer failures due to primary circuit breaker switching transients to show the severity of damage caused by the voltage surge and discuss the common contributing factors. Next, switching transient simulations in the electromagnetic transients program (EMTP) will give case studies which illustrate how breaker characteristics of current chopping and re-strike combine with critical circuit characteristics to cause transformer failure. Design and installation considerations will be addressed, especially the challenges of retrofitting a snubber to an existing facility with limited space. For the cement industry, situations where circuit breaker induced switching transients are likely to damage transformers will be discussed. Finally, several techniques and equipment proven to successfully mitigate the breaker switching transients will be presented including surge arresters, surge capacitors, snubbers and these in combination.

Index Terms - Switching Transients, vacuum breakers, SF-6 breakers, EMTP simulations, surge arresters, RC snubbers.

1.0 INTRODUCTION

Today, medium voltage metal-clad and metal-enclosed switchgear that use vacuum circuit breakers are applied over a broad range of circuits. These are one of many types of equipment in the total distribution system. Whenever a switching device is opened or closed, certain interactions of the power system elements with the switching device can cause high frequency voltage transients in the system. The voltage transient severity is exacerbated when the circuit breaker operates abnormally, i.e. current chopping upon opening and prestrike or re-ignition voltage escalation upon closing. Such complex phenomena in combination with unique circuit characteristics can produce voltage transients involving energies which can fail distribution equipment such as transformers. Transformer failures due to circuit breaker induced switching transients are a major concern, received attention in a new standard [1] and the focus of this paper. Emphasis is given to scenarios likely to be encountered in the cement industry.

1.1 FORENSIC EVIDENCE FOR A UNIQUE CASE

Consider the case study of a new Data Center with a 26 kV double-ended loop-through feed to six dry-type transformers each rated 3000 KVA AA/3390 KVA FA, 26/.48 kV, delta-wye solidly grounded as shown in Figure 1. The transformer primary winding is 150 kV BIL. A vacuum breaker was used to switch the transformer. The 4/0 cable between the breaker and transformer was 33 kV and 133% EPR. Primary arresters were installed. The transformers were fully tested, including turns ratio, insulation resistance, etc. Functional tests were complete including UPS full load, UPS transient, data center room validation, etc.

978-1-4673-5553-7/12/$31.00 © 2013 IEEE

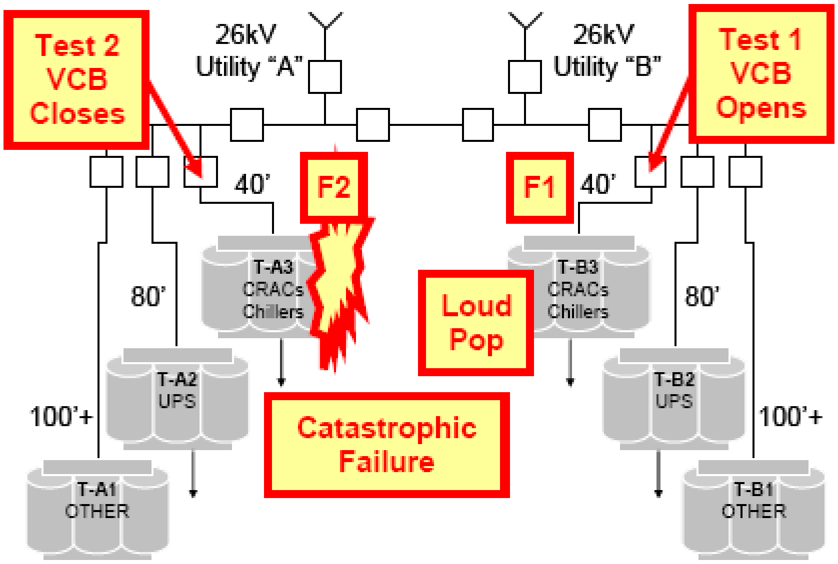

Figure 1. Simplified Electrical Distribution System for Data Center

In the final phase of commissioning, a "pull-the-plug" test was implemented with results as follows:

1) De-Energization Failure #1: Four electricians "simultaneously" opened four 26 kV vacuum breakers to simulate a general utility outage. All systems successfully transferred to standby generation but a "loud pop" was heard in Substation Room B and the relay for the vacuum circuit breaker feeding transformer TB3 signaled a trip.

2) Energization Failure #2: Minutes later, two electricians "simultaneously" closed two 26 kV vacuum breakers to substation Room A. Transformer TA3 failed catastrophically.

Failure #2 is shown in Figure 2. Examination of the primary windings revealed that the coil-to-coil tap burnt off and the winding terminal showed an upward twist. The burn marks from the initial flash indicated the transient concentrated on the first turns of the windings. Typically, closing the vacuum breaker to energize the transformer is the worst condition.

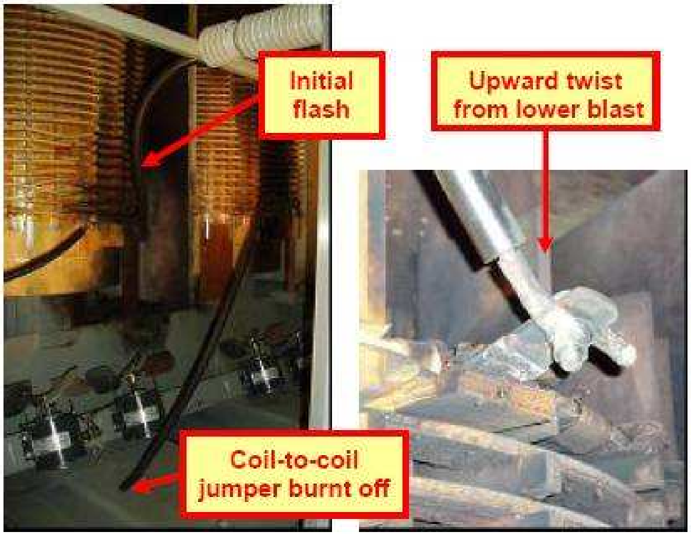

Figure 2. Transformer Failure #2 During Energization

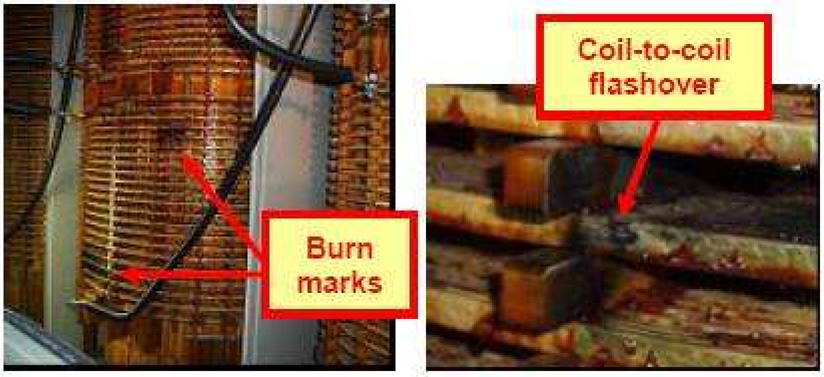

Figure 3. Transformer Failure #1 During De-Energization

Failure #1 is shown in Figure 3. Examination of the primary windings revealed flash and burn marks on the B-phase winding at the bottom and middle. Those at the top indicate a coil-to-coil failure, not a winding-to-winding failure, and indicate a transient voltage with high dv/dt. Those in the middle were a result of the cable (used to make the delta connection) swinging free. Supports were only lacking for this jumper (oversight during manufacturing) which could not withstand the forces of the transient. This transformer passed the BIL test at 150 kV BIL but ultimately failed at 162 kV BIL.

