Effectiveness of Surge Capacitors on Transformer Tertiary connected shunt reactors in preventing failures

- Field measurements and comparison with Transient study results

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Shunt Reactor Additions in Xcel Energy

Wind Generation Addition

- 825 MW wind power generation in Southern MN

CAPX 2020

- Joint Initiative of eleven transmission owning utilities in four states in upper Midwest.
- 800 miles of transmission at 345 kV and 230 kV
- Largest transmission project in 40 years to improve reliability of the grid in upper Midwest.
- Last line of the project expected to be energized in December 2018.

Applicable documents for Operating Voltage Range

- System voltage needs to be within the allowable range to prevent connected equipment failures.

- ANSI C84.1-2016 “American National Standard for Electric Power Systems and Equipment—Voltage Ratings (60 Hz)”. This standard establishes nominal voltage ratings and operating tolerances for 60 Hz electric power systems above 100V. The latest version includes preferred voltage ratings up to 1200kV which was covered earlier in IEEE 1312-1993.

Shunt Reactors

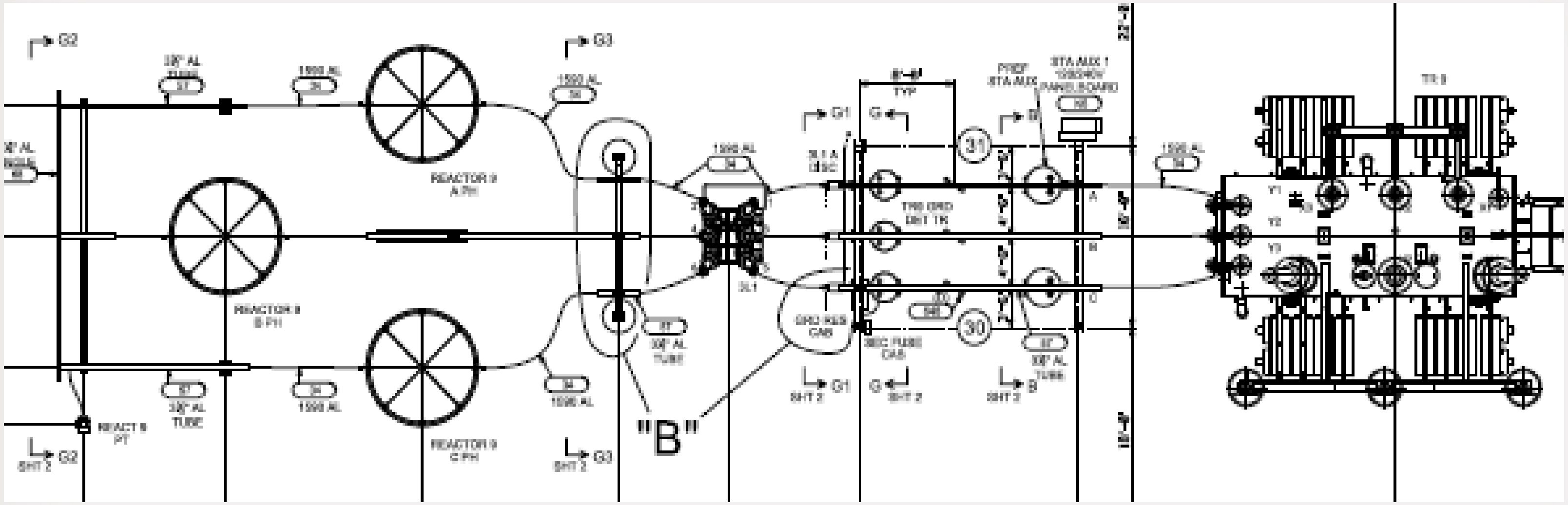
Installed to keep system voltage below maximum limit

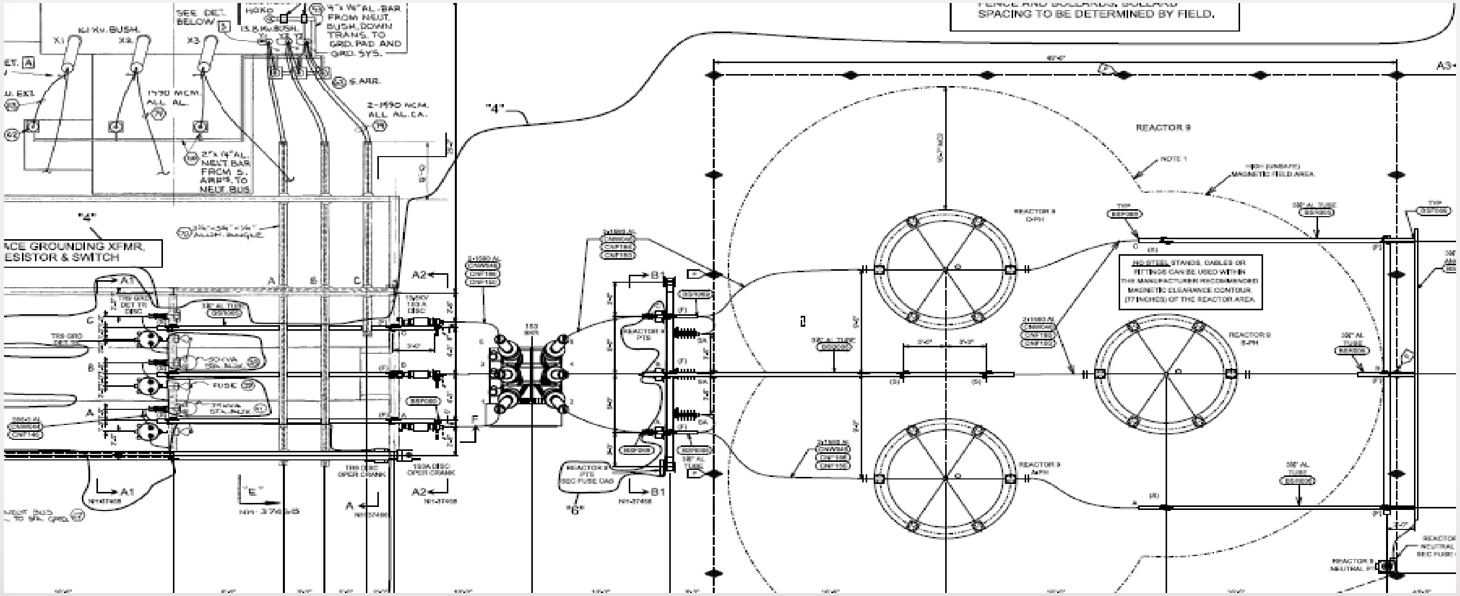
- Installed on Transmission lines
  - Either at both ends or at only one end.
  - Middle of the line.
  - Grounded “Wye” with or without Neutral Reactor
- Tertiaries of transmission transformers

