Effectiveness of Surge Capacitors on Transformer Tertiary connected shunt reactors in preventing failures- Field measurements and comparison with Transient study results

Pratap G. Mysore, P.E
Pratap Consulting Services, LLC
Plymouth, MN

Venugopal Tondupally, P.E.
HDR
Minneapolis, MN

Adi Mulawarman, P.E
Xcel Energy
Minneapolis, MN

Abstract

Transient studies initiated to determine the cause of the failures of shunt reactors showed that the failures were due to switching transients and breaker re-ignition. Surge Capacitors were installed at the terminals of the reactor as one of the mitigation methods. With the availability of relays with 1MHz sampling rate, Xcel Energy decided to capture high frequency transients during reactor switching to validate the studies. This paper presents issues associated with reactor switching especially during opening due to current chopping and available mitigation methods. Finally, field measurements are compared with transient study results to validate the effectiveness of surge capacitor application.

***Index Terms*—**Shunt reactor, surge capacitor, Switching Transients, Chopping current, recovery voltage

I. INTRODUCTION

CAPX2020, a joint initiative of eleven transmission owning utilities in four states in upper Midwest, have built nearly 800 miles of transmission at 345 kV and 230 kV during the past decade. This is the largest transmission project in recent years to improve the reliability of the grid in upper Midwest. Long transmission lines during light load conditions needed shunt reactors to control system voltages to be within the acceptable limits. They were installed either on transmission transformers tertiaries or on transmission lines. Shunt reactors on transmission lines were installed at both ends on lines longer than 100 miles or installed at only one end on shorter lines. Circuit breakers or circuit switchers were used on several shunt reactors and some were directly connected to transmission lines.

As part of these projects, several 34.5 kV, 50 MVAR shunt reactors were installed on the delta connected tertiaries of transmission transformers at various locations. These were connected in ungrounded wye configuration as opposed to grounded wye on the high voltage system.

Prior to CAPX2020, Xcel Energy had several installations with shunt reactors connected to 13.8 kV and 34.5 kV tertiaries in their system to prevent system overvoltage during light load periods due to variable wind generation. They were also switched more frequently, sometimes more than once a day. Several Failures of shunt reactors at Xcel Energy prompted an investigation to determine the cause of the failure and provide solutions to prevent these failures on existing and future reactor installations.

II. SHUNT REACTOR SWITCHING ISSUES

Circuit breakers or circuit switchers are normally used to switch LV ungrounded shunt reactors. Circuit breakers have higher interrupting current capability and perform well clearing short circuit currents during fault conditions. Breaker successfully isolates the circuit ideally at current zero crossing. Normal switching of shunt reactors with currents below 1000 amps by a circuit breaker rated for 25-40kA may cause the breaker to interrupt the current before it reaches zero as the energy of the arc across the opening contact is low during normal switching as opposed to interrupting high short circuit currents.

A. *Current Chopping –Transient voltage*

Normal load current in a reactor is lagging the voltage by 90^0 and when the circuit breaker interrupts the current at current zero, the voltage on the reactor will be at peak value. If the current is forced prematurely to zero before the natural current zero, this phenomenon is called current chopping. Since the current was still flowing in the inductor, the voltage at the terminal jumps to maintain this current flow. A simple circuit as shown in Figure 1 is used to understand the impact of current chopping. The capacitance of the bus work between the breaker and the reactor terminals is represented as C and the reactor inductance as L.

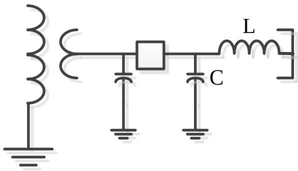


Figure 1: System model

If the circuit breaker chopping current is i_{ch}, the energy in the inductor will be $\frac{1}{2}*L*i_{ch}^{2}$. If the breaker interrupts current at current zero, the energy stored is zero. This stored energy is exchanged between the reactor and the bus capacitance, C and the transient voltage is determined by $Cv^2=Li^2$

Total energy exchange is actually ½ $CV^2 = 1/2CV_0{}^2 + 1/2Li_{ch}{}^2$
Where V_0 is voltage at which contact separation occurred
Transient voltage at the reactor terminals is expressed as

$$V = \sqrt{V_0{}^2 + \frac{L}{C} i_{ch}{}^2} \qquad (1)$$

All future discussions in the paper focus on the transient voltage developed due to current chopping. The actual peak voltage developed on the reactor bus is given by equation (1).

