Are snubbers required with Eaton's Cooper Power series liquid-filled hardened transformers?

David D. Shipp P. E.
CEO & Principal Consultant
Capstone Power Systems Engineering

Steven H. Buehler P. E.
Principal Engineer
Three-phase Transformers, Eaton

F. Albert Penner P. E.
Specialist Engineer
Three-phase Transformers, Eaton

Jeffrey A. Schneider
Engineering Manager
Three-phase Transformers, Eaton

Thomas J. Dionise P. E.
Advisory Engineer
Power Systems Engineering, Eaton

Thomas J. Natali P. E.
Technology Specialist
Power Systems Engineering, Eaton

Tamer Mellik PhD P. Eng.
Sr. Power Systems Engineer
Power Systems Engineering, Eaton

J. Antonio Trujillo M. Eng.
Engineering Director
Transformer Products, Eaton

Abstract

Many modern electrical distribution systems, such as those used in data centers, demand high power densities, small electrical footprints, high efficiency transformers, redundant systems and frequent testing requiring switching at primary voltages. These various parameters that ensure the highest reliability and availability to mission-critical loads also place the facility in the highest risk category for distribution transformer failures due to primary switching transients. Over the last decade, this phenomenon has been attributed to a significant number of failures of certain types of transformers involving primary circuit breaker switching in data centers and other facilities exhibiting similar characteristics. This white paper focuses specifically on data center transformers, however, the lessons learned here may apply to numerous applications.

E·T·N

Powering Business Worldwide

White Paper WP202001EN

Effective August 2016

Are snubbers required with Eaton's Cooper Power series liquid-filled hardened transformers?

Background

Eaton's investigation of these failures has determined the severity of the switching transient voltage. For example, high magnitude, high frequency, internal resonance and the damage caused by the transient voltage are determined by the following circuit characteristics:

- Short bus or cable distance between circuit breaker and transformer
- BIL rating of the transformer
- Inductive load being switched (lightly loaded transformer)
- Circuit breaker switching characteristics: chop current (vacuum or SF_6) or restrike/reignition (vacuum)
- Winding configuration

The circuit breaker-induced switching transients may be amplified by the short bus or cable length between the breaker and transformer as shown in Fig. 1. This amplification is due to the vacuum breaker chop current and the system stray capacitance, especially that of the short bus or cable, interacting with the nonlinear inductance of the transformer. The severity of the voltage transient at the transformer is influenced by the circuit breaker chop current; the higher the chop current is, the more severe the voltage transient. In similar systems of Fig. 1, the transformers with short cables failed, but the transformers with longer cables did not.
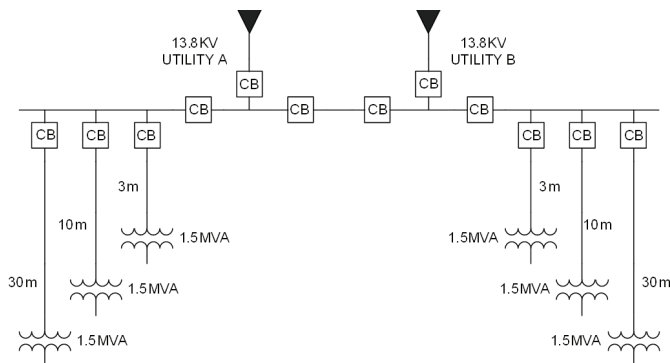

Figure 1. Typical breakers close-coupled to transformers in a data center

As a result of these failure investigations, Eaton has successfully designed and installed Resistor-Capacitor (RC) Snubber circuits in parallel with surge arresters to safely mitigate such transients. In all cases where the transformers failed, there were no subsequent failures after snubbers were installed. Proactively designing snubbers through transient simulations and installing snubbers prior to startup and commissioning has also resulted in no transformer failures.

An alternative solution: Hardened Data Center (HDC) transformer

Although the RC snubber has been proven to safely mitigate the transient overvoltage imposed on the primary winding of the transformer, Eaton has continued to look for other solutions to the primary switching transients problem. While a very good solution, snubbers do represent added equipment that must be maintained over the life of the facility and another failure point affecting data center reliability assessments. The majority of the data center transformer failures investigated by Eaton have been Vacuum Pressure Impregnated (VPI) dry-type or cast-coil (95 percent of the failures), with very few liquid-filled failures. In contrast, Eaton's Cooper Power series liquid-filled distribution transformers have experienced no voltage transient failures in data center applications with well over 2,500 MW of installed capacity. This proven track record supported the introduction of Eaton's Cooper Power series liquid-filled distribution transformer, called the Hardened Data

Center (HDC) transformer, as a solution for the primary switching transient problem occurring in data centers. (See Fig. 2.) The HDC transformer is a more robust distribution transformer design that includes specially insulated coils and leads and is based on years of experience with applications that require high reliability.