All six transformers and cables were identical, but only two failed during the vacuum circuit breaker switching. The significant difference was the two failed units had 40 feet of feeder cable while the others had 80 or 100 feet of feeder cable. This short 40 feet of cable, high efficiency transformer and vacuum circuit breaker proved to be the right combination to produce a damaging voltage transient on both energization and de-energization.

1.2 HISTORY OF FAILURES AND FORENSIC REVIEW

The previous example is not an isolated case. Instead, it is representative of a growing number of transformer failures due to primary switching of vacuum breakers. Table 1 details a history of transformers related to primary switching of vacuum breakers occurring within the past three years. In Case 1 at a hydro dam, the transformer was “value engineered” with a 13.8 kV primary winding BIL of 50kV BIL. The BIL should have been 95 kV BIL for the 13.8 kV class. 1955 switchgear was replaced with modern vacuum breakers with only 20 feet of cable to the transformer. The user chose to energize the transformer before conducting a switching transient analysis and failed the transformer primary winding. The post mortem analysis revealed no surge protection was applied.

TABLE 1 HISTORY OF TRANSFORMER FAILURES RELATED TO PRIMARY VACUUM BREAKER SWITCHING

		Circuit		Transformer***				Vacuum Breaker	
Case	Facility	Voltage	Cable Feet	Bil	Type	Arrester	Failure Mode	Vendor	Switching
1*	Hydro Dam	13.80	20	50	Dry (VPI)	No	1st turn	A	Close
2	Hospital	13.80	27	95	Dry (VPI)	No	1st turn	A	Close
3	Railroad	26.40	37	150	Liquid (layer wound)	N/A	middle	A	Open
4	Data Center	26.40	40	150	Dry (VPI)	Yes	1st turn	B	Close/Open
			80	150	Dry (VPI)	Yes	None	B	Close
5	Oil Field	33.00	7		Dry	No	1st turn	C	Close
6**	Oil Drill Ship	11.00	<30	75	Cast coil	Yes	1st turn	C	Close

Notes: * = 40-50yrs. old with new breaker. ** = 2 yrs. old. All others new.
*** = All transformers unloaded or lightly loaded when switched.

In Case 2 at a hospital, the vacuum breaker was close- coupled through 27 feet of cable to a 2500 kVA, dry type transformer with a 95 kV BIL primary winding. The vacuum breakers were supplied with no surge protection because the particular vacuum breaker installed had a very low value of current chop. During vacuum breaker switching of the transformer, the transformer failed. The transformer was rewound and surge protection/snubbers were installed.

In Case 3 at a railroad substation, vacuum breakers applied at 26.4 kV were used to switch a liquid filled rectifier transformer with 150 kV BIL primary winding. The switching transient overvoltage failed the middle of the primary winding. Forensic analysis determined a rectifier with DC link capacitors and the transformer inductance formed an internal resonance that was excited by the switching. Such an LC series resonance typically fails the middle of the transformer primary winding.

In Case 4 at a data center, vacuum breakers applied at 26.4 kV were used to switch six dry type transformers with 150 kV BIL primary windings under light load. Two transformers failed, one on breaker closing and the other on opening. The failed transformers were connected by 40 feet of cable to the vacuum breaker, while the other transformers had either 80 feet or 100 feet of cable. Arresters were in place at the time of failure, but there were no snubbers.

In Case 5 in an oil field, a dry type transformer for a VSD had multiple windings to achieve a 36-pulse effective “harmonic free” VSD. A vacuum breaker at 33 kV was separated from the transformer by only 7 feet of cable. Arresters were applied on the primary winding. However, upon closing the breaker, the transformer failed.

Finally, in Case 6 on an oil drilling ship, vacuum breakers designed to IEC standards were applied at 11 kV and connected by 30 feet of cable to a dry type cast-coil propulsion transformer rated 7500 KVA. The transformer was also designed to IEC standards and the primary winding had a BIL of 75 kV. The IEC transformer BIL is much lower than the ANSI BIL for the same voltage class winding. The transformer failed on opening the breaker.

1.3 COMMON PARAMETERS

The severity of the voltage surge; i.e. high magnitude and high frequency, and the damage caused by the voltage surge are determined by the circuit characteristics. Below are some “rules-of-thumb” to screen applications for potentially damaging switching transient voltages:

- Generally, short distance between circuit breaker and transformer (about 200 feet or less)
- Dry-type transformer (oil filled and cast coil not immune) and low BIL
- Inductive load being switched (transformer, motor, etc.)
- Circuit breaker switching characteristics: chop (vacuum or SF6) or restrike (vacuum)

1.4 UNDERLYING CONCEPTS

The operation of a vacuum breaker involves several underlying concepts explained below:

1) Current Chop: When a vacuum breaker opens, an arc burns in the metal vapor from the contacts which requires a high temperature at the arc roots [2]. Heat is supplied by the current flow and as the current approaches zero, the metal vapor production decreases. When the metal vapor can no longer support the arc, the arc suddenly ceases or “chops” out”. This “chop out” of the arc called “current chop” stores energy in the system. If the breaker opens at a normal current zero at 180 degrees, then there is no stored energy in the system. If the breaker opens chopping current at 170 degrees, then energy is stored in the system.

2) Current chop in vacuum circuit breakers is a material problem. Older vacuum interrupters used Copper-Bismuth. Modern vacuum interrupters (VIs) use Copper-Chromium. Most Copper-Chromium VIs have a low current chop of 3-5A, offering excellent interruption performance and a moderate weld

TABLE 2 CURRENT CHOP VS. CONTACT MATERIAL

Contact Material	Average (A)	Maximum (A)
CU	15	21
Ag	4	7
Cr	7	16
W	14	50
Cr-Cu (75 wt %)	3	5
Cr-Cu-Bi (5 wt %)	1	3
Cr-Cu-Sb (9 wt %)	4	11
Cu-Bi (0.15 wt %)	6	21
WC-Ag (50 wt %)	1.5	2.5
W-Cu (30 wt %)	5	10
Co-AG-SE	0.4	0.8
Cu-Bi-Pb	1	9

strength. Table 2 shows the average and maximum levels of current chop for Copper-Chromium, Copper-Bismuth and other contact materials. It should be noted that both vacuum and SF6 interrupters current chop. Current chop is not unique to vacuum breakers.