Transformer Tertiary connected Reactors

- Economical Installation at lower voltage
- Air core Construction – voltages up to 34.5 kV
- Up to 50 MVAR
- Ungrounded “Wye” configuration
- Frequency of switching – Daily or more frequent

Reactor connections and Physical Layout





Reactor and Switching Device ratings

- 34.5 kV, 50 MVAR Reactor; Rated Current 836A
- 13.8 kV, 50 MVAR Reactor; Rated Current 2091A
- 72.5 kV, 3000 A, 40 kA SF6 Gas circuit breaker with gas pressure at 65 PSI
- 34.5 kV Reactor Load current is 2% of the short circuit current interruption rating
- 13.8 kV reactor current is 5% of the short circuit current interruption rating.
- Breaker load current interruption is less than 5% of maximum short circuit rating.

Circuit Breaker Characteristics

- Circuit breakers are designed to interrupt high short circuit current -40kA
- Have no problem interrupting low load currents but, the current is forced to zero before the natural current zero occurs – Phenomenon referred to as current chopping.
- C37.015-2017,"IEEE Guide for the Application of Shunt Reactor Switching" assumes low current region to be less than 300A.
- Xcel energy 34.5 kV reactors (load current 836A) have failed due to suspected current chopping.
- One circuit breaker failure and few 34.5kV reactor failures were attributed to transient voltages due to current chopping

Bus Capacitance and Shunt Reactor Inductance

- Bus work between the circuit breaker terminals and shunt reactor
  - Less than 100 feet –Typical 50-80 feet.
  - Capacitance of the bus (as per C37.011- Transient Recovery Voltage Application guide for Circuit breaker): 2.2-5.5 pf/ft.
  - Total bus capacitance with breaker bushing – assumed to be around 250pf.
- 50 MVAR reactor inductance, $L = \frac{kV^2}{MVAR*2\pi*60}$
- 13.8 kV, 50 MVAR reactor, L= 0.0101 Henry
- 34.5 kV, 50 MVAR reactor, L=0.063Henry

Effect of Current Chopping

- If Chopped Current is i_{CH}, the stored energy in the inductor is $½*L*i_{CH}^2$
- There is an energy exchange between the bus capacitance $(1/2*C*V^2)$
- Total energy exchange is $1/2CV^2 - 1/2CV_0^2 = Li_{CH}^2$

Where, V_0 is the voltage at which current is chopped.

- Voltage developed, $V = \sqrt{[V_0^2 + (L/C) * i_{CH}^2]}$

$\sqrt{(L/C)}$ is the surge impedance

Surge Impedance Transient volta

Surge Impedance: Assuming 250 pf capacitance,

13.8 kV Reactor bus: $Z = 10^6\sqrt{(0.0101/250)} = 6.36\ k\Omega$

34.5 kV Reactor bus; $Z = 10^6\sqrt{(0.063/250)} = 15.89\ k\Omega$

Transient voltage Peak:

- $\sqrt{[V_0^2 + (6.36 * i_{CH})^2]}$ kV at 13.8 kV
- $\sqrt{[V_0^2 + (15.89 * i_{CH})^2]}$ kV at 34.5 kV
- V_0 is the voltage at which contacts interrupted the current.

Transient Voltage

- The value of current chopped is dependent on:
  - Capacitance on both sides of the breaker
  - Chopping number λ, a characteristic value of the circuit breaker
  - SF6 Puffer type $\lambda = 4x10^4$ to $19x10^4$
  - Total current chopped = $\lambda\sqrt{C}$; With 250 pf on both sides of the breaker and $\lambda=10x10^4$, C=250pf/2, $i_{CH} =$ 1.1A; This can vary up to 4A depending on λ and capacitance.
- Chopping current is higher at load currents.

Transient Voltage rate of rise

- Transient voltage on 13.8 kV, 15.89 kV

  With 4A chopped current, transient voltage: 63.56kV

Frequency of oscillation: $= \frac{10^6}{2\pi\sqrt{(0.0101*250)}} =$ 100kHz (40kHz at 34.5 kV)

Rate of rise of the voltage = $4*f*V/10^3$ = 25kV/µs

Circuit breaker specs limit rate of rise to 4.42 kV/µs (C37.06-2009)

Breaker re-ignites as RRRV is higher than dielectric recovery rate.