Transient voltage developed is the current times the surge impedance of the circuit $\sqrt{\frac{L}{C}}$. The frequency of oscillation is given by

$$f = \frac{1}{2\pi\sqrt{LC}} \qquad (2)$$

34.5 kV, 50 MVAR installation is used in this paper as an example. The inductance of the reactor is $34.5^2/(377*50) = 0.063$ H.

The surge impedance on the reactor side of the breaker with overhead bus connection with 250 pf total capacitance is $\left(\sqrt{\frac{0.063}{250}}\right) * 10^6$ =15.87 kΩ

Transient peak voltage =15.87*i_{ch} kV and the frequency of oscillations of the transient voltage will be around 40 kHz.

IEEE guide, C37.015-2009 [1] provides details to determine the chopping current for SF6 circuit breakers based on λ, chopping number and the total capacitance including capacitance of both sides and the capacitance across the breaker contacts. The chopping current is $i_{ch} = \lambda * \sqrt{C_{total}}$
Using typical number for SF6 puffer type, $\lambda = 15*10^4$ (4-19*10^4 Range) and with total capacitance of 125 pf (250 pf on each side of the breaker), the breaker chopping current would be around 1.67A that can vary from 1.0 A to 4.3A or higher depending on the range of λ.
The transient voltage can vary from 15.87 kV to 68.2 kV oscillating at 40 kHz. The maximum rate of rise of the transient voltage on the reactor side roughly would be $4*68.2*40/10^3$ kV/µs or 10.9 kV/µs. These equations are oversimplified to illustrate that current chopping result in high magnitude switching transient voltages at high frequency.

The voltage excursions on the transformer side of the reactor may be limited due to a strong source and change in voltage resulting from inductive load drop (5% of the rated). The frequency of oscillations will depend on the effective bus capacitance on the transformer side and the transformer impedance. To check the rate of rise of recovery voltage (RRRV), voltage across the breaker needs to be examined.

IEEE C37.06-2009 [2], table 7 specifies RRRV limit of 4.42 kV/µs for 72.5 kV class S2 breakers interrupting currents of ten percent of the interrupting rating. The load current of the circuit breaker is 837A with breaker rated at 72.5 kV, 40 kA interrupting rating and this is well below ten percent number used in the standard. For lack of exact RRRV value, ten percent specified value is used in our discussions.

The transient voltage peak and the RRRV calculated at current chopping level of 4.3A in the previous paragraph exceeded the specified limits in the IEEE document but, RRRV calculated at 1.0 A is below the IEEE limit. The peak voltage is below 200 kV BIL value specified on the reactor. It is to be noted that the applied overvoltage is not an impulse as specified for BIL (and switching levels are not defined for 34.5 kV voltage class).

Xcel Energy did see insulation failure at the terminals of the reactors and has documented one breaker failure. From the failures seen at Xcel Energy, it was suspected that the chopping current levels were higher than the expected values as determined in C37.015-2009 document.

III. Effect of Surge Capacitance addition

Capacitor with 0.25 µf capacitance was installed on the phase terminals of the shunt reactor to increase effective capacitance in the LC circuit of figure 1.
Stray capacitance of the bus can be ignored as the surge capacitance value is several orders of magnitude higher than the stray capacitance.

The surge impedance is $\left(\sqrt{\frac{0.063}{0.25}}\right) * 10^3$ = 501 ohms

And the frequency of oscillations after opening the breaker reduces from 40 kHz to $f = \frac{1000}{2\pi\sqrt{(0.063*0.25)}}$ =1.26 kHz.