3) Re-ignition: Current chop, even though very small, coupled with the system capacitance and transformer inductance can impose a high frequency transient recovery voltage (TRV) on the contacts. If this high frequency TRV exceeds the rated TRV of the breaker, re-ignition occurs. Repetitive re-ignitions can occur when the contacts part just before a current zero and the breaker interrupts at high frequency zeros as shown in Figure 4. On each successive re-ignition, the voltage escalates. The voltage may build up and break down several times before interrupting. Although current chop escalation with modern VIs is rare, a variation of this concept applies on closing called pre-strike.

4) Switching Inductive Circuits: The transformer is a highly inductive load with an iron core. The effect of switching this inductive load and core must be considered. The current cannot change instantaneously in an inductor. Energy cannot be created or destroyed; only the form of energy is changed. The energy in the inductor is described by the equation below:

$$\tfrac{1}{2} LI^2 = \tfrac{1}{2} CV^2 \text{ or } V = I\sqrt{L/C} \qquad (1)$$

From the energy equation, it can be seen that for short cables, C is very small which results in a very high surge impedance $\sqrt{L/C}$. Energizing a cable produces a travelling wave which reflects when it meets the discontinuity in surge impedance between the cable and the transformer. The surge impedance of a cable may be under 50 ohms while the surge impedance of the transformer is 300 – 3000 ohms. In theory, the reflection can be as high as 2 per unit.

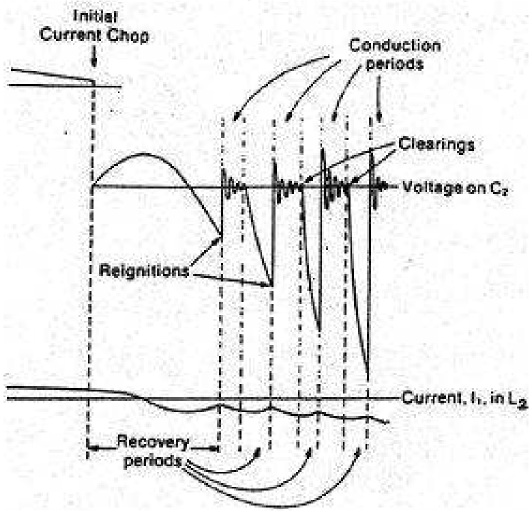

Figure 4. Voltage Escalation Due to Sucessive Reignitions

Vacuum circuit breakers are prone to current chopping and voltage re-ignition while SF6 circuit breakers are more prone to just current chopping. Air circuit breakers are not prone to either of any significant magnitude. Manufacturers design vacuum circuit breaker contacts to minimize the severity and occurrence of abnormal switching leading to severe voltage surges (The lowest current chop characteristics are 3 – 5 A). Regardless of the circuit breaker manufacturer, voltage surges do occur.

1.5 CHARACTERISTICS OF THE VOLTAGE TRANSIENT AND TRANSFORMER LIMITS

The voltage transient that develops following the vacuum circuit breaker switching is influenced by three factors: stored energy, DC offset and the oscillatory ring wave. The voltage component is due to the stored energy. The DC offset is determined by the X/R ratio of the cable and transformer. The oscillatory ring wave is a result of the capacitance and inductance of the cable and transformer. The magnitude of the voltage transient is compared to the transformer BIL. If the magnitude is excessive, then the transformer winding will likely fail line-to-ground. If the voltage transient has excessive rate-of-rise (dv/dt), then the transformer winding will likely fail turn-to-turn (natural frequency of ring wave). For the transformer to survive the transient, the insulation must be able to withstand both the magnitude and dv/dt. Dry type transformers are particularly susceptible to vacuum or SF6 breaker switching transients. However, oil filled or liquid filled transformers are not immune. The oil has capacitance and acts like a surge capacitor to slow the rate-of-rise of the voltage transient. The trend in modern day power systems is to install transformers with the high efficiency design. As a result, these high efficiency transformers have a very small resistance which offers little or no damping to the voltage transient. Also, the repetitive effect, i.e. small indentations in the insulation can occur with each successive peak of the voltage transient.

2.0 PREDICTING PERFORMANCE WITH SIMULATIONS

2.1 MODELING THE CIRCUIT

When a statistical approach is taken for switching transients, complex modeling requires a frequency dependent transformer model and an arc model of the circuit breaker. For purposes of screening applications for potentially damaging switching transients, a simpler approach is suggested with the important circuit elements modeled in EMTP consisting of the source, breaker, cable and transformer as shown in Figure 5. The cable is represented by a Pi model consisting of the series impedance and half of the cable charging at each end. In some cases, multiple Pi models are used to represent the cable. The vacuum or SF6 breaker is represented by a switch with different models for opening (current chop), re-strike (excessive magnitude of TRV), re-ignition (excessive frequency of TRV) and closing (pre-strike). The three phase transformer model consists of the leakage impedance, magnetizing branch, winding capacitances from high-to-ground and low-to-ground. For oil filled transformers, the oil acts like a dielectric so the high-to-low capacitance is modeled. In cases requiring more detail, the transformer saturation and hysteresis effects are modeled.

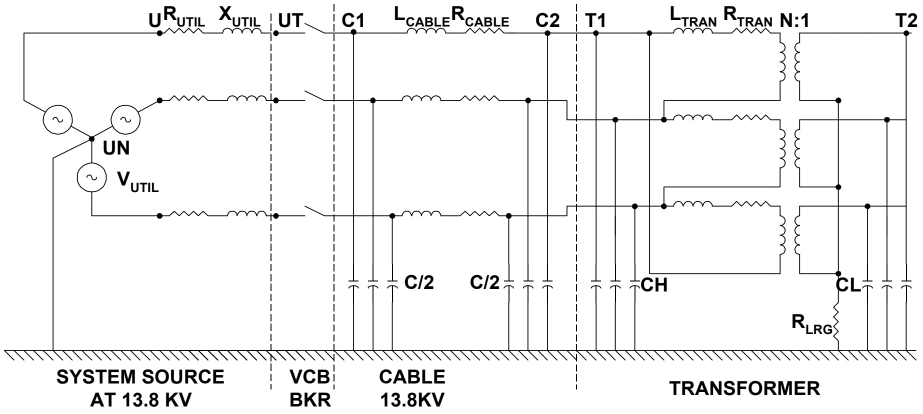

Figure 5. Important Ciruit Elements for EMTP Modelling

The choice of the integration time-step will depend upon the anticipated frequency of the voltage transient. If too large, the time steps will "miss" the frequency effects. If too small, then this will lead to excessive simulation times. The Nyquist criteria calls for a minimum sample rate of twice the anticipated frequency. In switching transients, the anticipated frequency is 3 – 25 kHz. When the circuit breaker opens, the transformer primary winding is ungrounded. Also, the ring wave is a function of the natural frequency of the circuit:

$$f_{natural} = 1 / (2\pi\sqrt{LC}) \quad (2)$$

The iron core of the transformer dominates the inductance of the circuit. The capacitance is very small for the dry type transformer and short cable. Consequently, the circuit's natural frequency is 3 – 25 kHz with relatively short cables.

