Protection and Control Issues associated with Shunt Compensated Transmission Lines

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CAPX2020 Project

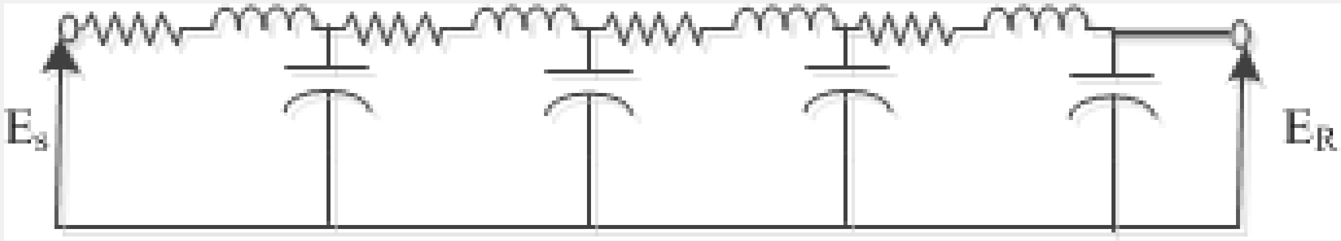
- Joint Initiative of eleven transmission owning utilities in four states in upper Midwest.
- 800 miles of transmission at 345 kV and 230 kV
- Largest transmission project in 40 years to improve reliability of the grid in upper Midwest.
- Last line expected to be energized in December 2018.

Acknowledgement

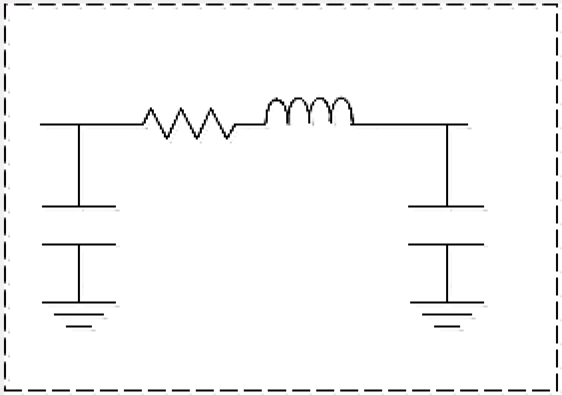
- American Transmission Company (ATC) study group for bringing up DCZ issues during the line design studies on one of the CAPX lines.
- Failures of Breakers tripping immediately following shunt compensated Line energization in Arizona.
- This prompted three utilities associated with CAPX to investigate the impact of shunt reactors on their lines and to determine mitigation methods.
- Paul Nyombi of Xcel Energy and Derrick Schlangen of Great River Energy for their support and contribution to this presentation.

Transmission Line Representation

- Long Transmission lines can be represented as several series connected modules made up of series resistance, series inductance and shunt capacitance.



- Lines are also represented with lumped parameters where the line capacitances are split between two ends.



Line Parameters – Typical

345 KV System

- Line Resistance: 0.033 Ω/Mile
- Line Reactance: 0.5-0.6 Ω/Mile
- Line Inductance: 1.459 mH/Mile
- Line Charging MVAR: 0.8-0.9 MVAR/Mile
- Line Capacitance:0.0189 μF/mile

Resistance can be ignored for our discussions.

Transmission Line voltages

- During light load or no load conditions, Transmission line has the same effect as capacitance connected to the system.
- System voltage increases with the connection of open ended or lightly loaded transmission line.
- Capacitance of the line is distributed over the entire length. Open ended line voltage increases with increase in length.

Shunt Reactor Application

- To keep system voltage below allowable maximum value
- System voltage needs to be within the allowable range to prevent connected equipment failures.

- IEEE 1312- 1993 (R2004) *"IEEE Standard Preferred Voltage Ratings for Alternating-Current Electrical Systems and Equipment Operating at Voltages Above 230 kV Nominal"*

- Installed on
  - –Tertiaries of transmission transformers
  - – On transmission lines –either at both ends or at only one end.
  - –Middle of the line.