Assuming same 4.3 A of current chopping, transient voltage developed is 4.3*0.501 = 2.15 kV when compared to 68 kV without surge capacitors and the rate of rise of recovery voltage on the reactor side reduces to
$4*2.15*1.26/10^3$ = 0.010836 KV/µs = 10.8 V/ µs
Such low rate of rise of recovery voltage will eliminate any re-ignition for a current chopping of 4.3A.

Replacing the frequency term and the voltage terms with actual L and C calculations, RRV = $4* \frac{1}{2\pi\sqrt{LC}} * \sqrt{\frac{L}{C}} * \frac{i_{ch}}{10^3}$

$$\text{RRV} = \frac{4}{2\pi C} * \frac{i_{ch}}{10^3} \text{ kV/ µs ; C is in µf} \qquad (3)$$

With 0.25 µf surge capacitance, RRV = 25V/ µs with 10A chopping current which is same as the value calculated earlier.

The Rate of rise of reactor bus voltage is dependent only on the bus capacitance and current chopped and not on reactor MVAR or the bus voltage though actual peak is the RMS of this peak with the voltage at the interrupting time.

The addition of surge capacitors of 0.25 µf reduces the transient voltage peak and frequency to levels that prevent re-ignition.

On 13.8 kV, 50 MVAR (=0.0101H) installation, same surge capacitors with 0.25µf were used. The frequency of oscillation will be $f = \frac{1000}{2\pi\sqrt{(0.0101*0.25)}} = 3.167$ kHz and the surge impedance will be $\left(\sqrt{\frac{0.01013}{0.25}}\right) * 10^3 = 200$ ohms

The rate of rise of reactor bus voltage will still be 10.8 V/µs for 10A of chopping current as per equation (3).

Voltage developed is still very low with higher chopping currents.

IV. Transient Study Modeling

Only special modeling aspects used in Alternate Transient program (ATP) are discussed below.

(a) Circuit Breaker modeling for Re-ignition

IEEE Transactions paper by Ma *etal* [3] provided details on dielectric recovery across opening contacts interrupting low currents and indicated that it is different from the characteristics during high short circuit current interruption.

As per the authors, the rate of the dielectric strength recovery characteristic is relatively slow during interruption of high short circuit currents whereas under normal low current switching condition, the dielectric strength recovery characteristic is inherent to the circuit breaker. Dielectric recovery characteristic referred to as cold recovery characteristic initially increases linearly with contact gap at a rate of 1.8 kV/µs after arc extinguishes and levels out at 1600 KV as indicated in the paper.

Attempts to get the actual cold recovery characteristics for the Xcel Energy breakers were unsuccessful. To simulate re-ignition, the dielectric strength across the opening contact was modeled as an exponential curve as shown in figure 2.

MODELS in ATP version of EMTP was used to compare the voltage across the breaker to bypass the breaker with a TACS control switch if the voltage cross the breaker contacts exceeded the value from the curve at the computational time with reference to contact opening time. Circuit breaker contact was modeled as a time controlled switch in parallel with the TACS switch.

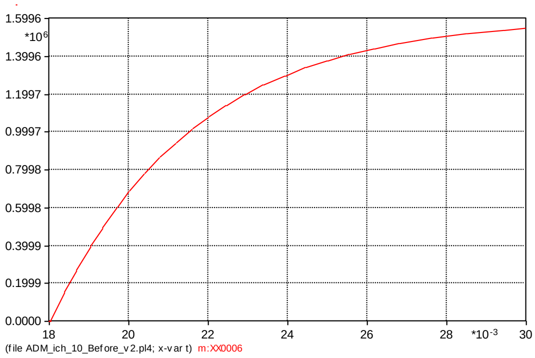


Figure 2: Cold recovery curve modeled as exponential curve after contact separation at 18.03ms

$V_{Recovery} = 1600\,(1-e^{-(t-18.03E-3)/(3.55E-3)})$ kV

(b) Shunt Reactor modeling

Shunt reactor Manufacturer provided a high frequency model with stray and winding capacitances as shown in Figure 3.