2.2 MITIGATING THE SWITCHING TRANSIENT

Various surge protection schemes exist to protect the transformer primary winding from vacuum breaker switching induced transients. A surge arrester provides basic overvoltage protection (magnitude only). The arrester limits the peak voltage of the transient voltage waveform. The surge arrester does not limit the rate-of-rise of the transient overvoltage. A surge capacitor in combination with the surge arrester slows down the rate-of-rise of the transient overvoltage in addition to limiting the peak voltage but does nothing for the reflection or DC offset. The number of arrester operations is greatly reduced because of the slower rate-of-rise. There is a possibility of virtual current chopping. Finally, adding a resistor to the surge capacitor and surge arrester provides damping, reduces the DC offset of the transient overvoltage waveform and minimizes the potential for virtual current chopping. The resistor and surge capacitor are considered an RC snubber. Selecting the values of resistance and capacitance are best determined by a switching transient analysis study, simulating the circuit effects with and without the snubber.

2.3 MATCHING THE MODEL TO MEASUREMENTS

The results obtained from simulation of switching transients in EMTP are only as good as the choice of model and data used. When available, field measurements taken during the switching transients enable verification of the EMTP model. The EMTP model can be adjusted as need to match the actual field measured conditions. To illustrate this approach, consider the ship propulsion electrical system of Figure 6. The system consists of 3 x 2865 kW generators, a 4160 V 3-phase bus, two 1865 kW drives/motors for forward propulsion and identical drives for reverse propulsion, eight 1185 kVA dry type transformers and

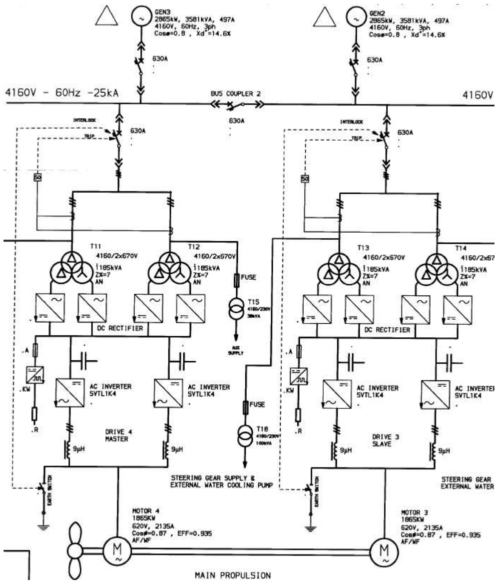

Figure 6. Simplified Electrical System for Ship Propulson Drive

eight 630 A vacuum circuit breakers. The critical parameters are the vacuum circuit breaker, 50 feet of cable and dry type transformer of 30 kV BIL. Figure 7 shows the EMTP simulation results match the transients captured in the field with a high speed power quality meter (closing). The simulation shows 4.96 kVpeak which is less than 30 kV BIL, however the oscillation frequency of 20.2 kHz exceeds an acceptable limit of dv/dt. Having verified the model, a series of current chop cases and re-ignition cases were run. Figure 8 shows the transient recovery voltage (TRV) leading to re-ignition and the TRV with a

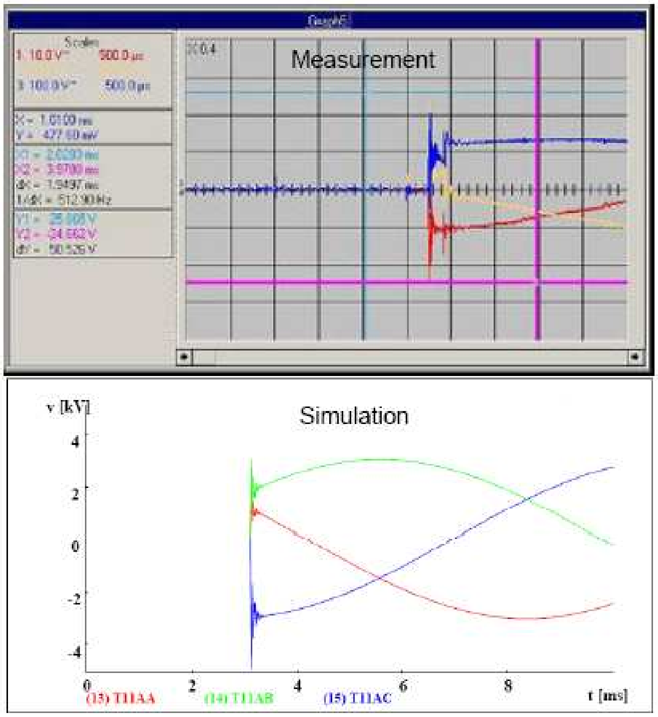

Figure 7. Matching the Simulation to Field Measurements

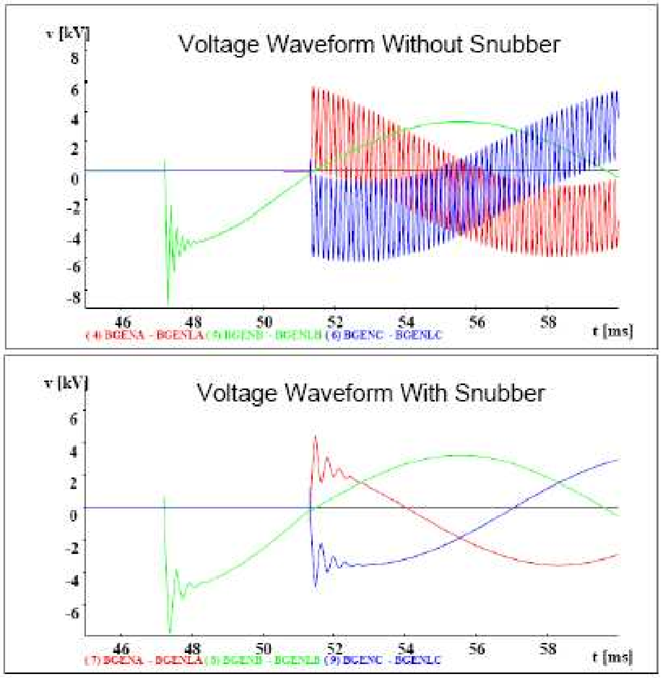

Figure 8. TRV Leading to Reignition During Energization of Drive Transformer With and Without Snubber

TABLE 3 CURRENT CHOP AND REIGNITION CASES FOR DRIVE PROPULSION TRANSFORMER SWITCHING

Case	Vacuum Breaker	Current Chop (A)	RC	TOV (kV)	Freq (Hz)	Transf BIL	Note
1	Close	N/A	N	4.965	20,203	30	U
2	Close	N/A	Y	3.982	<1000	30	A
5	Open	6	N	31.895	958	30	U
6	Open	6	Y	8.953	299	30	A
Case	**Vacuum Breaker**	**Current Chop Note1 (A)**	**RC**	**Transient Recovery Voltage**		**IEEE ANSI C37.06 Limit**	**Note**
				E2 (kV)	9.044	8.9	
				T2 (µsec)	79	50	
3	Reignition	6	N	RRRV (kV/µsec)	0.1145	0.178	U
				E2	7.702	8.9	
				T2	149	50	
4	Reignition	6	Y	RRRV	0.0517	0.178	A

Notes: U = unnacceptable. A = acceptable. 1 = current chop on breaker opening followed by reignition.

snubber installed. Re-ignition occurs because the TRV peak, time to crest and rate-of-rise of recovery voltage exceed IEEE ANSI C37.06 limits. The snubber reduces the TRV below the IEEE/ANSI limits for general purpose vacuum breakers [3] and for generator breakers [4]. Table 3 summarizes the re-ignition cases and the current chop cases. In all cases, the snubber is effective in reducing the transient voltage.