Shunt Compensated Lines

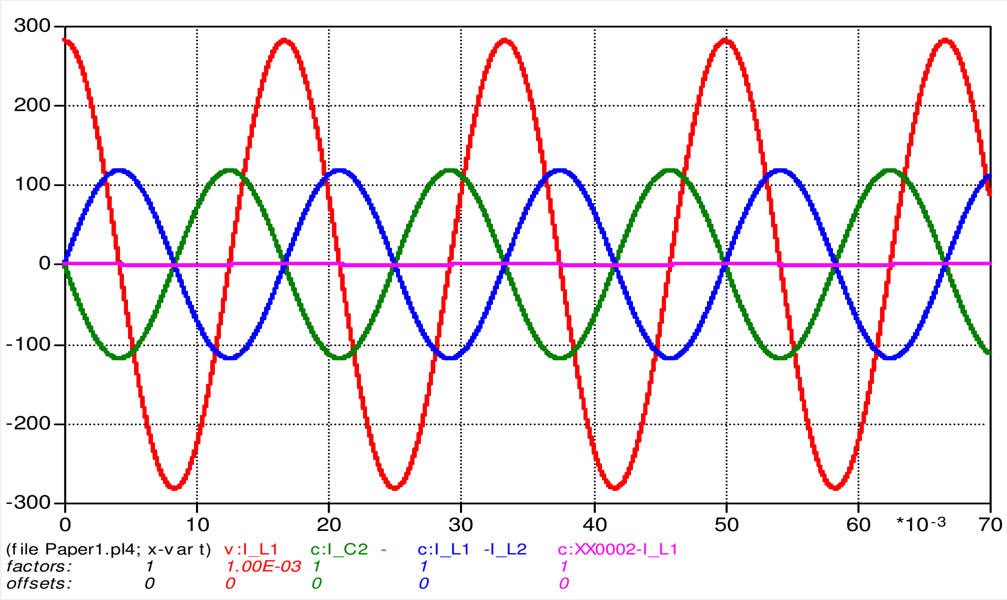
- Transmission lines with shunt reactors connected.
- Total shunt reactor MVAR_R = Sum of all shunt reactors connected on the line.
- Degree of compensation, $M = \frac{MVAR\_R}{MVAR\_C}$

  Where, MVAR_C is the line charging MVAR

Degree of compensation (Reactor MVAR rating) is determined by planning studies – Can exceed 100%.

Effect of Shunt Reactors

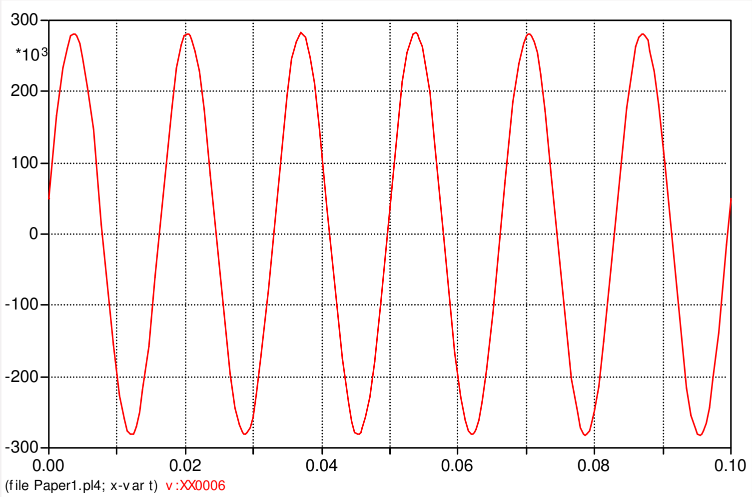
- Decreases the voltage by compensating for the capacitive charging currents.
- Reactor current, I_L lags voltage by 90^0
- Capacitor (line charging) current, I_C leads voltage by 90^0
- Decreases the current through the breaker current ($|I_C| - |I_L|$)



Steady State current and Voltage phase relationship

Line Currents During Energization

- Voltage waveform: V Sin ($\omega t + \varphi$) where φ is the delay angle of switching on the voltage waveform from voltage zero.



- Charging (capacitive) current: I Sin($\omega t+\varphi+90$)
- Reactor current: MI [Sin ($\omega t+\varphi-90$)+ Cosφ $e^{-t/\tau}$]

Line Breaker Current

- $I_C = I \, Cos(\omega t+\varphi)$
- $I_L = MI[-Cos(\omega t+\varphi)+ Cos\varphi \, e^{-t/\tau}]$
- Breaker Current, $I_{BR\varphi}= I_L+I_C$
- $I_{BR\varphi}= I_L+I_C =(1-M)I \, Cos(\omega t+\varphi) + MI \, Cos\varphi \, e^{-t/\tau}$