Figure 2. Eaton's Cooper Power series HDC transformer

To thoroughly vet this solution, Eaton's Cooper Power series transformer product line collaborated with Eaton's Power Systems Engineering Group to conduct a comprehensive evaluation of the HDC transformer. The objective of this evaluation was to prove analytically, through a combination of simulations and field tests, that the HDC design will withstand switching transients without the need for transient mitigation using RC snubbers, relying only on conventionally applied surge arresters. A HDC transformer test prototype, rated 1500 kVA, 13.8/0.48 kV, 125 kV BIL with integral Vacuum Fault Interrupter (VFI), was filled with Envirotemp™ FR3™ fluid and special high-voltage test points for voltage distribution measurement were included. The prototype included a snubber on the transformer cover and the VFI for testing purposes.

Comprehensive evaluation

The five-part evaluation consisted of 1) switching transient analysis simulations, 2) field tests of the transformer to determine parameters for modeling, 3) development of lumped parameter and distributed parameter models for the HDC transformer, 4) staged transient testing of the transformer at Eaton's Thomas A. Edison Technical Center High Power Lab (HPL), and 5) follow-up refinement of modeling techniques and detailed engineering analysis of the test results.

The evaluation began with switching transient analysis in the Electromagnetic Transient Program (EMTP), a universally recognized simulation tool in the transient community. A detailed circuit model consisting of the supply system, circuit breaker, cable and transformer were modeled. Special emphasis centered on the circuit breaker current chop characteristics, cable capacitance and transformer lumped parameter model. The chop current was varied from 3-5 A on the low end to 19-21 A on the high end. Cable sizes representative of field installations for this size transformer were selected. Cable lengths varied from 3 to 30 m, again representative of those found in modern data centers. The simulations were conducted to predict transient overvoltages imposed on the primary winding, i.e., magnitude and rate of rise and/or ring frequency.

Are snubbers required with Eaton's Cooper Power series liquid-filled hardened transformers?

White Paper WP202001EN
Effective August 2016

Field Tests: SFRA and Insulation Power Factor

A frequency scan of the HDC transformer was conducted using a Doble M5400 Sweep Frequency Response Analyzer (SFRA). The frequency scan, when excited from the medium-voltage side, determined the internal resonant frequencies of the transformer winding impedances. The results of these scans were incorporated into the switching transient analysis and are shown in Fig. 3. The switching transient frequency was compared to the internal resonant frequencies of the transformer to determine if internal resonance may damage the winding. For the same transformer, winding capacitances were measured using a Doble M4000 test set, i.e., high to ground (CH), low to ground (CL) and high to low (CHL). The results of these tests were incorporated into the model of the transformer used in the switching transient analysis.
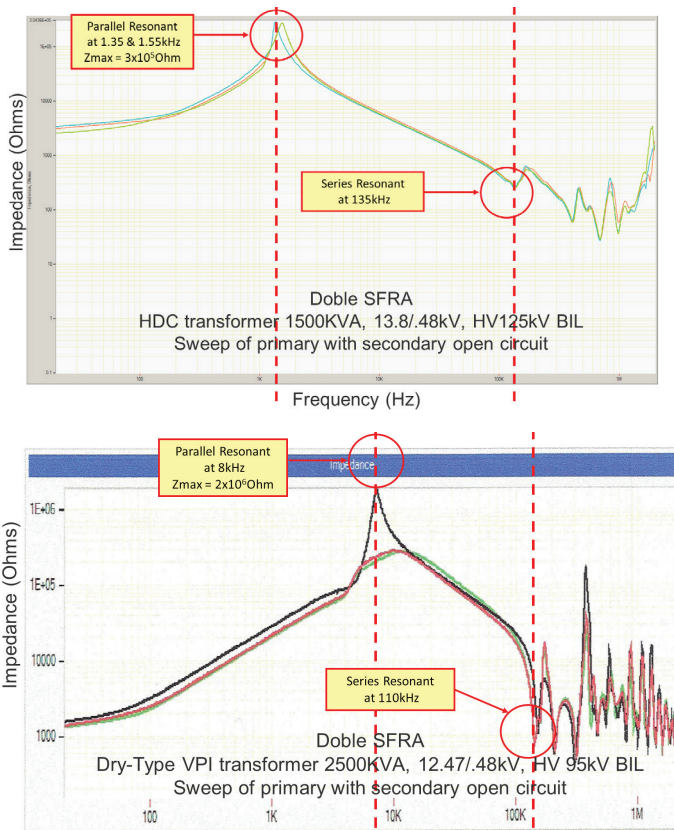