2.4 A BORDERLINE CASE

It is important to note that not all applications involving primary switching of transformers using vacuum breakers require snubbers. The large majority of applications do not require snubbers. Switching transient studies are conducted to determine when snubbers are needed. In this paper, the cases were selected to show different situations requiring snubbers. For the system shown in Figure 9, the results were borderline, so a snubber was still applied for reliability purposes. The Figure 9 system is a Tier III Data Center with two 24.9 kV incoming lines, two 12.5 MVA 25/13.2 kV transformers, 13.2 kV ring-bus, two 2250 KW generators, six 3750 kV cast coil transformers.

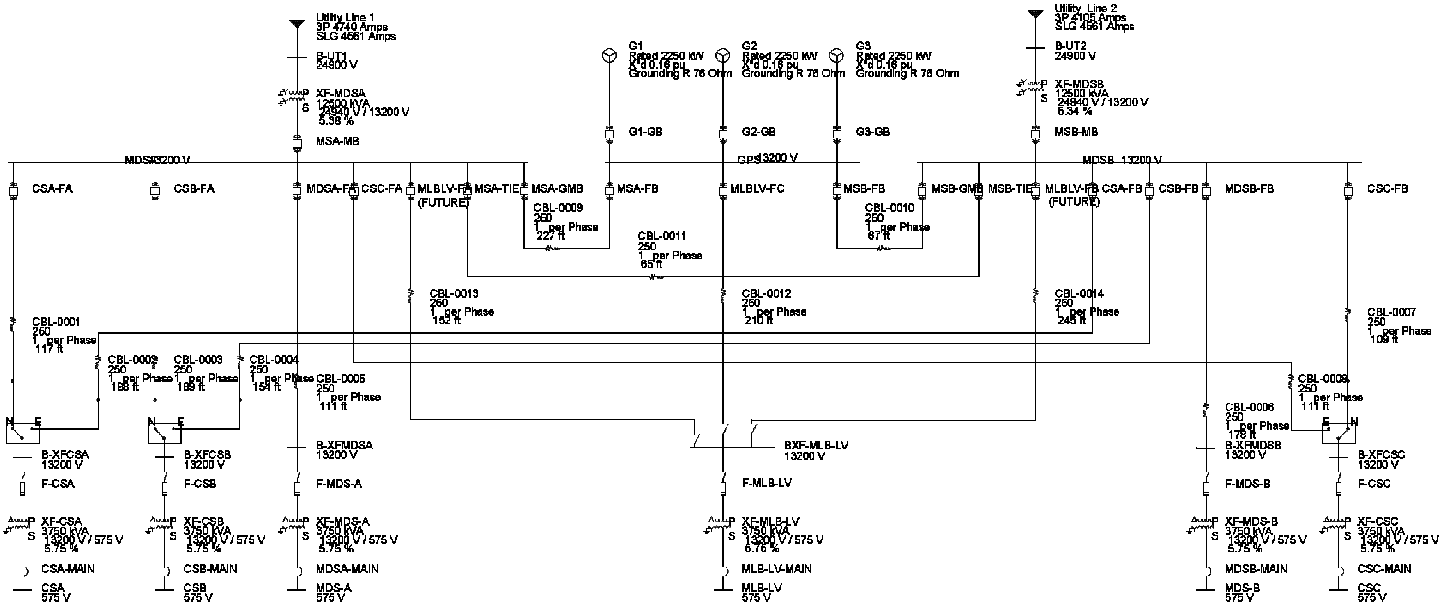

Figure 9. Simplified Electrical Distribution System for Tier III Data Center

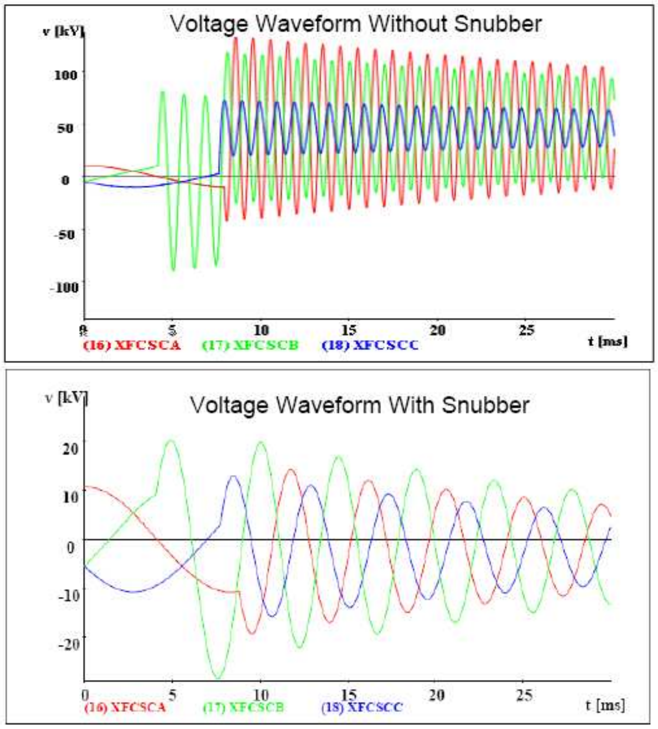

Figure 10. TOV initiated by Current Chop During De-Energization of Cast Coil Transformer With and Without Snubber

Data centers fall into the highest risk categories because of their high load density, close proximities of circuit components, highly inductive transformers (high efficiency designs) and frequent switching. The critical parameters for the Figure 9 system are vacuum circuit breakers, 90 kV BIL transformers and cable lengths ranging from 109 to 249 feet. For the cable of 109 feet, the results of opening the vacuum breaker with current chopping of 8 A is shown in Figure 10. The transient overvoltage (TOV) is as high as 123 kVpeak on phase-A which exceeds the transformer BIL of 95 kV. The TOV exhibits a significant DC offset because there is very little resistance in the highly inductive circuit. The oscillation frequency of 969 Hz is slightly less than the acceptable limit.