Note that the peak voltage adds on the voltage value at which the current was chopped

Addition of Surge Capacitance

- Surge Capacitance $C_{surge} = 0.25\ \mu F$
- **Surge Impedance**

13.8 kV Reactor bus: $Z = 10^3\sqrt{(0.0101/0.25)} = 200\ \Omega$

34.5 kV Reactor bus; $Z = 10^3\sqrt{(0.063/0.25)} = 502\ \Omega$

- **Transient Voltage magnitude and Frequency: 10A chopped**

13.8 kV bus: 200*10 =2kV; Frequency:3.167 kHz RRRV=25 V/μs

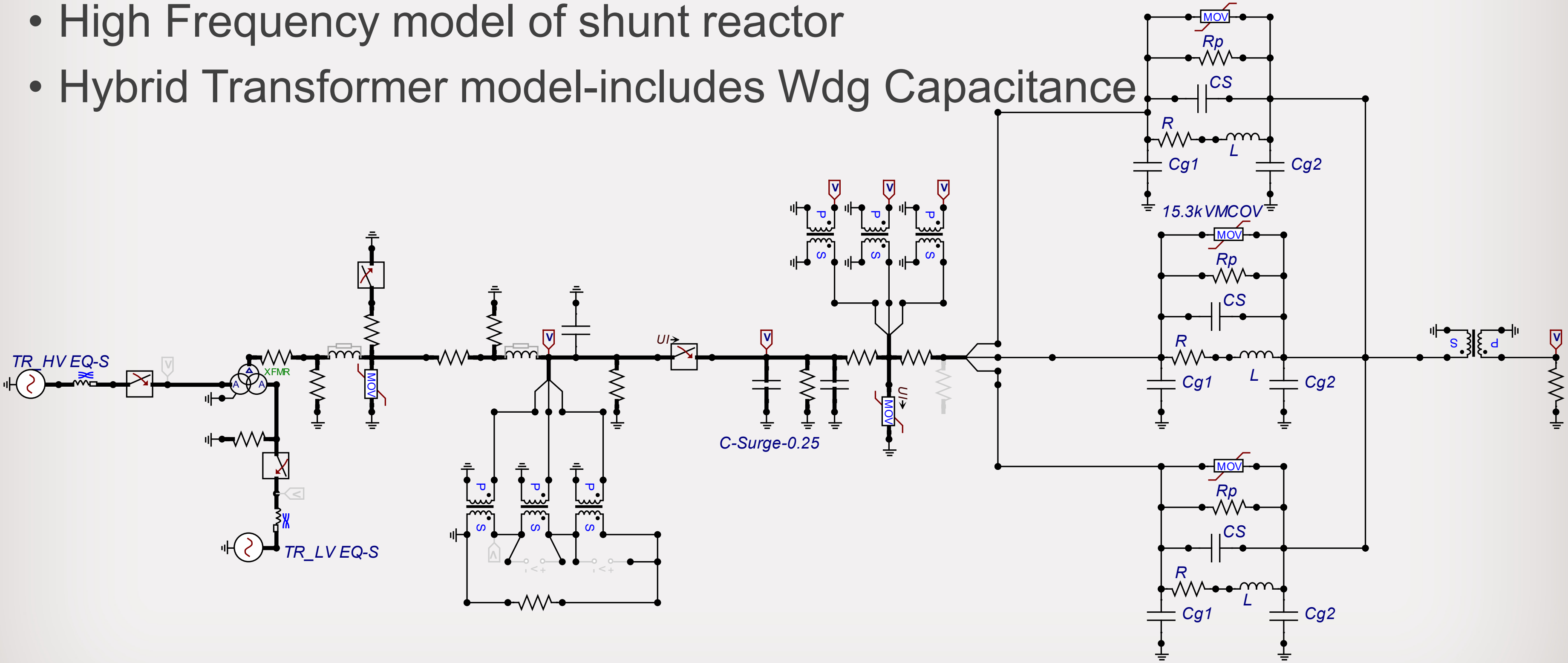
34.5 kV bus: 502*10 =5kV; Frequency:1.26 kHz RRRV=25 V/μs

Surge Capacitor

- Reduces Peak Transient Voltage
- Reduces the frequency of oscillation
- Reduces the Rate of rise of transient voltage on the Reactor bus
- Reduces the transient recovery voltage rate of rise across the breaker.
- Minimizes Breaker reignition