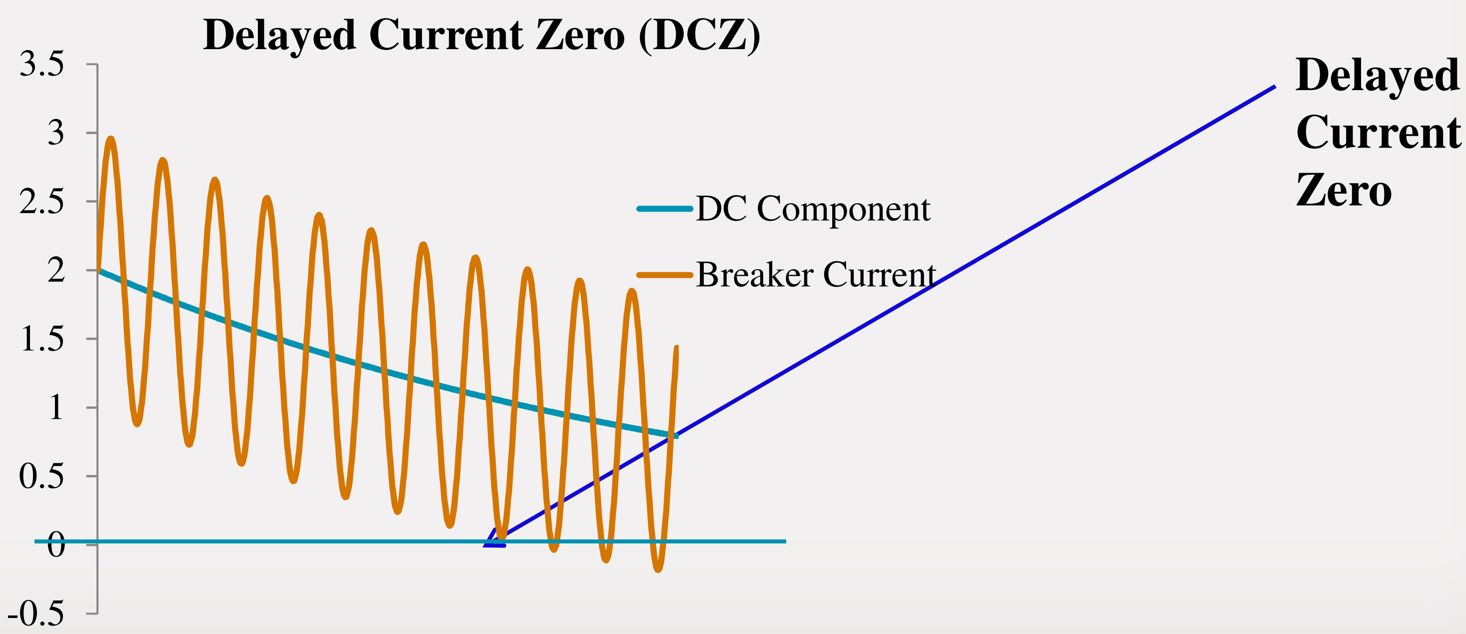
- Maximum DC offset is seen when the line with reactor is switched at voltage zero crossing.
- $\mathbf{I_{BR0} = (1-M)I \, Cos(\omega t) + MI \, e^{-t/\tau}}$

Line Breaker Current Components

- AC sinusoidal wave has a peak value of (1-M)I
- DC component has a value of MI and is exponentially decaying with time constant of τ sec.
- X/R of oil filled reactors are in the range of 600-750; τ can be as high as 2 seconds (~=750/377).
- DC component will decay to less than 2% of the initial value after 4τ time.

Line Breaker Delayed Current Zero

- If AC component peak (1-M)I is greater than DC component MI, AC waveform will always cross current zero axis or else, current zero occurs after a delay.
- If the DC peak MI is greater than (1-M)I, first current zero appears after several cycles

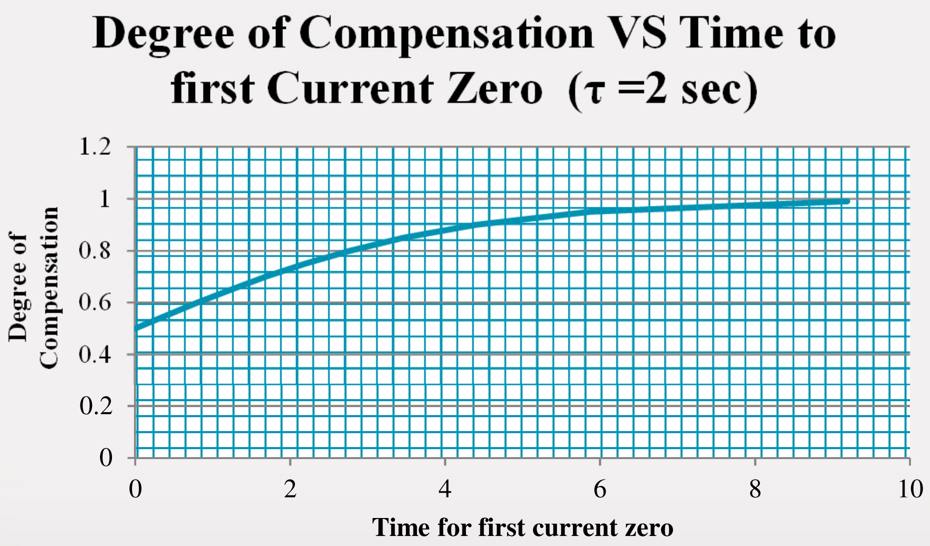


Criterion to Prevent DCZ during Normal Switching

- Boundary Condition: (1-M)I = MI;
- M = 0.5;
- Under normal switching, the degree of compensation, M should not exceed 50% to prevent Delayed Current Zero on breaker current.