A snubber is required to reduce the peak below 95 kV BIL. The results of adding a snubber are shown in Figure 10. Note the significant reduction in the DC offset. The resistor in the snubber provides the reduction in DC offset as well as damping. The peak is reduced to 28.6 kV and oscillation of 215 Hz, both within acceptable limits. Finally, field measurements were taken after snubber installatipn to ensure they performed as designed. The field test setup for the snubber performance measurements is discussed in Section IV. The field measurements showed the snubber limited the TOV within acceptable limits.

2.5 CASE OF REDUCED VOLTAGE AUTO TRANSFORMER STARTER

Normally we do not think of vacuum contactors (vs. breakers) as being a device that is subject to switching transient issues. However, in a few cases, they can be. The majority of the previous failures described in this paper had to do with magnitude or dv/dt. With cast coil or layer wound transformers, it is possible to excite an internal voltage resonance internal to the winding – typically between 3 kHz and 12 kHz. Such was the case for the following example involving vacuum contactor switching of a 4160V reduced voltage auto transformer (RVAT). This 4160V/5000HP motor was equipped with surge capacitors on the motor terminals and the RVAT failed layer-to-layer during a starting sequence in the middle of the winding (highest internal resonant voltage point) as shown in Figure 11. Since it is extremely difficult to model all the internal inductance and capacitances of these transformers, a sweep frequency resonance analysis (SFRA) measurement approach is a good alternative.

Figure 11. 4.16 kV Reduced Voltage Auto Transformer Starter Failure Due to Breaker Switching Transients

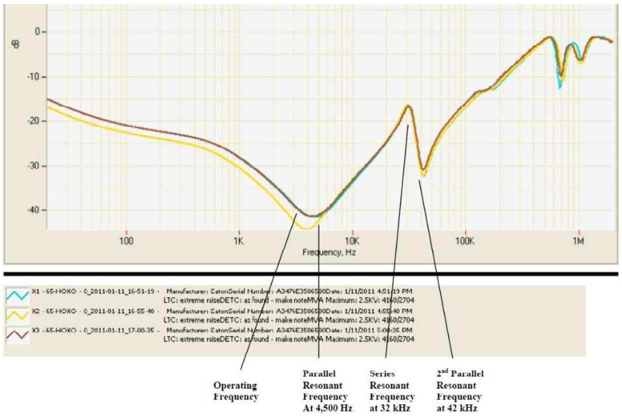

Figure 12. Sweep Frequency Test of 4.16 kV Reduced Voltage Auto Transfomer

The SFRA plots the impedance (admittance shown) of the transformer as a function of frequency as shown in Figure 12. The parallel resonant frequency of the transformer is indicated to be 4500Hz, but with a relatively flat bandwidth in the resonant frequency range as shown in Figure 12. In Figure 13 (top), the computer simulation determined the system resonant frequency was in the 3500 to 3800 Hz range. This is close enough to the transformer resonant frequency to invite internal resonance. The addition of snubbers dropped the resonant frequency to a few hundred Hertz, not anywhere close to the resonant frequency as shown in Figure 13 (bottom). No additional failures have occurred since mitigation. See Figure 14 for a picture of the snubber installation.

2. 6 CONCERNS FOR THE CEMENT INDUSTRY

The previous examples illustrate that circuit breaker induced switching transients can fail transformers for specific combinations of circuit parameters and breaker characteristics. The examples show the problem is not unique to one industry, application, vendor's breaker or transformer design. For the cement industry, there are many situations where circuit breaker induced switching transients are likely to damage transformers. The following examples are some of the more common scenarios likely to be encountered in the cement industry:

1) *Vacuum breaker retrofit for primary load break switch in a unit substation.* In the cement industry, there are unit substation installations with primary load break fused switch and no secondary main breaker or situations with high arc flash incident energy on the secondary side. These arrangement results in arc flash issues on the low voltage secondary. Limited space on the low voltage side prevents installation of a secondary main breaker to mitigate the arc flash issues, or exposure between the transformer secondary and the main breaker is unacceptable. Retrofitting a vacuum

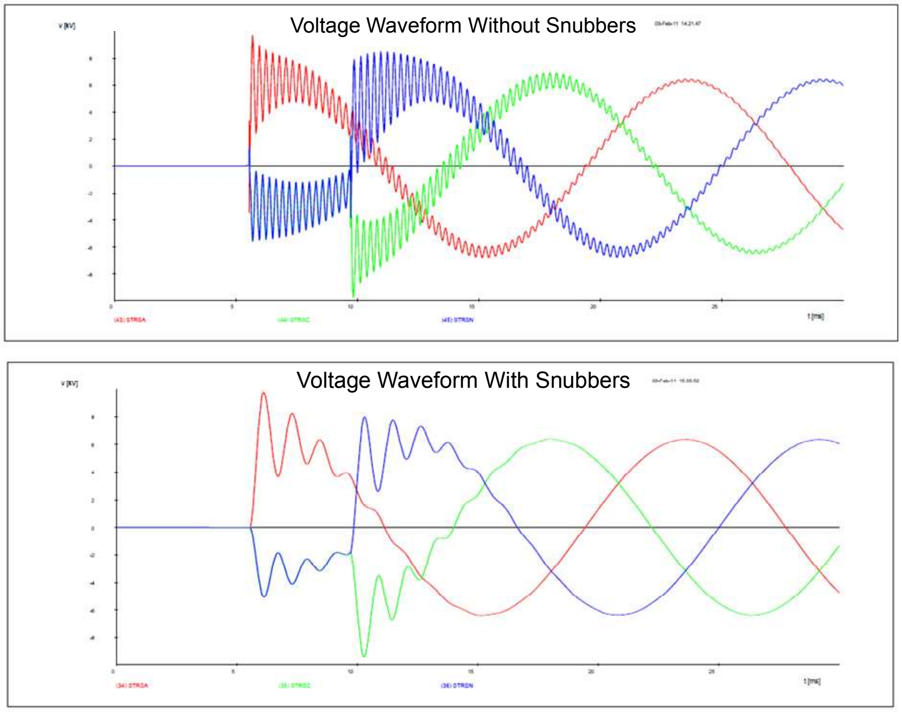

Figure 13. TOV for Reduced Voltage Auto Transformer Starter With and Without Snubber Protection

Figure 14. Reduced Voltage Auto Transformer Starter With Snubber Protection Installation

circuit breaker in the primary of the unit substation, in place of the primary load break switch, and sensing on the secondary, is a solution that provides both primary and secondary fault protection [5]. Unit substations may have oil filled or dry type transformers. The secondaries may be solidly grounded or resistance grounded. With the vacuum breaker closely coupled to the transformer, surge arresters and snubbers are most likely needed.

2) *Vacuum breaker and large VSD transformer installation*. VSD transformers are installed to serve drives such as those needed for rod or ball mills or kilns. Phase shifting transformers (or isolation transformers) are installed to serve a large VSD. Primary voltages may be 13.8 kV or 4.16 kV. In

both situations, vacuum breakers are installed in the primary and closely coupled to the transformer through a short run of bus or cable. Often these transformers are inside and dry type design.