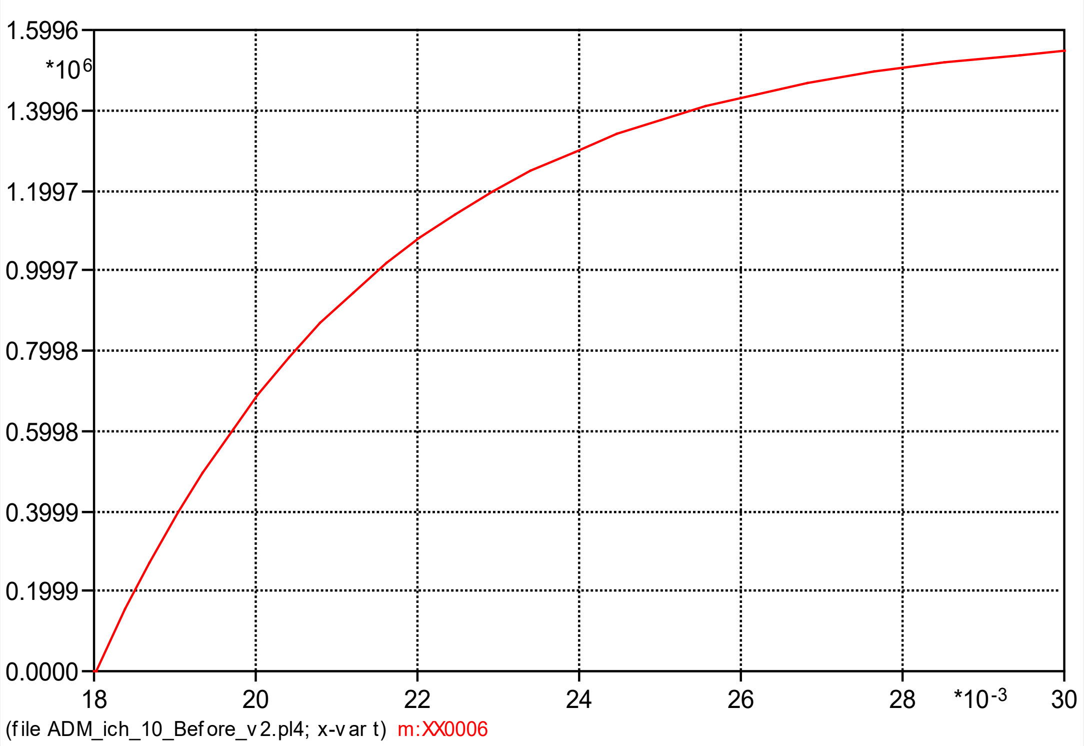
Transient Studies

- Used Alternate Transient Program (ATP) , a version of Electro-magnetic transient Program(EMTP)
- Breaker re-ignition modeled using 'MODELS' blocks
- High Frequency model of shunt reactor
- Hybrid Transformer model-includes Wdg Capacitance



Breaker Dielectric Recovery Characteristics

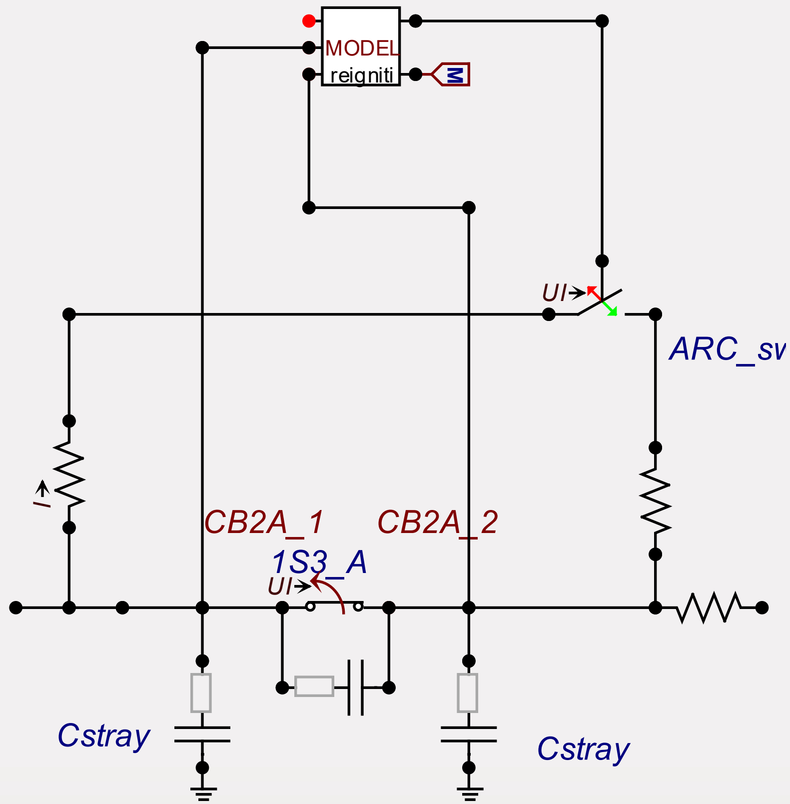
- Cold dielectric recovery Characteristic at Low current Interruption
- Inherent to the specific breaker (Initial Rate of rise -1.8kV/μs)
- Modeled in EMTP_ATP using 'MODELS' as an exponential function



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

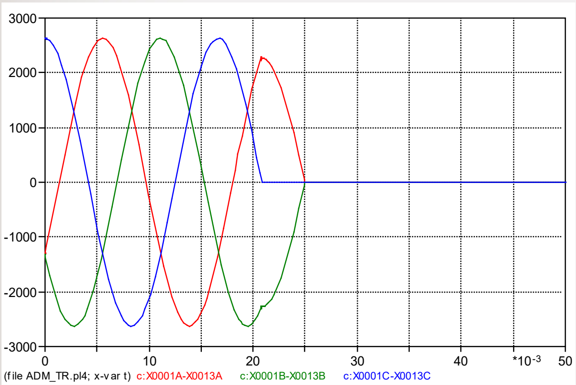
Dielectric Recovery at Load Current Interruption

- Arc re-ignites if the voltage across the contacts exceeds
- Dielectric Recovery voltage after current interruption.