Figure 3. Sweep Frequency Response Analysis SFRA for HDC and dry-type transformers

A close look at these 2 SFRA graphs is revealing. An estimate of the internal transient voltage amplification factor can be approximated by looking at the ratio of –

$$Amp. F = Zmax/Z60$$

Where Zmax is the SFRA impedance at desired frequency (all transformers will have a switching frequency impedance) compared to its 60 Hz impedance (Z60). Assuming a typical switching frequency of 8kHz:

HDC transformer $Amp F = 8 \times 10^3 / 4500 = 1.78$

Dry-type transformer $Amp F = 2 \times 10^6 / 1600 = 1250$

If a transformer is excited at or near its resonant frequency, the internal voltage will be amplified many times, resulting in failure. Of particular observation, is how much lower the amplification factor is for the specially designed HDC transformer compared to dry-type transformers. The transient voltage amplification factor of the HDC

transformer is more than 700 times lower. Also note that the first parallel frequency is much lower than in dry-types. For most power systems, the frequencies that would be prevalent impinging on the transformer, are above the parallel resonant frequency and way below the next higher series resonant frequency.

Distributed Parameter Model for transformer

Next, Eaton incorporated a distributed parameter model for the primary winding developed by the transformer designer during his Ph.D. research, as shown in Fig. 4. This model in MatLab, another recognized tool in the simulation community, represented the model transformer primary winding in detail, accounting for the windings of the transformer that consist of conductors with insulation, multiple turns of insulated conductors and multiple layers with insulation between the layers. The conductors and insulation represent a complex matrix of inductances and capacitances. This model was converted to EMTP to enable simulation of primary switching. An advantage of this distributed parameter model of the winding was the capability to see the voltage distribution in the winding rather than just at the terminals.
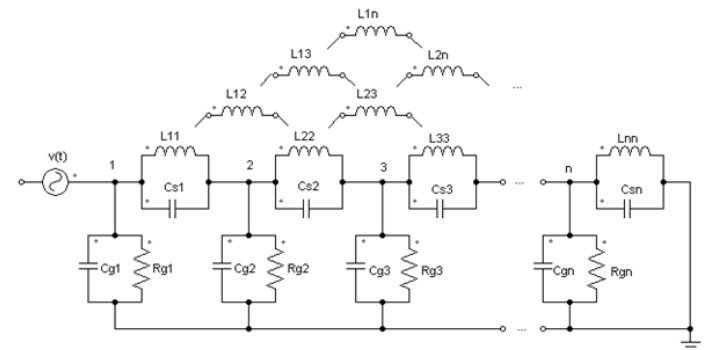

Figure 4. Distributed Parameter Model for HDC transformer

Staged transient testing of the HDC transformer

After completion of the switching transient study of the HDC transformer, Eaton conducted staged switching transient tests and transient measurements in the high-power lab at its A2KA-accredited Thomas A. Edison Technical Center in Franksville, WI. using the 500 MVA short circuit generator. The tests quantified the magnitude and frequency of transient line-to-ground voltages at the 13.8 kV primary of the HDC transformer during primary vacuum circuit breaker or internal VFI openings and closings. Specialized direct measurements at 13.8 kV captured the waveforms at the transformer winding produced during switching of the primary vacuum circuit breaker or VFI internal to the HDC transformer tank (with primary bushings and special taps at 1/3 and 2/3 of it). The test circuit consisted of the source, breaker, transformer, cable and load bank as shown conceptually in Fig. 5a. The prototype HDC transformer under test is shown in Fig. 5b.
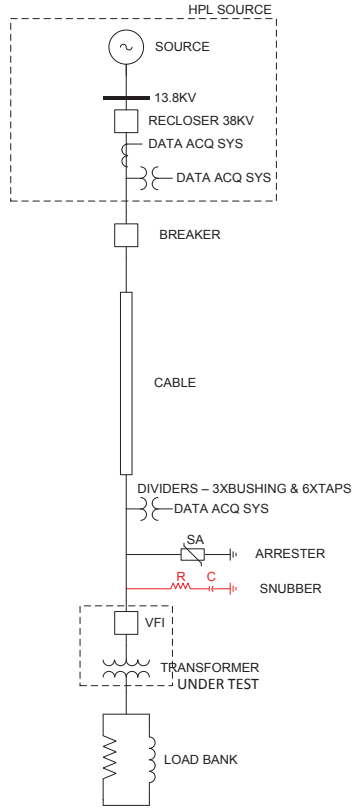
White Paper WP202001EN
Effective August 2016

Are snubbers required with Eaton's Cooper Power series liquid-filled hardened transformers?