Time to first Current Zero

- If the Degree of compensation is greater than 50%, the AC waveform will cross current zero line when the peak equals or exceeds the decayed DC component
- $(1\text{-}M) = M^{*}e^{-t/\tau}$
- Solving for t, $t_{Seconds} = \tau \ln \frac{M}{(1-M)}$



Effect of Inserting resistance in the circuit

- The time constant of DC Component is the overall time constant of the system: ($X_{total}/R_{total)}$)
- If breakers are equipped with pre-insertion resistors (250-400 ohms)
- Overall X/R reduces. DC component decays faster.
- $Z_{Reactor}$ = 3.174 + j2380.49 (50 MVAR, X/R =750)
- Z_{system} = 2.491 + j47.5 (assuming 2500MVA , X/R= 17)
- Without pre-insertion resistor, Z_{total} = 5.665+j2428 (X/R=428)
- Pre-insertion resistance = 400 ohms
- Z_{total} = 405.665 +j2428 (X/R= 6); Time constant: 16ms

Energizing a Faulted line

- Fault location : At the Shunt reactor
- Voltage on B-Phase (PU) for A-G fault:

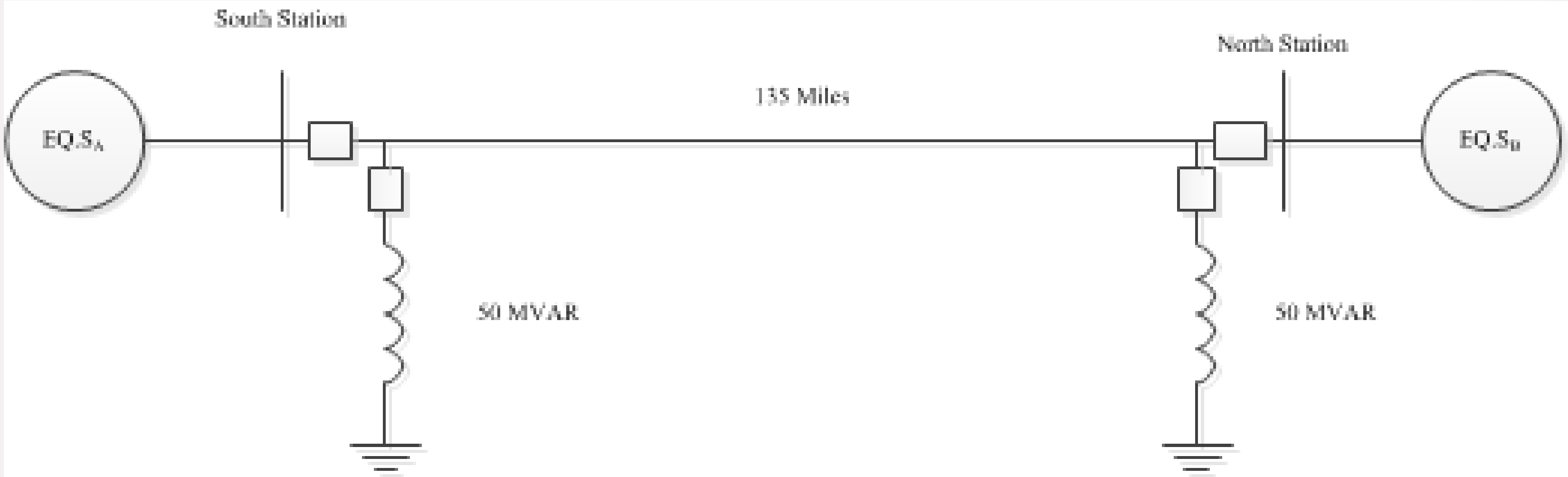
$$|VB| = |e^{j240} - \frac{(k-1)}{(k+2)}|$$, where $K = \frac{Z0}{Z1}$

- B-C-G fault, $|VA| = \frac{(3k)}{(1+2k)}$ PU
- Assuming a value of K =2.8; Voltage rise on unfaulted phases for line to ground fault will be around 1.23 PU and 1.273 PU for double line to ground fault.
- The compensation need to be lower than 50% to prevent DCZ

Mitigation Methods – Control and Protection Considerations

- Energize a line without shunt reactor
- Use a breaker capable of interrupting DC current – Single interrupter SF6 design has very low DC interrupting capability
- Use controlled closing – Has mechanical tolerance limitation
- Use of resistance in the neutral of the reactor bank.
- Use of pre-insertion resistor
- Limit or reduce degree of compensation to less than 50% during line energization or during reclosing
    - Switching issues associated with tripping the reactor during line faults and also during re-energization onto the energized line.
    - Tripping issues for shunt reactor faults