3) *The approach to new equipment design often incorporates a unit substation with primary vacuum breaker to accommodate a small footprint in the cement plant.* Such a new design might include metal enclosed vacuum switchgear and a new transformer with primary voltages of 13.8 kV or 4.16 kV. The vacuum breaker will be connected to the transformer through a short run of bus on the order of 5 feet. While doing Coordination and Arc Flash studies of the design, the switching transient issue should be identified and addressed. With this approach, the snubbers may be designed and installed in the factory, and shipped to the site for startup and commissioning with the switchgear.
4) *An interest in the use of cast-coil transformers by electrical system designers raises new concerns*. Breaker pre-strike can excite the internal resonance point of the cast-coil transformer, even with very long cables. The internal resonance depends upon the transformer design as well as the selected breaker's characteristics and, as a result, is vendor specific. Breaker pre-strike exciting internal resonance of the cast-coil transformer is a different problem and less frequently encountered.

The screening criteria previously mentioned identifies the above examples for potential damaging switching transient voltages due to vacuum breaker switching. The vacuum breaker or SF6 breaker, short distance to transformer and dry type transformer (or aged oil filled transformer) are key variables to consider. With such short distance between breaker and transformer, most of these installations will require snubbers. One might conclude standard snubbers could be applied. However, a switching transient study is still recommended to determine the unique characteristics of the circuit and custom design the snubber for the application. Given the limited space in each of these examples, it is unlikely off-the-shelf standard snubbers would fit. A substantial part of the design effort includes determining how best to fit the snubbers into the new or existing unit substation or transformer enclosure.

3.0 DESIGNING THE SNUBBER

The preceding analysis has shown that in some cases switching transients can produce overvoltages that can result in equipment insulation failure. If the results of the switching transient study indicate a risk of over voltage greater than the BIL of the equipment and/or dv/dt limits are exceeded, a surge arrester and snubber should be applied. The switching transient study may also indicate that multiple locations require surge arresters and snubbers to protect the generator, transformer, or large motor. Additionally, the study specifies the necessary protective components and determines how close the protection must be placed to provide effective protection.

3.1 DESIGN REQUIREMENTS

At this point, custom engineering design determines how best to provide the protection needed for the equipment. The following questions must be answered to ensure the snubber design meets all criteria and specifications.

- Is the switching transient protection cost effective?
- What is the value of the equipment being protected?
- What is the cost of lost production if the equipment fails from switching transients?
- Can the protection be installed within existing equipment enclosures?
- Will equipment modification void equipment warranties?
- Are there standard equipment packages that can accomplish the switching transient protection?
- Is the application an indoor or outdoor application?
- Is there available space to mount the protective equipment in an external enclosure?
- How can it be verified, if the switching transient protection components are working effectively?
- What alarms are necessary if the protective equipment components fail?

3.2 CUSTOM ENGINEERING DESIGN

Figure 15 shows the typical snubber arrangement for transformer protection. A non-inductive ceramic resistor and a surge capacitor are the basic components of a snubber design. Resistance values range from 25 ohms to 50 ohms typically. Standard capacitor ratings range from 0.15 μF to 0.35 μF are the basis of the design. Figure 16 Shows a standard 15 kV surge protection package. The arresters are mounted on the top of the enclosure. A three phase surge capacitor is mounted on the bottom. Insulators and bus are located in the center. The cables can enter from top or bottom. A ground bus is located on the center right. If space heaters are required for outdoor locations, they are located on the lower left.

Figure 17, shows one phase of a custom snubber circuit. The custom design was required because there was not enough room in the transformer for the snubber components. The enclosure had to be mounted above the transformer. The cable connections from the transformer were field installed and land on the copper bus. 15 kV non-shielded jumper cable was used to make the connection. Each phase passed through an insulation bushing to the transformer below. Bus work was required to provide a solid support for the fragile resistors. Normally only one resistor would be provided, but for this application, to achieve the delivery schedule, parallel resistors were designed to obtain the correct ohmic value (the correct single resistor value had long delivery).

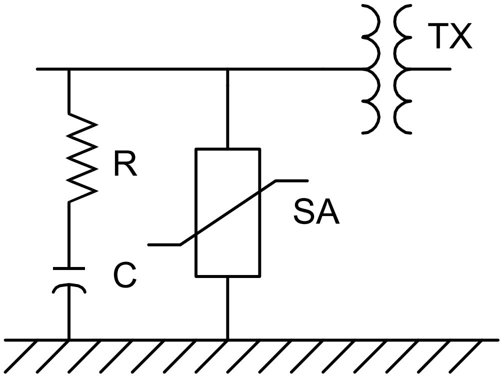

Figure 15. Typical Snubber and Arrester Arrangement for Transformer Protection

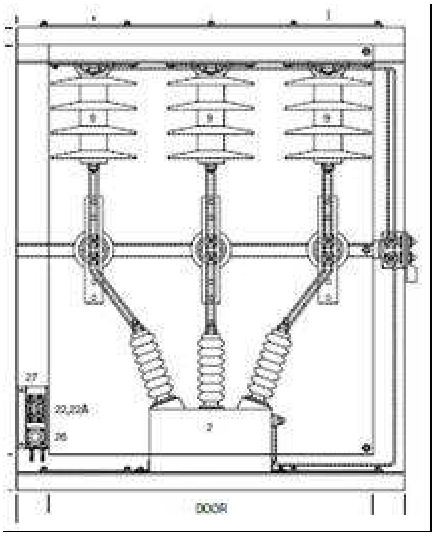

Figure 16. Example of Standard Snubber Package for Transformer

978-1-4673-5553-7/12/$31.00 © 2013 IEEE

Figure 18a and 18b show a snubber assembly mounted in medium voltage switchgear. The photo on the left shows the single phase surge capacitors mounted vertically. The black cylinders are ceramic resistors. A variety of options are available to detect if the snubbers are functional. They range from nothing (oversized but treated like a lightning arrester) to very sophisticated loss of circuit detection. Glow tube indicators are shown in Figure 18a and a close-up in Figure 19a. These glow tubes are visible through a window in the switchgear door and provide a visual indication of snubber continuity. The purpose of the blue current sensors at in Figure 18a is to monitor the continuity of the resistor and fuse (optional) and alarm on loss of continuity.

A close-up of the current sensor is shown in Figure 19b. Some industries mandate fused protection. If there should be a broken resistor or a blown fuse, an alarm signal can be sent to the plant DCS or SCADA system to alert the operating personnel that these snubber components have failed. Figure 18b is a continuation of the same snubber assembly. Three fuses are attached to the tops of the resistor. The fuses will isolate any fault that may occur in the snubber assembly and prevent loss of the breaker circuit.