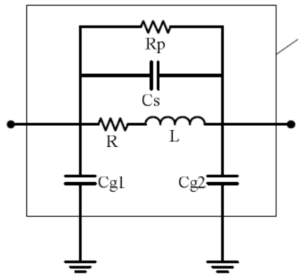


Figure 3: High Frequency model of shunt reactor

V. Case Study

34.5 kV, 50 MVAR installation and 13.8 kV 50 MVAR installations were modeled in two case studies to determine the effectiveness of adding surge capacitance of 0.25 µf.

13.8 kV reactor installation was commissioned recently and voltage transients were recorded using relays with 1MHz sampling rate. Since 34.5 kV installation was delayed and the actual field records are not available, the rest of the paper presents simulation studies on the 13.8 kV reactor to compare it with actual field recordings.

(a) 13.8 kV, 50 MVAR ATP simulations

The inductance of a 13.8 kV, 50 MVAR reactor is $13.8^2/(377*50) = 0.0101$H.

The surge impedance with 400 pf of stray capacitance is $\sqrt{(0.0101/400)} * 10^6 = 4.1$kΩ. Additional capacitance is considered due to reactor and other equipment capacitance in addition to the bus capacitance.

The frequency of oscillation without surge capacitors is $\frac{10^6}{2\pi\sqrt{(0.0101*400)}} = 79$ kHz

Transient voltage with 10A of chopping current is 10*4.1kV = 41 kV with Rate of rise of 16 kV/µs.

Breaker currents are as shown in figure 4. This is with no re-ignition modeled.

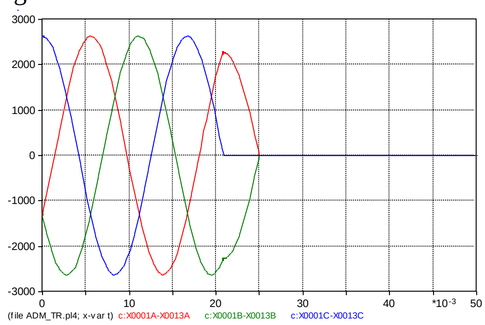


Figure 4: Reactor breaker currents

Three phase voltages at reactor terminals are shown in figures 5 and 6.

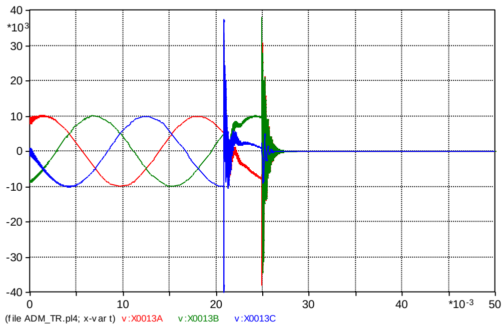


Figure 5: Phase voltages

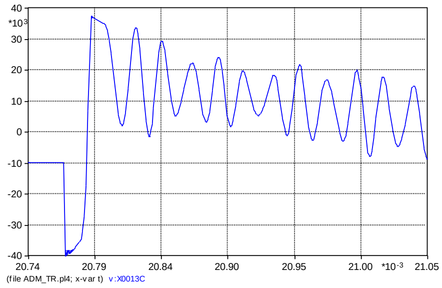


Figure 6: C-Phase Voltage

The peak voltage gets clipped by the surge arrestor to around 40 kV. It is to be noted that the frequency of oscillations is around 47 kHz when the first phase (C-Phase) opens and reduces to 44 kHz when all phases open. This is different from what is explained in C37.015 document where the source is assumed to be grounded. The measured rate of rise is around10 kV/µs.

(b) Simulations with re-ignition modeled

Another ATP case study with breaker re-ignitions modeled based on cold load characteristics resulted in multiple re-ignitions even with 10A chopping current before actual current zero. Reactor terminal voltage waveforms and Breaker TRV waveforms are as shown in Figures 7 and 8.