Figure 5. A. Test circuit replicating a data center application

The performance test consisted of 1) closing a vacuum circuit breaker or VFI to energize the transformer without load, 2) applying a highly inductive light load consisting of a load bank to the secondary, 3) opening the vacuum breaker or VFI to de-energize the transformer after some time had elapsed, and 4) repeating steps 1 through 3 varying the X/R ratio of the light load. This test was conducted for switching of the vacuum breaker or VFI.
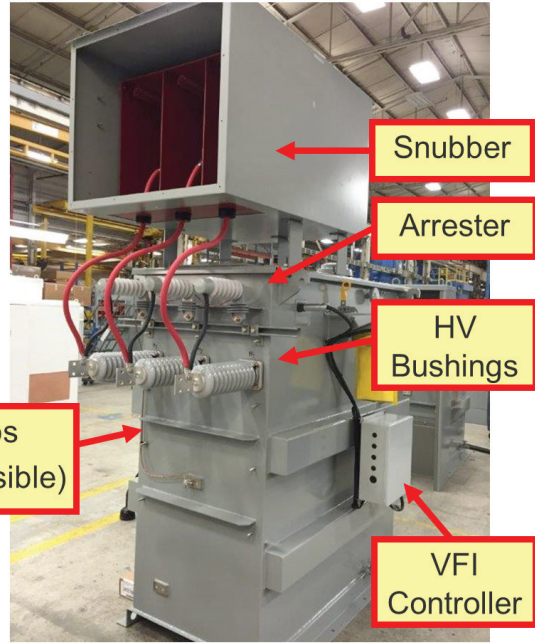

Figure 5. B. Eaton's Cooper Power series HDC transformer (prototype for testing purposes)

Three vacuum devices obtained for the test were selected to provide current chop of 3-5 A on the low-end and 19-21 A on the high-end, these magnitudes represent the range of commercially available medium-voltage vacuum circuit breaker characteristics. The vacuum breakers were separated from the transformer by cable distances of 3 or 30 m and cable sizes of #2 or 250MCM. The VFI was coupled directly to the primary winding internal to the transformer tank from the medium-voltage terminals. A series of parametric tests varied: vacuum interrupter type (two external breakers, one with high and one with low current chop or VFI), cable lengths and sizes, with and without snubbers, and with and without surge arresters. Different loading conditions were also included. A total of 157 tests were performed. Fig. 6 summarizes test results obtained for the most significant testing conditions.

trace	VCB or VFI	Snubber	Arrester	Cable	Length (m)	Full Winding Transient Overvoltage						Tap Transient Overvoltage			
						major peak		secondary peak		tertiary peak		1/3 tap		1/3 of winding	
						kV	kV/usec	kV	kV/usec	kV	kV/usec	kV	kV/usec	kV	kV/usec
10	VCB#1[1]	No	18kV	250	30	-63	83.2	-60.1	91.5	-59.2	91	-39.2	2.8	-21.9	0.7
14	VCB#1	Yes	27kV	250	3	14.26	0.008	-14	0.008	10	0.008	8.05	0.008	7.61	0.008
40	VCB#1	No	27kV	#2	3	-81.9	183	-79.1	266	-72.7	298	-44.1	8.1	-25.6	0.4
57	VCB#2[2]	No	27kV	250	30	59.7	0.4	-40.6	0.75	-21.7	0.37	45.2	0.4	27.7	0.23
78	VCB#2	No	27kV	#2	3	81.8	190	78.6	168	69.7	123.5	35.6	8.2	-25.1	1.4
93	VFI[3]	No	27kV	#2	3	N/A	N/A	N/A	N/A	N/A	N/A	-57.2	0.39	54.9	0.39
131	VCB#2	No	No	#2	3	71.95	302.5	-66.5	242	62	146	52.4	5.7	18.46	5.2
141	VCB#2	Yes	No	#2	3	30.16	0.024	N/A		N/A		22.56	0.017	15.4	0.013
146	VCB#2	No	No	#2	3	76.65	189.5	-76.45	65.3	37.25	200	-42.9	9.5	-25.38	0.5
148	VCB#2	No	No	#2	3	-77.9	184.5	-72.7	106.8	-67.9	235.5	-57.33	25.54	23.835	5.58
156	VCB#2	No	No	#2	3	78.8	86.5	73.3	115.25	55.8	143.7	56.8	5.7	30	0.74

Notes:

1. VCB#1 bolt-in 15kV, 1200A, 25kAIC and 3-5A chop. **2.** VCB#2 1985 vintage 15kV, 1200A, 18kAIC and 19-21A chop. **3.** VFI 35kV, 600A, 12.5kAIC and 3-5A chop.