Simulation Results- Simplified System Model

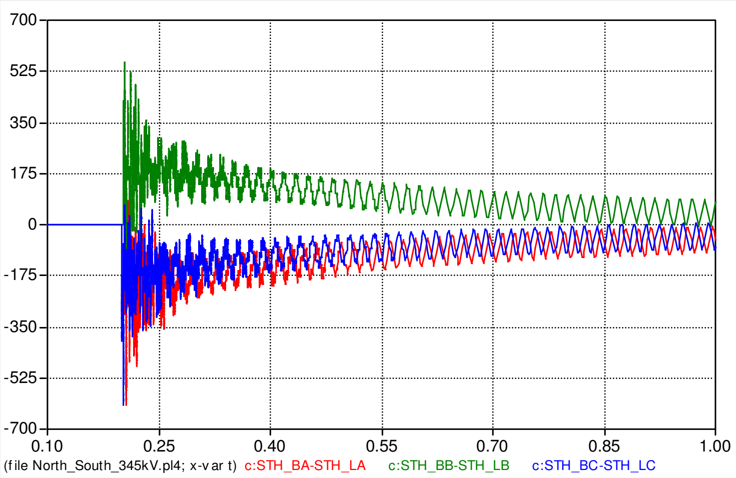


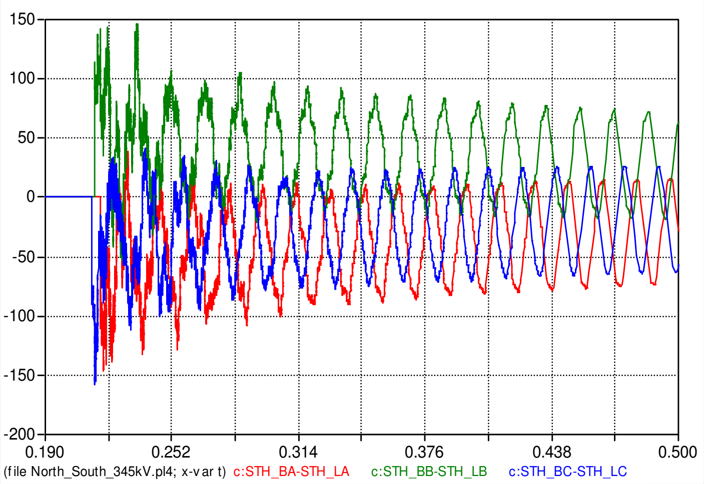
Delayed Current Zero Mitigation Methods

A. Use of pre-insertion resistors

a. With both shunt reactors connected (approx. 86% compensation)

b. With both shunt reactors connected and utilization of 425ohm pre-insertion resistors inserted for 13ms



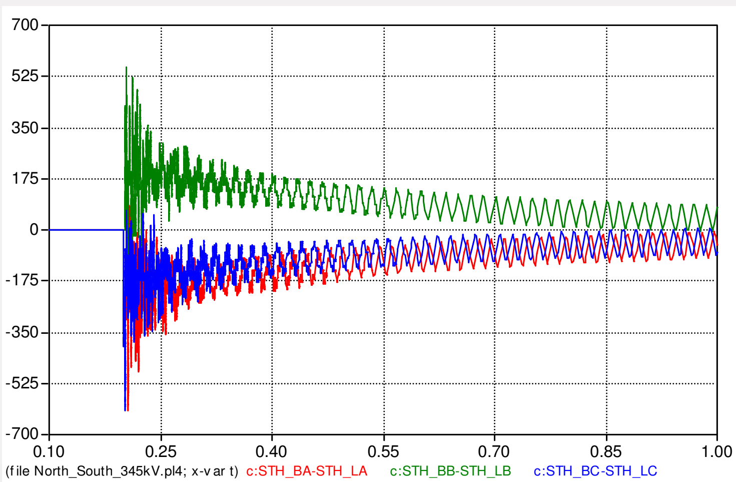


Delayed Current Zero Mitigation Methods

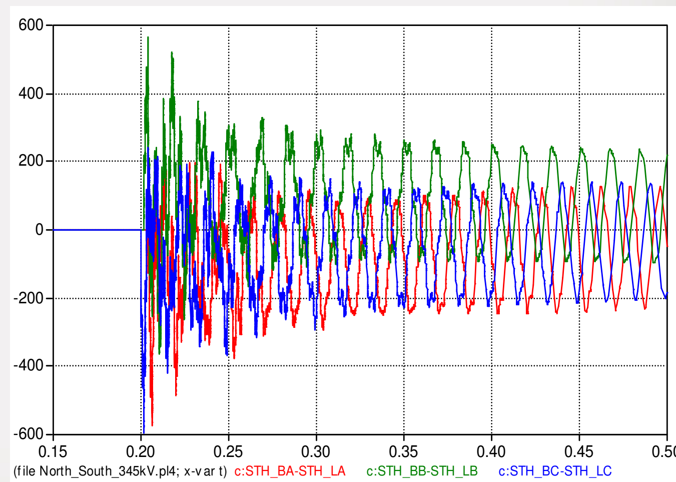
B. Energizing the line with reduced degree of compensation

Line energization cases – Line breaker currents

a. With both shunt reactors connected (approx. 86% compensation)