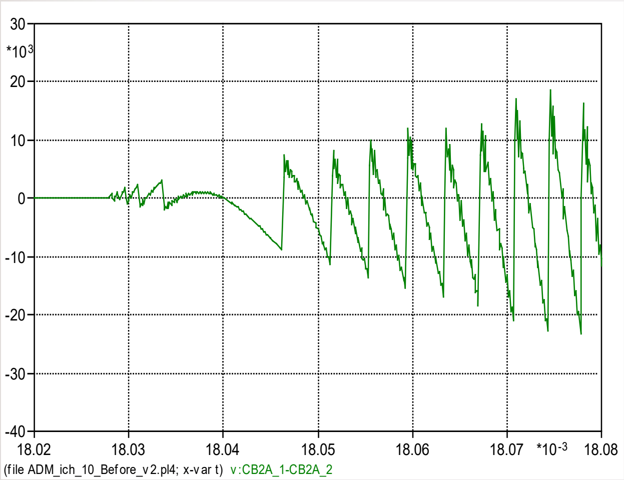


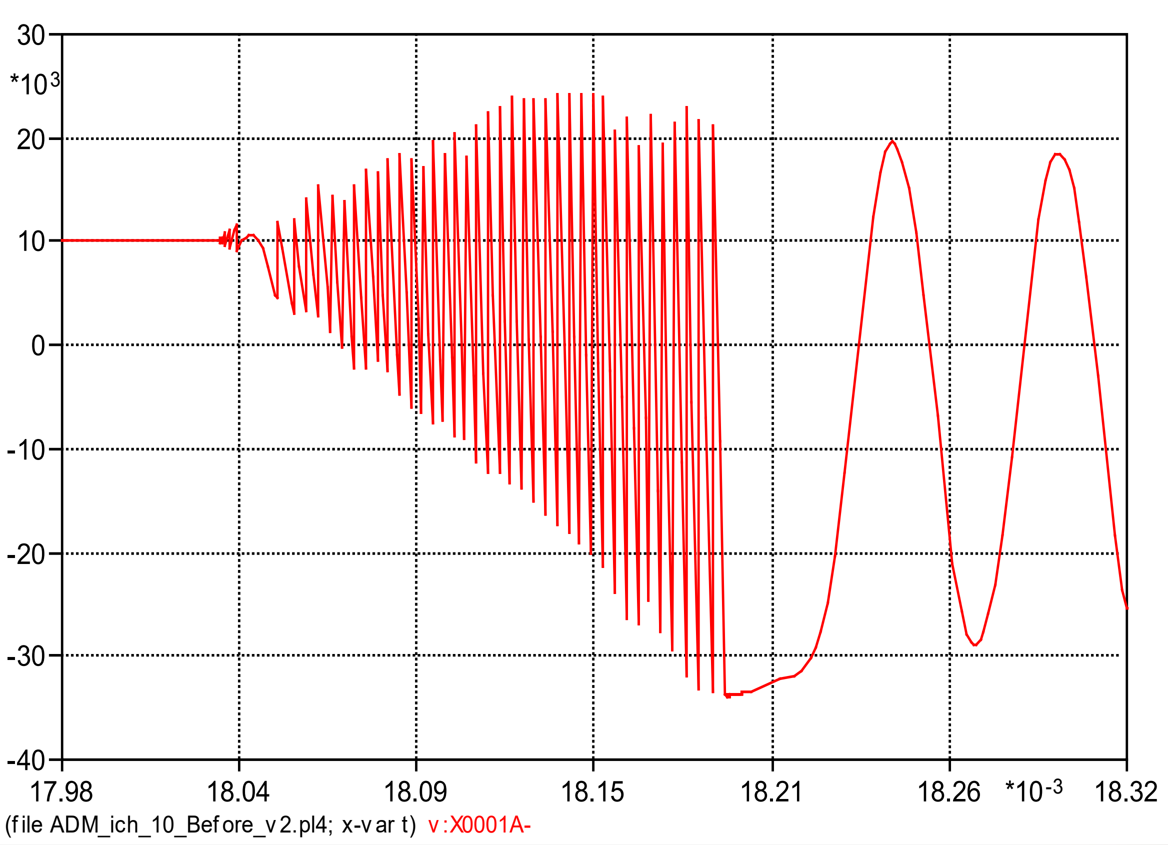
Reignition Switch Model

Results with 10A Chopping Current

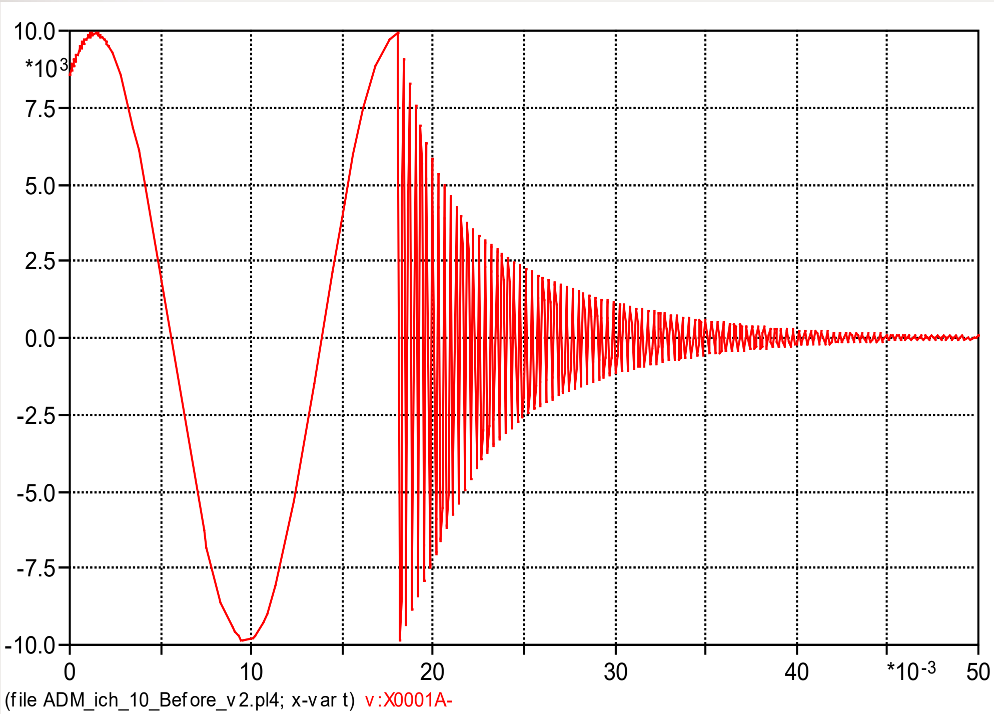


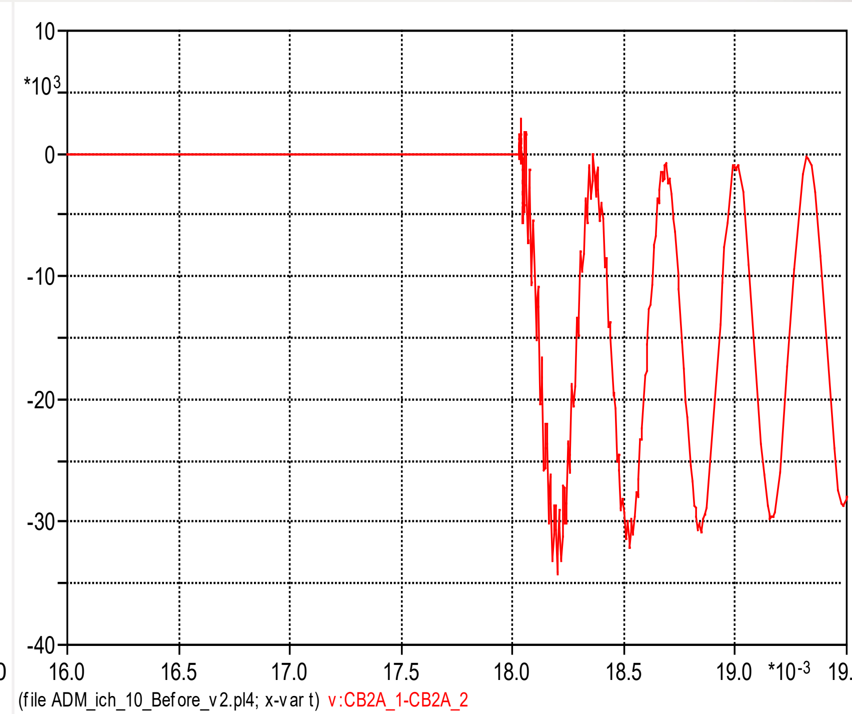