3.3 SPECIAL DESIGN CONSIDERATIONS

The nature of high frequency switching transients require special design considerations. The snubber designer should consider the location of the switching transient source when developing the custom design layout of the protective equipment. Abrupt changes in the electrical path should be avoided. A low inductive reactance ground path should be designed, using non-inductive ceramic resistors and flat tin braided copper ground conductors. The minimum clearances of live parts must meet or exceed the

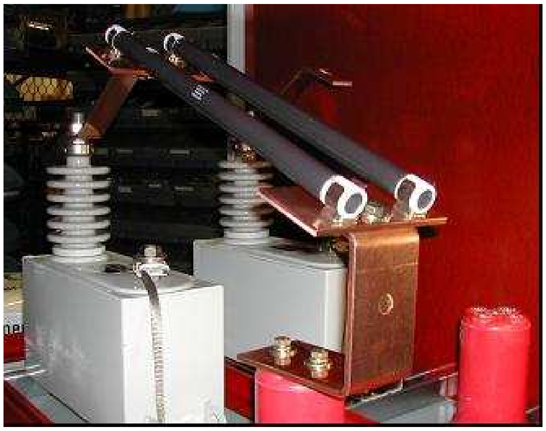

Figure 17. 15 kV Snubber Mounted Above the Transformer

(a) (b)

Figure 18. 15 kv Snubber Mounted in Switchgear with Glow Tubes and Current Sensors

978-1-4673-5553-7/12/$31.00

(a) (b)

Figure 19. 15 kv Snubber Visual Indication (Glow Tubes) and Contintuity Verification (Current Sensors)

(a) (b)

Figure 20. Snubber with Surge Capacitor Three-Phase (left) and Singel-Phase (right) for a 13.8 kV Industrial Facility

phase to phase and phase to ground clearances of NEC Table 490.24. The enclosure should be designed to meet the requirements of IEEE Standard C37.20.2 1999. When the enclosure is mounted greater than ten feet from the equipment to be protected, NEC tap rules may apply to cable size required and additional circuit protective devices may be required.

3.4 CUSTOM DESIGNS FOR THE CEMENT INDUSTRY

As mentioned previously, given the limited space in each of the examples related to the cement industry, it is unlikely off-the-shelf standard snubbers would fit. Instead, a substantial part of the design effort includes determining how best to fit the snubbers into the new or existing unit substation or transformer enclosure. Below are three examples of the custom design effort needed for snubber installations in industrial facilities which would be quite common in a cement facility:

1) 13.8 kV Solidly Grounded System. A vacuum breaker was retrofitted into the enclosure for the primary load break switch of the unit substation with a dry type transformer. The space for the snubber was extremely limited as shown in Figure 20a. Because the system was solidly grounded, the voltage on the surge capacitor was limited to 8 kV line-to-ground, so it was possible to use a 3-phase surge capacitor. The tight clearance required the use of glastic to insulate the components at line potential from ground.

2) 13.8 kV Low Resistance Grounded System. Another example of retrofitting a vacuum breaker for a primary load break switch with a 30 year old oil filled transformer. Because this snubber was needed immediately, the only available resistors had to be paralleled to obtain the desired resistance as shown in Figure 20b. Again, glastic was used for insulation and to support the resistors.

3) 13.8 kV Low Resistance Grounded System. Snubbers were provided for new metal enclosed vacuum switchgear and a new transformer rated 7500 KVA with primary voltage of 13.8 kV as shown in Figure 21. Single-phase surge capacitors rated 13.8 kV were used because it is not possible to buy three-phase surge capacitors rated for 13.8kV line-to-ground. Single resistors of the right ohmic value were available. Adequate clearance did not require the use of glastic.

4.0 MEASUREMENTS TO VERIFY SNUBBER PERFORMANCE

Following installation of the snubbers, power quality measurements may be taken to ensure the proper operation of the snubbers. A high speed scope or power quality disturbance analyzer should be used to measure the transient overvoltage waveforms at the transformer primary produced during switching of the primary vacuum circuit breaker. The measurements are used to verify the waveforms do not exhibit excessive high frequency transients (magnitude, rate-of-rise and frequency).

The test measurement setup generally consists of voltage dividers and a transient recording device. The voltage dividers should be made of capacitive and resistive components with a bandwidth of 10 MHz. The scope or power quality meter should be capable of transient voltage waveshape sampling, 8000 Vpeak full scale, 200 nsec sample resolution (5 MHz sampling).

An outage and lockout/tagout are needed to install the voltage dividers, make connections to each of the three phases at transformer primary bushing and make secondary connections to the transient recorder. Figure 22 shows the test measurement setup for a typical cast-coil transformer. Voltage divider connections to the transformer primary were made as shown in Figure 23. Additionally, for tests requiring load at a transformer, a portable load bank may be connected to the transformer secondary. A resistive load bank configurable to different load levels (300 kW or 100 kW) prevents destructive testing.

Figure 21. Snubber for Metal Enclosed 13.8 kV Vacuum Breaker

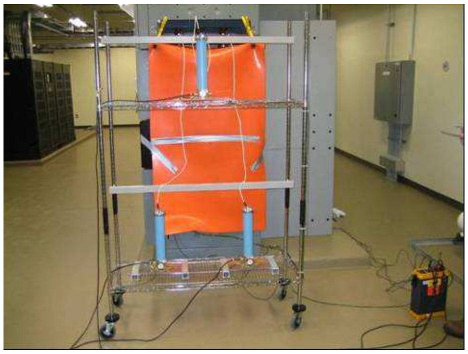

Figure 22. Subber Performance Measurement Setup for 15 kV Transformer Using High Bandwidth Voltage Dividers

Figure 23. Voltage Divider Connections at 18 kV Surge Arrester on Transformer Primary Bushing

5.0 CONCLUSIONS

This paper reviewed recent transformer failures due to primary circuit breaker switching transients to show the severity of damage caused by the voltage surge and discuss common contributing factors. Next, switching transient simulations in EMTP were presented to illustrate how breaker characteristics of current chopping and re-strike combine with critical circuit characteristics to cause transformer failure in unique situations. In these limited instances, mitigation of the transients is accomplished with snubbers custom designed to match the specific circuit characteristics. Design and installation considerations were addressed, especially the challenges of retrofitting a snubber to an existing facility with limited space. Finally, the performance of the snubbers is verified with field measurements at the medium voltage primary winding of the transformer.

6.0 REFERENCES

[1] ANSI/IEEE, IEEE Guide to Describe the Occurrence and Mitigation of Switching Transients Induced By Transformers, Switching Device, and System Interaction, C57.142-2010.

[2] D. Shipp, R. Hoerauf, "Characteristics and Applications of Various Arc Interrupting Methods," *IEEE Transactions Industry Applications*, vol 27, pp 849-861, Sep/Oct 1991.

[3] ANSI/IEEE, Standard for AC High-Voltage Generator Circuit Breakers on a Symmetrical Current Basis, C37.013-1997.

[4] ANSI/IEEE, Application Guide for Transient Recovery Voltage for AC High-Voltage Circuit Breakers, C37.011-2005.

[5] D. Durocher, “Considerations in Unit Substation Design to Optimize Reliability and Electrical Workplace Safety”, ESW2010-3, 2010 IEEE IAS Electrical Safety Workshop, Memphis.