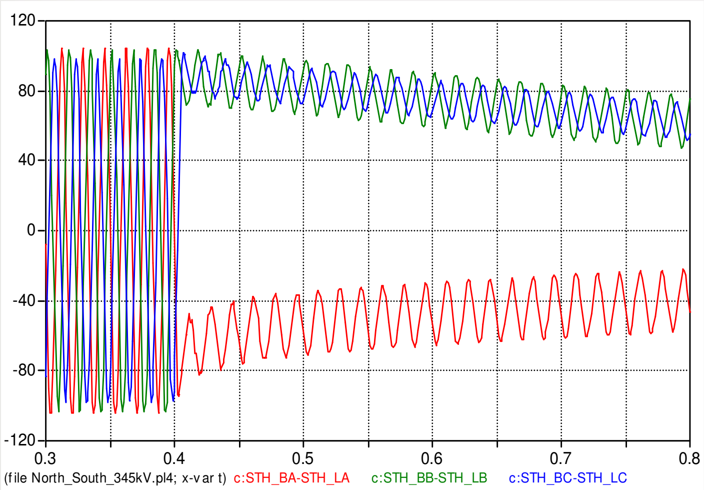


b. With only north end reactor connected

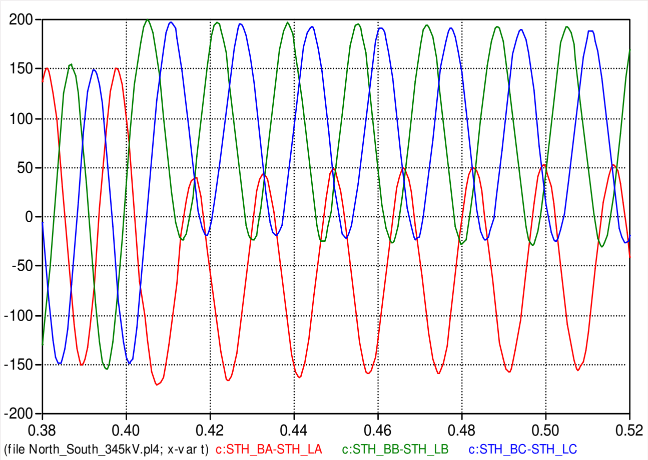


Delayed Current Zero Mitigation Methods

C. Utilization of controlled switching of shunt reactors and the impact of power flow on line breakers

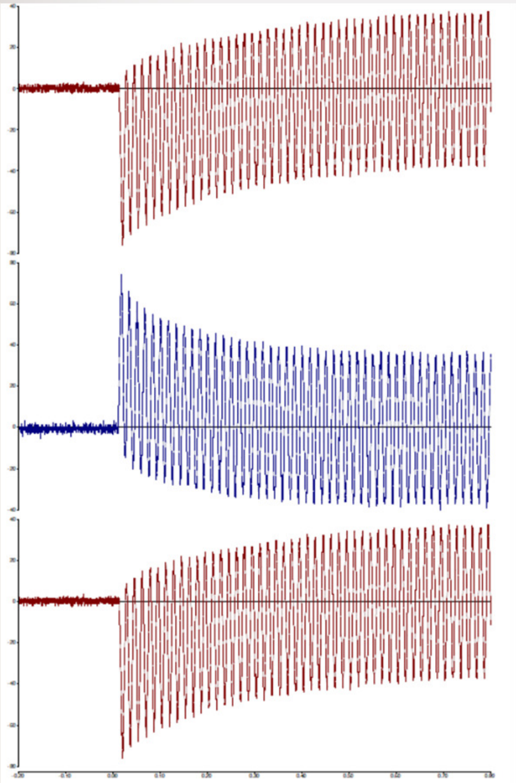


South Substation line breaker current following uncontrolled closing of South line-end reactor with limited power flow on the line

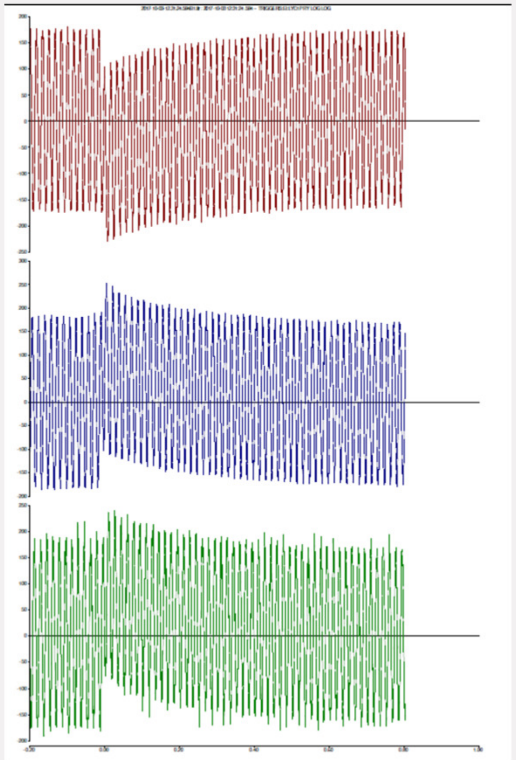


South line end current following energization of South line-end shunt reactor on a closed through transmission line with North line-end reactor connected. Approx. 46 MW are flowing on the line