Figure 6. Worst-case tests conducted on the HDC transformer

Are snubbers required with Eaton's Cooper Power
series liquid-filled hardened transformers?

White Paper WP202001EN
Effective August 2016

Prestrike or reignition

The switching transients captured at the HDC transformer primary winding terminals and taps exhibited the characteristics of switching a highly inductive current, i.e., multiple reignitions followed by voltage escalation. When a prestrike or reignition occurs, there is a very abrupt change in voltage magnitude as shown in Fig. 7 by the near vertical lines in the voltage measurement. This creates a very high rate of rise of voltage, or high dv/dt.
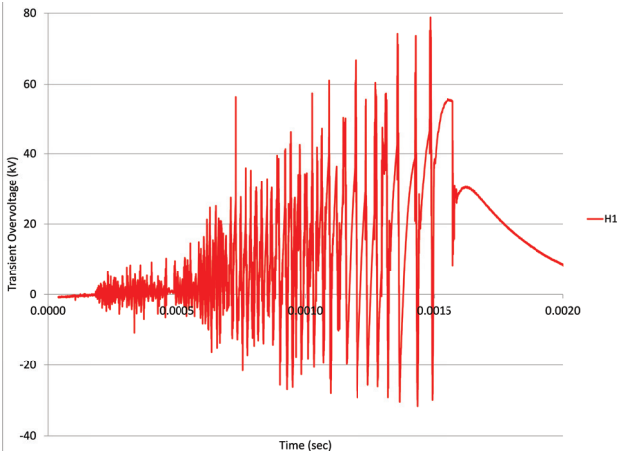
Figure 7. Reignition followed by voltage escalation common in data center switching (Trace#156)

dv/dt explained

High dv/dt can damage equipment that has windings because the voltage step is not evenly distributed across the entire winding. The dv/dt wavefront is very steep and has a short physical wavelength. As the dv/dt increases, the wavelength gets shorter and becomes comparable to the length of the winding, or the length of a few turns. Said another way, a voltage waveform with high dv/dt (high frequency equivalent) cannot travel through the inductance of the winding but finds almost a short circuit path through the turn-to-turn insulation capacitance. When the wavefront enters the transformer winding, the total voltage can be applied across the turn-to-turn insulation of the first few turns. The turn-to-turn insulation can be degraded by this voltage stress, and eventually weaken to the point of failure. Additionally, overvoltages with high dv/dt are generated by high frequency currents and internal stored magnetic energy released during switching operations.

Repetitive effect

Each dv/dt event weakens the insulation. The effect is cumulative, and repeated exposure to dv/dt will lead to failure. Therefore, how often a dv/dt event occurs also affects equipment failure. Transformers that are switched a few times a year are less likely to fail due to dv/dt because there are relatively few dv/dt events over the service life of 20 years. However, transformers that are switched daily and/or multiple times monthly (as in a data center), will have 100 times more dv/dt events and will be more likely to fail.

Criteria for evaluating dv/dt

Transformers are not rated expressly for dv/dt. However, they do have a Basic Impulse Level (BIL) rating. As shown in Fig. 8, the lightning impulse test is a high voltage, steep wavefront test that is common for most electrical equipment. The test applies a voltage waveform with a rise time of 1.2µS and decays to 50% magnitude in 50µS. Maximum voltage varies with equipment rating.
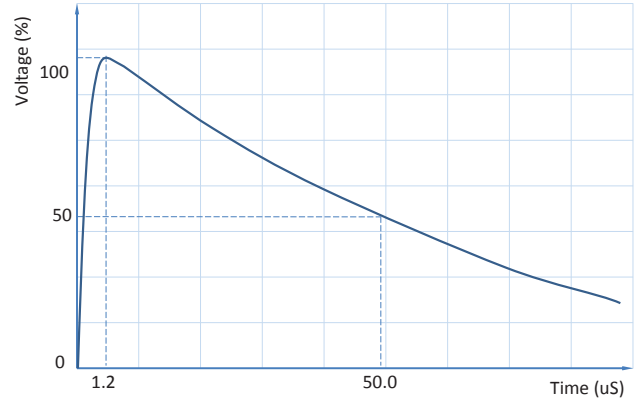