Reactor Current





Bus Voltage -Switching with Surge Capacitor

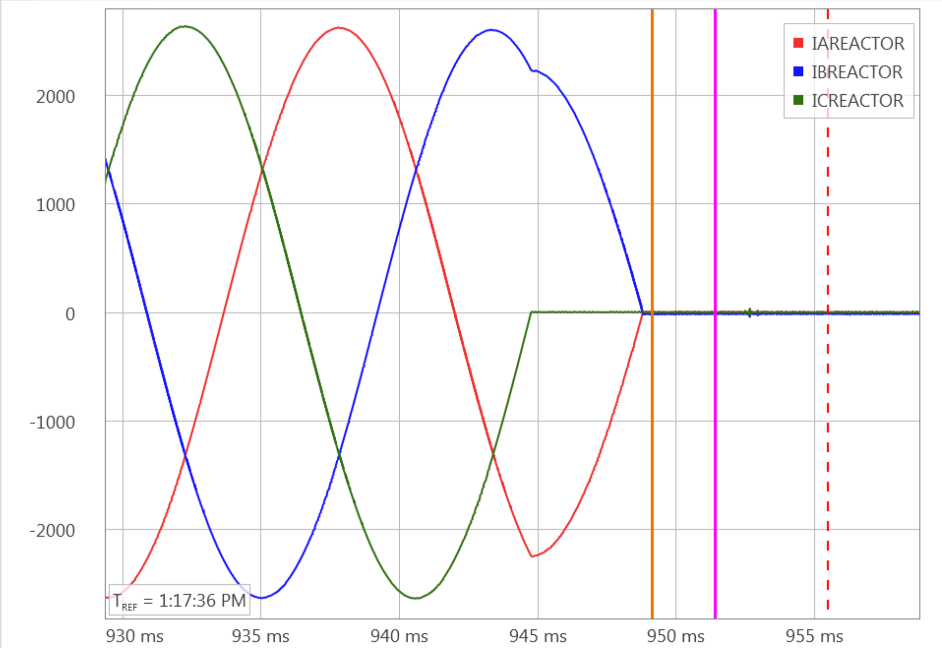


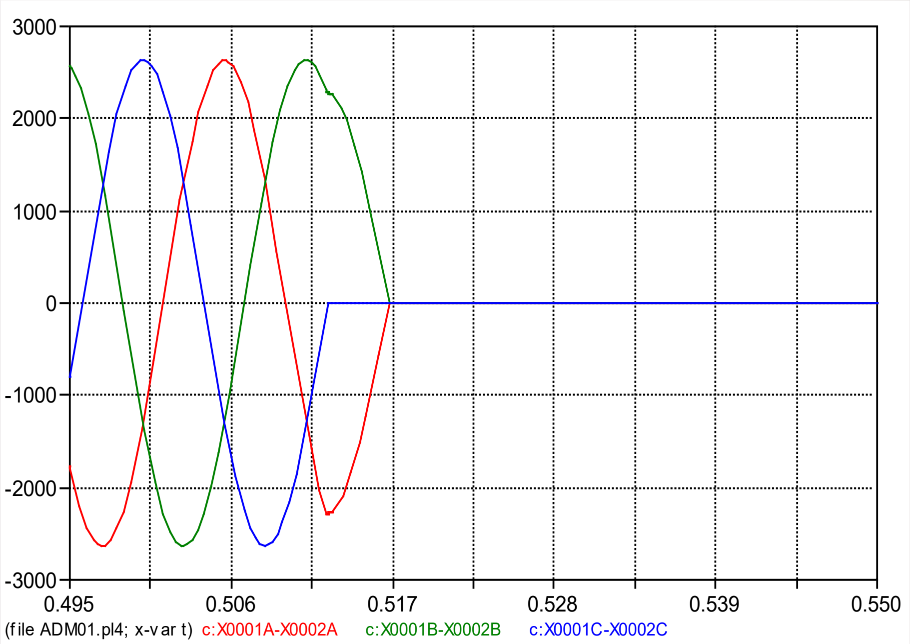


Bus Voltage

Breaker TRV (Voltage Across Breaker)