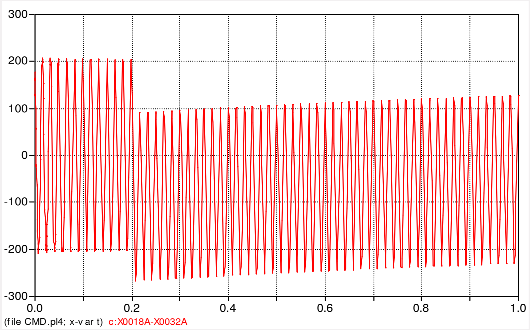
Reactor Energization Field Record



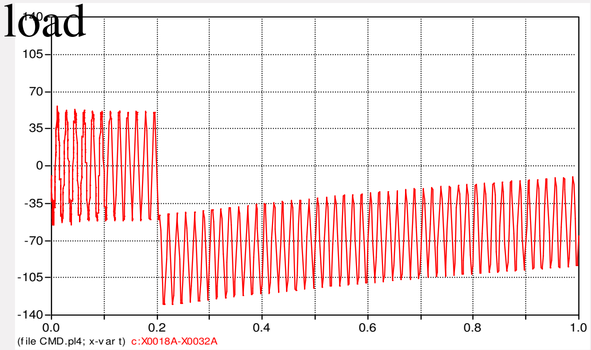
Reactor Currents



Line breaker Currents
With 74 MW load



ATP Simulation -Line breaker Current (A-Ph) with 74 MW load



ATP Simulation -Line breaker Current (A-Ph) with No load

Other Delayed Current Zero Mitigation Methods

- Consider moving some reactors (or some of them) from transmission lines to substation buses

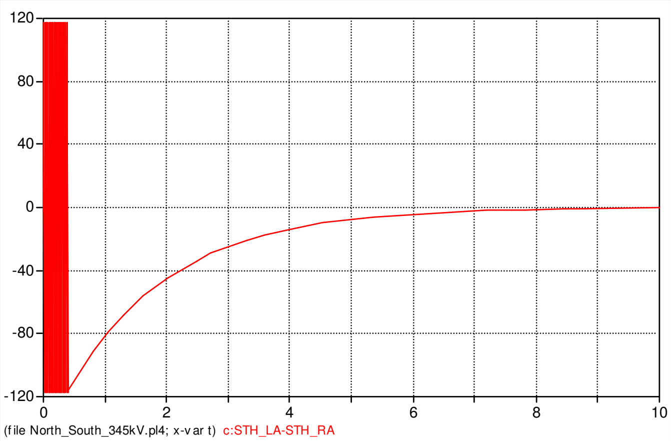
Tripping and reclosing considerations for shunt compensated lines

First, consider a SLG fault on the line

Reactor current following a SLG fault:

- A-Phase to ground fault is considered to occur at A-Phase voltage zero crossing.
- Shunt reactor current takes several cycles to decay to zero;

  τ~ 1.68s

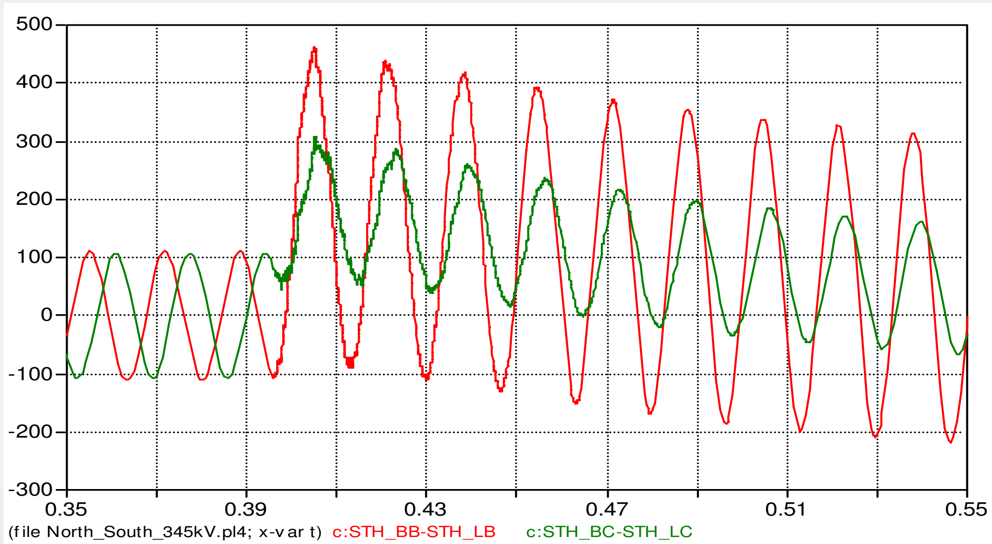


Tripping and reclosing considerations for shunt compensated lines

- For faults on transmission lines, only the line breakers should be tripped.
- It's recommended to disable high-speed reclosing. For lines with more that 50% compensation, some shunt reactors may need to be switched out, after the shunt reactor current decays to zero, before re-energization of the line. However, this may take as long as 4*1.68 ~ 7 seconds.
- Radial energization of the line, with reduced compensation is suggested. Remote breaker may synch-close after a definite time delay