Figure 8. Lightning impulse test waveform (1.2x50µS)

BIL test waveform

The HDC transformer tested was rated 125 kV BIL. From the BIL rating, a dv/dt rating can be estimated by dividing the maximum voltage by the rise time. The BIL rating of 125 kV produces a dv/dt rating of 104.2 kV per microsecond. As shown in Fig. 9 for trace #156, the magnitude of 78.8kV with rise time of 0.91µS gives dv/dt of 86.6kV/µS.
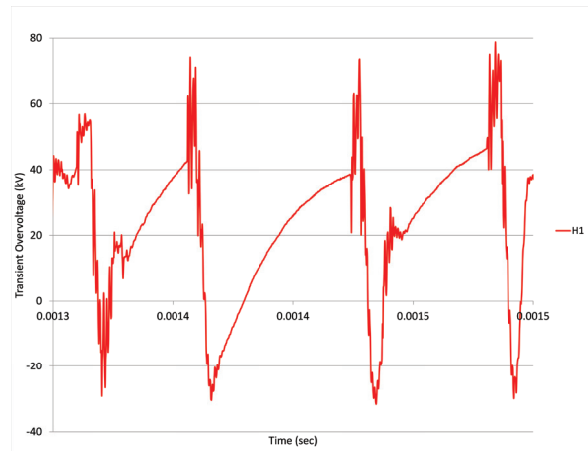

Figure 9. Calculating dv/dt from reignition transient of test (Trace#156)

The measured dv/dt values were then compared to the estimated withstand based upon the BIL rating of the transformer. As the measured dv/dt values approach the estimated withstand, damage due to dv/dt is possible, even likely. A failure would be expected to occur, depending on how frequent the dv/dt events occur.

dv/dt across partial winding

The voltage across the portion of the winding from the primary bushing to the 1/3 tap (or 2/3 tap) is of interest because the transient voltage is not evenly distributed across the entire winding. The voltage across this portion of the winding can be calculated from the measured transient overvoltage waveforms at the primary bushing and 1/3 tap. Below is the calculated voltage across H1 (primary bushing) to H1A (1/3 tap bushing). The dv/dt on this portion of the winding can be calculated as explained above.
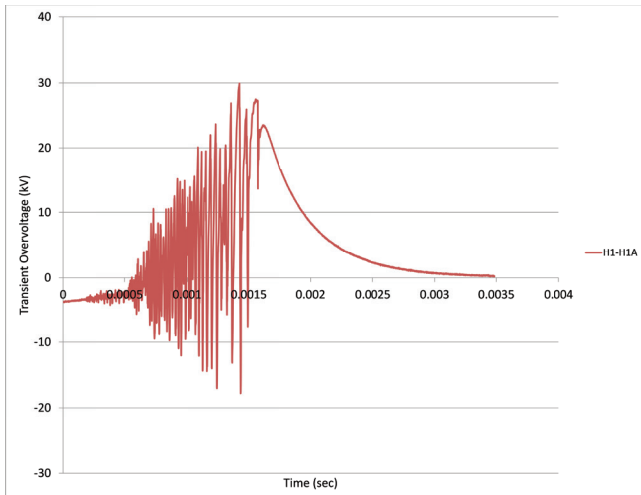
White Paper WP202001EN
Effective August 2016

Are snubbers required with Eaton's Cooper Power
series liquid-filled hardened transformers?

**Figure 10. A. Typical voltage between primary bushing
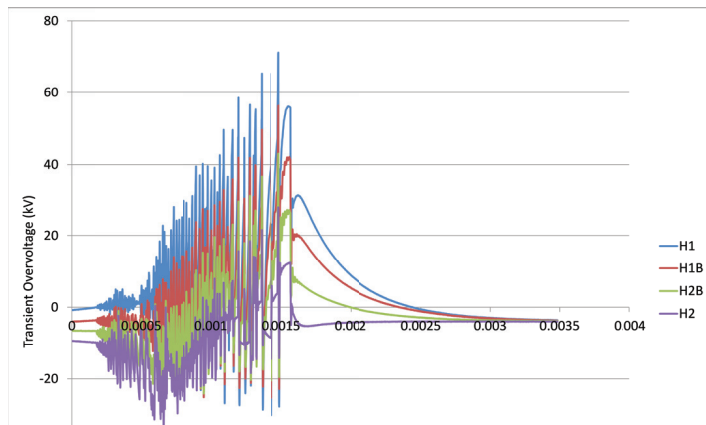and 1/3 tap**

**Figure 10. B. Typical voltage across the entire winding referenced
to ground (H1B = 1/3 of B C)**

Another reason for looking at the 1/3 to 2/3 points in the windings
is that these are typical points internally where the resonant
voltages will be highest if the impinging waveform happens
to match one of these resonant frequencies.