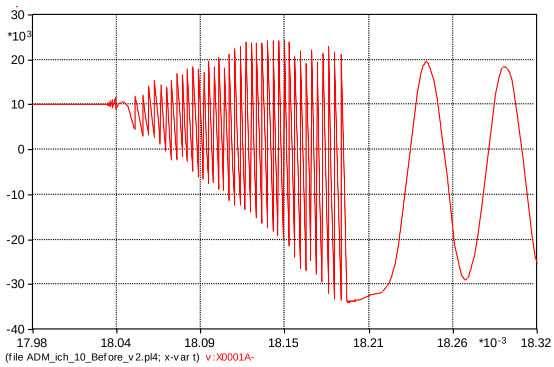


Figure 7: Reactor terminal voltage with re-ignitions

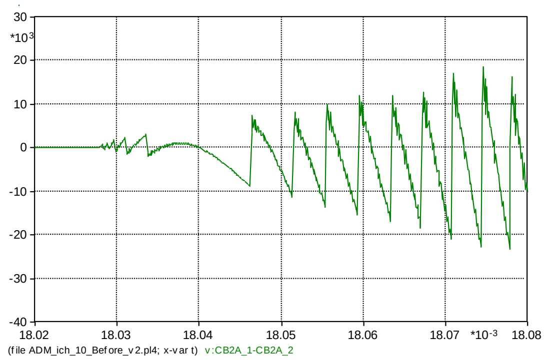


Figure 8: Breaker TRV with re-ignitions

(c) Simulations with surge capacitors

With surge capacitors installed, the voltage at the terminal of the breaker and the TRV across the breaker are as shown in Figures 9 and 10.

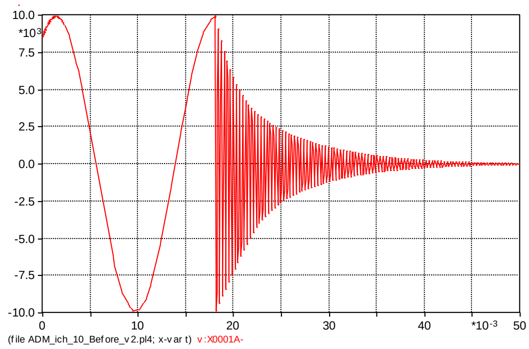


Figure 9: Reactor Terminal Voltage

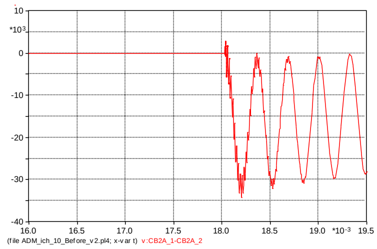


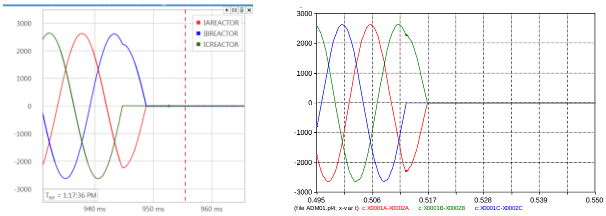
Figure 10: Breaker TRV

Thus, addition of surge capacitors at the phase terminals of reactor mitigates re-ignition due to current chopping at 10 A.

VI. Field Measurements – Simulation Comparison

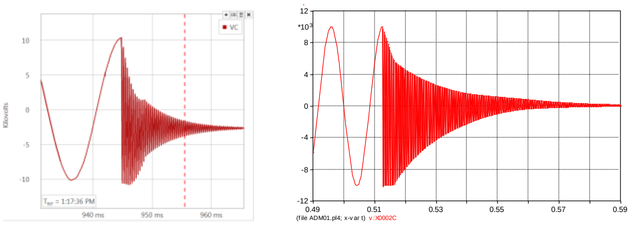
A relay with 1 MHz sampling rate was used to record reactor terminal voltages and reactor currents during switching out the reactor.