Comparison of ATP simulations with Field Records



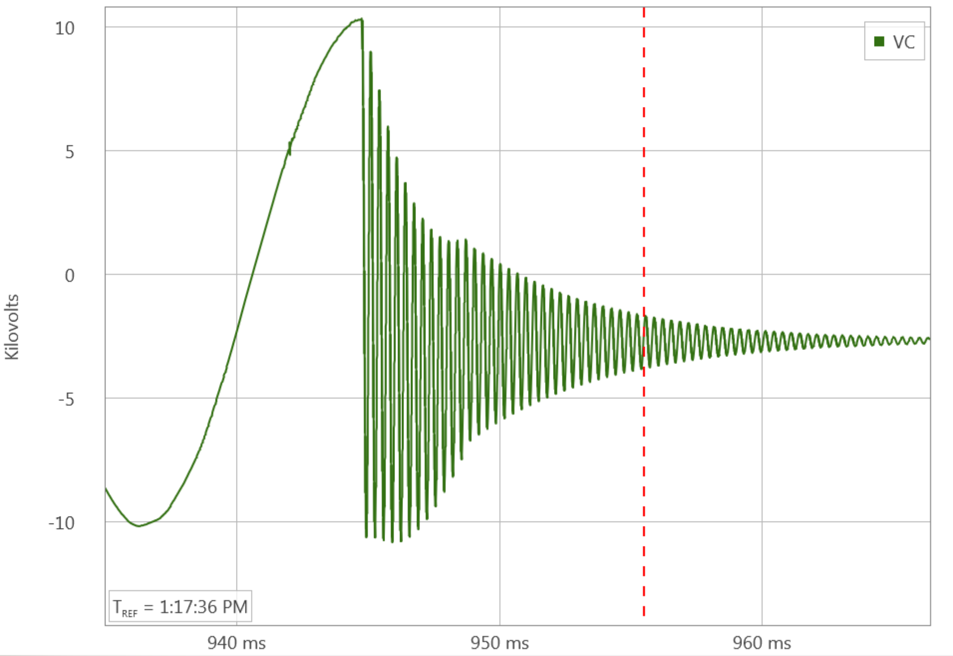


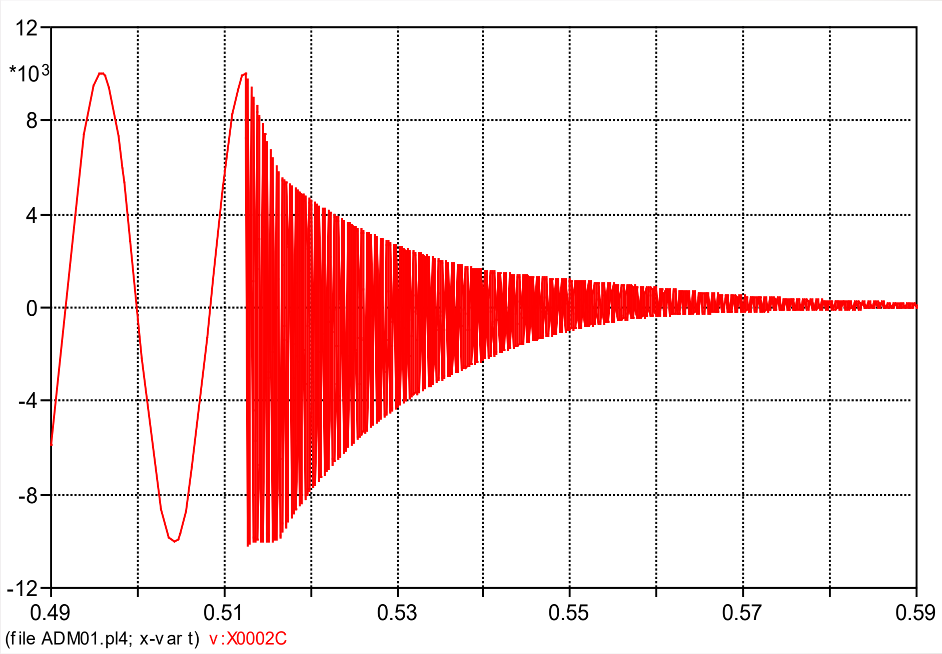
Field Recorded

ATP Simulation

Shunt Reactor phase Currents

Bus Voltage –After Breaker First Pole Opens

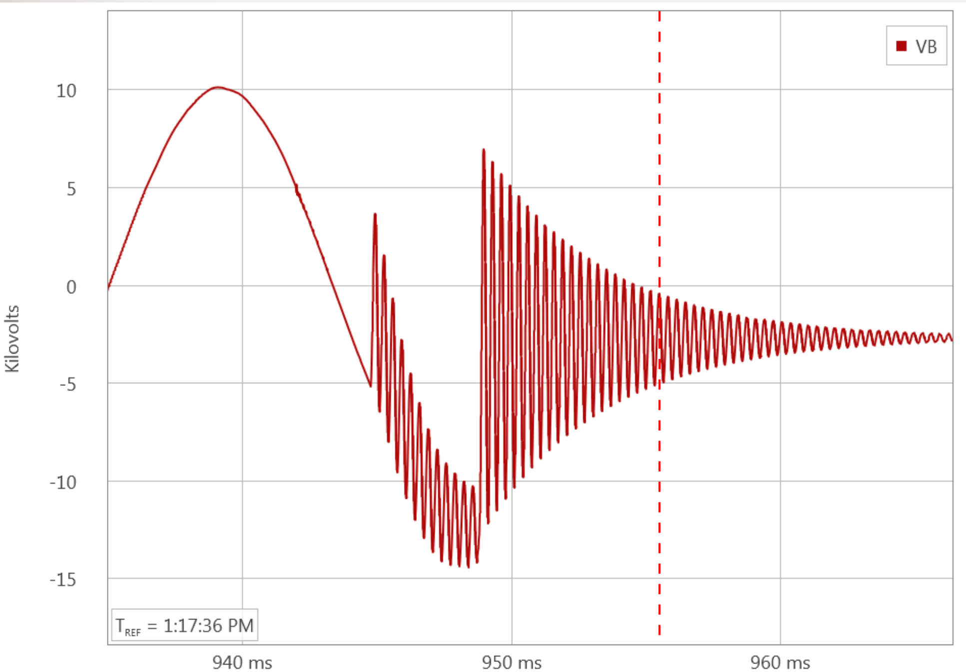


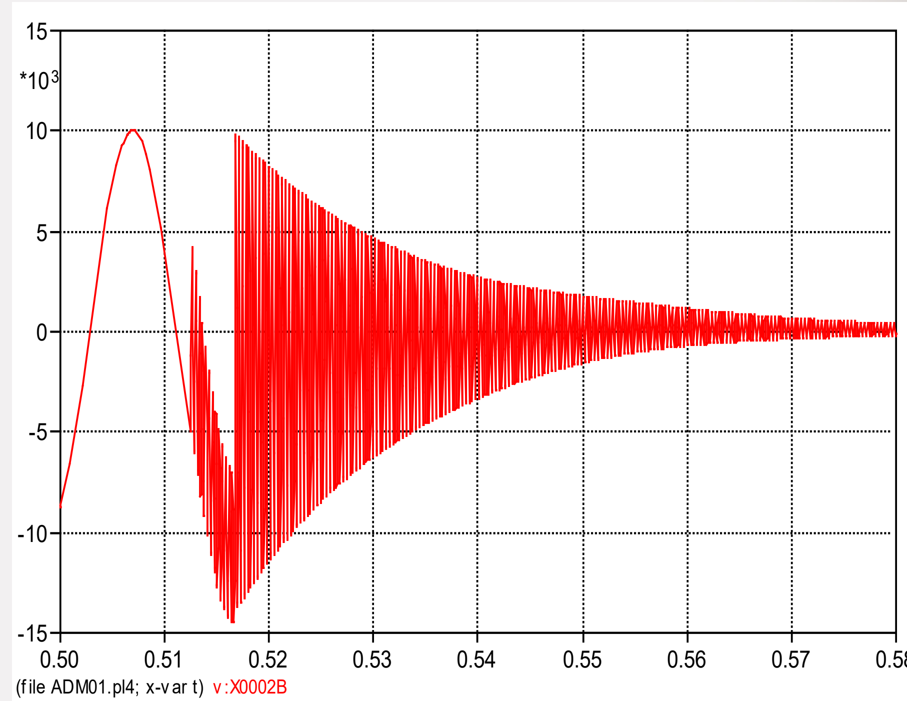


Relay Captured –V_C voltage
Frequency- 3.03 kHz, RRRV-67V/µs

ATP Simulation–V_C voltage
Frequency: 3.11 kHz

Reactor Bus Voltage – After next Poles Open





Relay Captured –V_B voltage
Frequency- 3.03 kHz, Changes to 3.07kHz
After all poles open

ATP Simulation–V_B voltage
Frequency 3.11 kHz
Calculated Frequency:3.167 kHz

C37.015 calculations assume grounded Source with Ungrounded Reactor Configuration
-Frequency after first pole opens is lower than the frequency of oscillations after all poles open. This is not true if the source is ungrounded.

Conclusions

- Addition of Surge Capacitors at the terminals of the reactor mitigates re-ignitions.
- At 13.8 kV, 50 MVAR reactor Load current is high enough not to cause current Chopping as seen at 34.5 kV.
- 34.5 kV installation to be commissioned in the near future will provide the proof of effectiveness of Surge capacitors for lower reactor currents.
- Need to have a High sample recording device with Two Voltage inputs to record Breaker TRV

Questions?