Test results

The evaluation of the HDC transformer commenced in February
2015; the tests were completed in October 2015 and the engineer-
ing analysis was completed in May 2016. After reviewing all the
test and simulation data, Eaton can share the following findings
and conclusions:

1. The HDC transformer was subjected to over 150 close-open
operations involving one of the three vacuum interrupting devices
over a one-week period. The large number of switching events is
representative of the duty imposed on a unit substation transformer
during commissioning and testing in a data center, as well as regular
testing of backup systems throughout the life of the data center.
For a given test configuration, a series of switching events took
place with rapid succession, sometimes less than a minute between
close-open events. This frequency of occurrence also is representa-
tive of commissioning and testing when the breaker is often used
as an on-off switch.

2. During breaker opening, current chop ranged between 3 A and
22 A depending upon the breaker type or VFI. Opening of the
vacuum breaker with such chop current of light but highly induc-
tive load current resulted in repetitive reignitions, sometimes 10
or more. With each repetitive reignition, the voltage escalated.
The peak phase voltage on the H1, H2 or H3 terminal resulting
from such voltage escalation ranged from 30 kV to 82 kV. As
predicted by the EMTP simulations, the #2 cable with length
of 3 m with no snubber, no surge arrester and breaker with the
highest chop current produced the highest peak voltages. The
corresponding peak voltages at the 1/3 and 2/3 taps ranged from
15 kV to 55 kV.

3. The Doble SFRA showed the first internal modes in the range
of 1200 Hz followed by the next mode at 100 kHz when excited
from the medium-voltage side. The frequency of this first mode
is much lower compared to a dry-type of the same kVA rating
that may have 8-10 kHz for the first mode (see Fig. 3). This is
significant because switching frequencies for 13.8 kV cable
systems typically range from a few kHz to 50 kHz. It is important
that the switching frequency avoids the natural mode(s) of the
transformer. During the switching, none of the breaker-cable
combinations excited internal resonance.

4. Because most of the test cases resulted in breaker reignition,
there was not a classic ring wave. However, it was possible to
estimate the reignition frequency of the multiple reignitions for a
given opening event. The reignition frequency ranged from
7.8 kHz to 21.5 kHz. Again, these frequencies were well between
the first internal mode of 1.2 kHz and the next internal mode of
100 kHz. The captured waveforms did not show evidence of full
or partial internal resonance.

5. The testing also included opening the breaker during
transformer inrush current. Again, this condition is very likely
during startup and commissioning because the relay settings
on the primary breaker may not be set properly or fully tested.
If that is the case, the breaker may close and then immediately
trip, interrupting inrush current that may be on the order of 10 to
20 times full load amperes and is highly inductive. For these test
cases where inrush current was interrupted, followed by multiple
reignitions, the peak phase voltage on H1, H2 or H3 ranged
from 30 to 64 kV.

6. Diagnostic tests were conducted on the HDC transformer
before and after the staged switching. The tests beforehand
established a baseline upon which to compare. The tests
afterward indicated the relative change, if any, to the baseline.
Insulation power factor tests afterward were consistent with
the baseline. The gas analysis showed no change in combus-
tible gases, indicating no damage to the insulation system.
Transformer turns ratio (TTR) and insulation resistance tests
showed no change. Additionally, the SFRA was repeated on
the primary and secondary windings and showed no change
in the sweeps. Routine dielectric tests were performed after
transient measurements, and the transformer passed them all.

Are snubbers required with Eaton's Cooper Power
series liquid-filled hardened transformers?