Figures 10 and 11 show reactor currents and terminal voltages captured during breaker opening and ATP simulation outputs. There were no re-ignition and no current chopping observed.



a. Field captured b. ATP simulation

Figure 11: Reactor currents

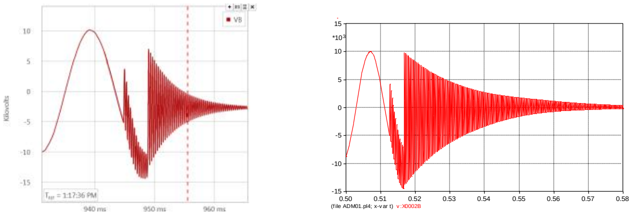


a. Field captured b. ATP simulation

Figure 12: V - First phase to open

The transient over voltages on the reactor terminals were less than 1.3 PU and the frequency of oscillations were 3.11 kHz. The RRRV across the breaker in simulations was 67V/µs which is well below the breaker rating of 4.42kV/µs.

The transient voltage on reactor for the next opening of remaining phase is as shown in Figure 13 with simulation waveforms.



a. Field captured b. ATP simulation

Figure 13: V - Next phase to open

The change in frequency of oscillation seen after first phase opening and after the next two phases opening was very minimal from 3.03 kHz to 3.07 kHz. The measured frequency is close to the calculated frequency of 3.167 kHz in earlier section.

VII. Conclusions

Circuit breakers designed to interrupt high short circuit currents tend to interrupt low load currents before current zero, a phenomenon known as current chopping. Current chopping generates high transient voltages during interruption of shunt reactors resulting in reactor insulation failure or breaker failures. Surge capacitors installed on the phase terminals of reactors reduce the peak transient voltage and the frequency of oscillation reducing the rate of rise of recovery voltage and mitigate reactor and breaker failures.

VIII. References

[1] IEEE Std C37.015-2009, "IEEE Guide for the Application of Shunt Reactor Switching

[2] IEEE Std C37.06-2009, "IEEE Standard for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis— Preferred Ratings and Related Required Capabilities for Voltages above 1000 V".

[3] Z. Ma, C.A. Bliss, A.R.Penfold, and A.F.W. Harris. "An Investigation of Transient Overvoltage Generation when Switching High Voltage Shunt Reactors by SF6 Circuit Breaker" IEEE Transactions on Power Delivery, Vol. 13, No. 2, April 1998

Authors

Pratap G. Mysore, Founder-Pratap Consulting Services, has over forty years of experience in the power industry. He is a registered Professional engineer in the state of Minnesota. He is the chair of IEEE Power Systems Relaying and Control Committee and a member of IEEE T&D Capacitor Subcommittee. He has taught power systems protection course at the University of Minnesota and developed media modules for the Consortium of Universities for Sustainable Power (CUSP), a DOE sponsored program. Pratap has authored several papers and presented tutorials at MIPSYCON and relay conferences. He is a member of the WPRC planning committee.

Venugopal Tondupally is currently working as a Project Engineer in System Protection & Studies group, with HDR Engineering Inc. He has Master's Degree in Electrical Engineering from New Mexico State University.
His project experience includes relay settings for utility substation equipment, transmission lines up to 345 kV and programming of communication devices. He has also worked on short circuit studies using fault programs, CAPE and ASPEN and Transients studies using Alternate Transient Program. He has assisted utilities in compliance issues in the areas of PRC-023, and PRC-005 documentation.
He has a professional Engineering License in the state of New Mexico.

Adi Mulawarman is currently working as a principal system protection engineer at Xcel Energy. He has a Bachelor of Science and Master of Engineering Degree from University of Minnesota. His experience includes designing of protection and control system for distribution and transmission substation, relay settings and testing, and transient studies. He has designed and rebuilt protection and control equipment using IEC-61850 protocol. He is a registered professional Engineer in the state of Minnesota.
He is also an active member of IEEE PES Power System Relaying and Control Committee.