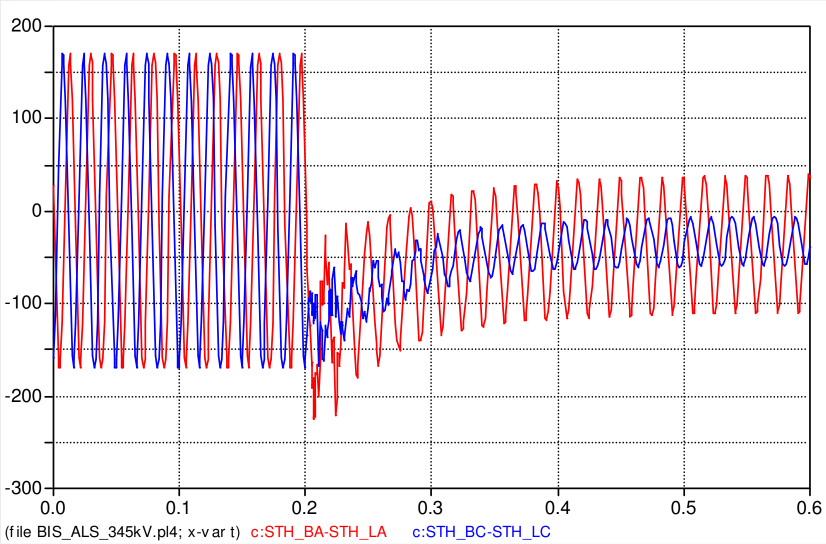
Tripping and reclosing considerations for shunt compensated lines

- Delaying line breaker tripping for transmission line faults is suggested – allows for appearance of current zero crossing for faults (during light load periods) on lines with more than 50% compensation. South line-end currents are shown below for close-in A-G fault

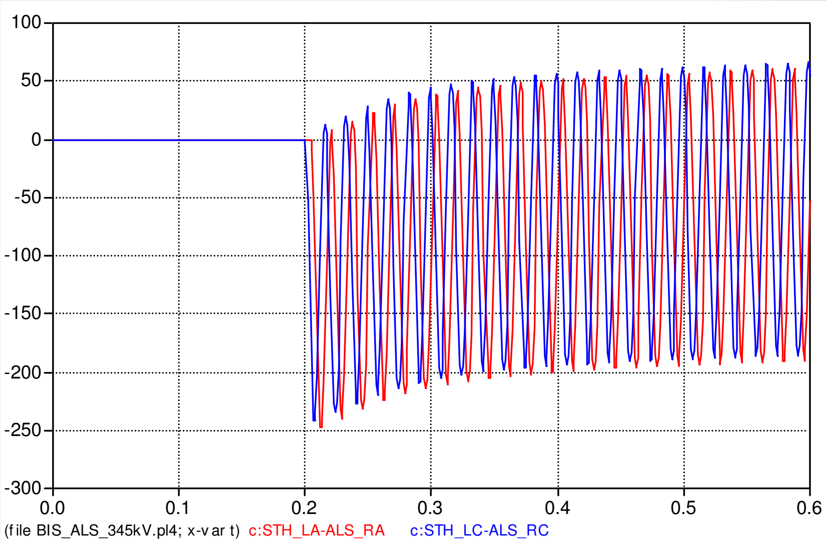


Tripping for shunt reactor faults

- Trip only the shunt reactor for reactor faults and not the line especially during shunt reactor switching onto the energized line



Line breaker currents on unfaulted phases



Unfaulted phase reactor currents

Conclusions

A. On line energization to prevent DCZ

- If shunt reactor(s) on the line is not required to limit open end voltage to acceptable level, energize the line without shunt Reactors.
- Keep shunt compensation below 50% during line energization.
- Energize the line through breakers equipped with pre-insertion resistors that provide enough damping to produce current zeros within breaker interrupting time. This is dependent on the resistor value and duration of insertion. It may not work under all the cases if the degree of compensation is close to 100%.

Conclusions

B. On Shunt reactor energization onto energized lines, to prevent DCZ

- Switch shunt reactors less than 50% of the total charging current.
- Switch shunt reactor at voltage maximum point on the wave.
- Switch shunt reactors if the minimum load on the line, in MW exceeds reactor MVAR rating.

Conclusions

C. Tripping for line faults

- Trip only the line breakers and not shunt reactors.
- Shunt reactors need to be tripped only after several seconds delay to allow full decay of reactor current on the faulted phase.
- Total interrupting time of faults on lines with shunt compensation greater than 50% may need to be at least few cycles to allow presence of current zeros on healthy phase(s) during faults. This is dependent on the zero sequence currents flowing on the healthy phases or the minimum load on the healthy phases.

Conclusions

D. Tripping for shunt reactor faults
   - Trip only the shunt reactors

Conclusions

E. Reclosing on Lines:

- Instantaneous reclose is disabled on lines where shunt reactor switching is required to reduce the degree of compensation.
- Time delay reclose is enabled after the reactor is switched out.
- Synch-check reclosing at the other end after energizing the line may generate offsets on the currents. DC offset is dependent on the load picked up after restoration.

Research topics

- Mechanisms to interrupt DC
- Breakers with longer Pre-insertion times
- Controls to insert reactors immediately following simultaneous closing of line breakers at both ends.

Questions