White Paper WP202001EN

Effective August 2016

Simulation results

The EMTP simulations using the distributed parameter model for the transformer predicted transient overvoltages similar in response to those captured in the HPL for the same switching conditions. The modeling of breaker reignition in EMTP achieved the voltage escalation on each successive reignition. For a more severe case on a breaker with 21A chop, no snubber, no arrester and 3 m of #2 cable, Figs. 11a and 11b compare the simulated response to the lab measurements and show consistency. An accurate model and proven simulation method will allow future evaluation of other transformer designs in other system applications without the need for such detailed testing in the HPL.
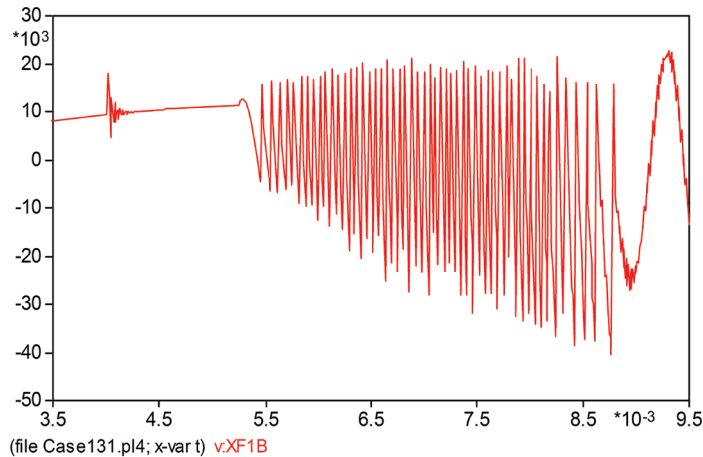

(file Case131.pl4; x-var t) v:XF1B

Figure 11. A. Transient overvoltage as simulated in EMTP
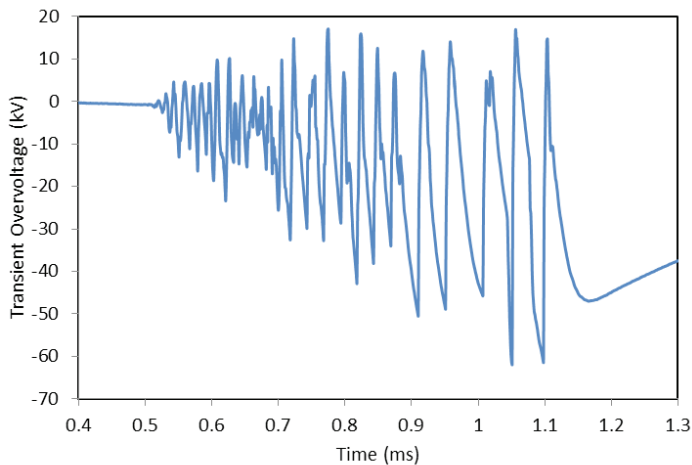

Figure 11. B. Transient overvoltage as measured in the HPL

Conclusions

Eaton's Cooper Power series HDC 1500 kVA, 13.8/0.48 kV, 125 kV BIL, liquid-filled transformer was capable of withstanding the harsh transient conditions imposed on it in the Thomas A. Edison Technical Center, including the non-snubber and non-arrester protection scenario.

Eaton's Cooper Power series transformers' natural frequencies are attractive at avoiding resonance produced in conjunction with vacuum or SF_6 switching devices. However, resonance is highly circuit dependent and should be evaluated on a case-by-case basis for all transfomers where validation of switching transient performance is not available. For those instances, SFRA testing and transient simulation analysis are recommended to determine if dangerous internal resonance conditions exist.

As predicted by EMTP simulations, the highest peak voltages were seen in the circuit with 3 m of #2 cable without snubbers and surge arresters. Likewise, as predicted by simulation, the breaker with the highest chop current typically generated the highest transient overvoltage.

Eaton's HDC transformer withstood the peak dv/dt observed during worst-case testing conditions. This finding confirms Eaton's superior field performance in data center transformers, however hardened transformers can be used in a variety of applications, including hospitals, factories, processing plants and anywhere else where switching transients may exist.

Eaton's other Cooper Power series transformers ranging from 1000 kVA to 10,000 kVA were evaluated through SFRA, showing similar natural frequency characteristics to the 1500 kVA transformer evaluated in this study. As a result, the switching transient withstand capability and transient simulations can be extrapolated to other Eaton Cooper Power series hardened transformer designs.

This study shows that Eaton's Cooper Power series hardened transformers do not require snubbers, although our testing has shown that snubbers are an effective means of mitigating switching transients. For installations on systems where the potential for switching transient conditions exist, Eaton recommends the use of snubber circuits unless the manufacturer can provide documentation from an accredited testing laboratory that the transformer is able to withstand these transient voltages and avoid harmful resonant frequencies.

White Paper **WP202001**
Effective August 2016

Are snubbers required with Eaton's Cooper Power
series liquid-filled hardened transformers?

F·A·T·N
Powering Business Worldwide