Transient Recovery Voltage (TRV) and Rate of Rise of Recovery Voltage (RRRV) of Line Circuit Breakers in Over Compensated Transmission Lines

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INTERNATIONAL COUNCIL
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Introduction:

This paper will focus on the unique effects over compensation of transmission lines has on the Transient Recovery Voltage (TRV) and Rate of Rise of Recovery Voltage (RRRV) of Line Circuit Breakers and possible mitigation techniques.

The findings of this paper are based on time domain simulations performed on a sample over compensated system with varying degrees of compensation levels to demonstrate how the level of compensation affects the level TRV and RRRV.

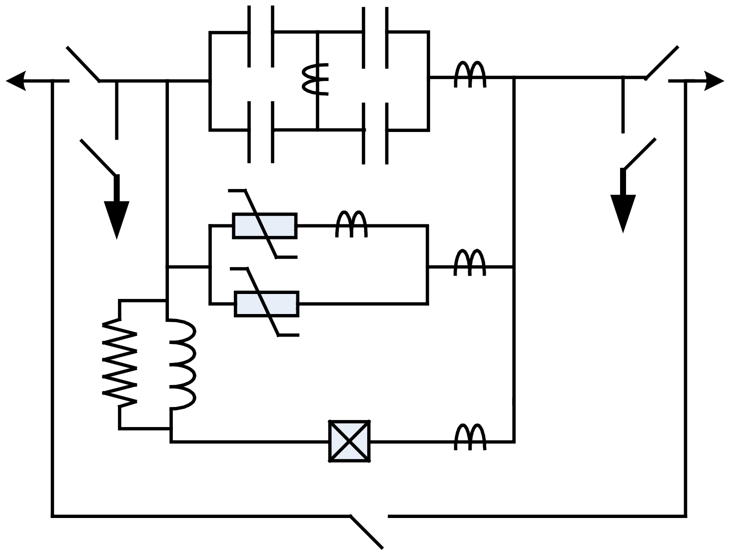
As the grid of the future is becoming more complex, and many countries have issues with adding extra overhead transmission lines, a solution to add series compensation to the existing lines has become a necessity. Series Capacitors allow Transmission System Owner/Operator to increase the amount of power transmitted without adding additional lines. The series capacitors also allows the system to be more stable.

Series Compensation however does have certain negative effects on the transmission line where it does increase the Transient Recovery Voltage (TRV) and also the Rate of Rise of Recovery Voltage (RRRV).

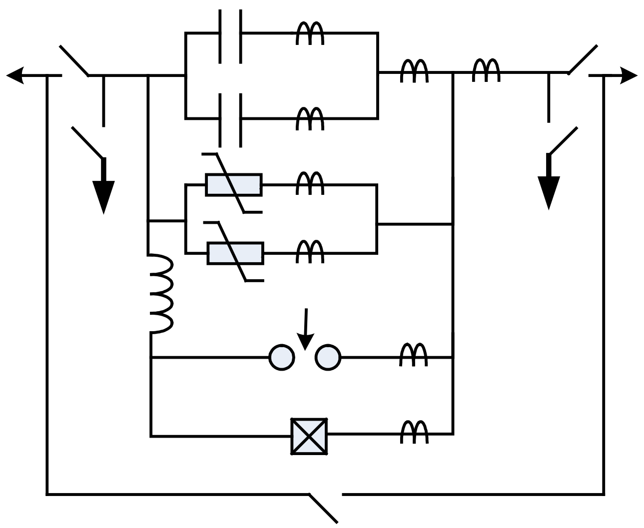
Depending on the level of compensation selected Series capacitors increase the impact of TRV on Circuit Breakers. Over compensation of lines while needed, can make TRV impact challenging.

Certain mitigation techniques can be applied to overcome these issues. This paper deals with TRV, RRRV and the results of a system study on this phenomenon.

Different Designs Compensation More Than 60 % Or May Be > 100 %



Gapless



Triggered Gap

Overcompensation:

Degree of compensation defined in terms of the capacitive reactance of the S/C compared to the inductive reactance of the line.

A simple transmission line with series compensation is presented in figure 1.

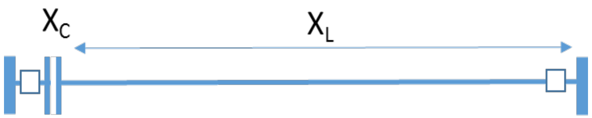


Figure 1

The degree of compensation (KC) in percent is the ratio of the capacitor reactance over line reactance as shown in equation (1.1).

$$K_C = \frac{X_C}{X_L} * 100$$

Eq 1.1

Where:

X_c: Total capacitive series reactance installed in the line from one line end breaker to the next line end breaker

X_L: Total inductive line reactance from one line end breaker to the next line end breaker

Transmission line overcompensated when compensation degree KC is greater than 100% .

The Transient Recovery Voltage (TRV) is:

- Voltage that appears between the contacts of the circuit breaker after arc extinction during opening process while clearing a fault.
- The Rate of Rise of Recovery Voltage (RRRV) is defined as peak transient recovery voltage divided by the total time from zero voltage to peak voltage.
- Level of TRV and the RRRV are key factors in determining whether the fault can be cleared successfully

Transient Recovery Voltage:

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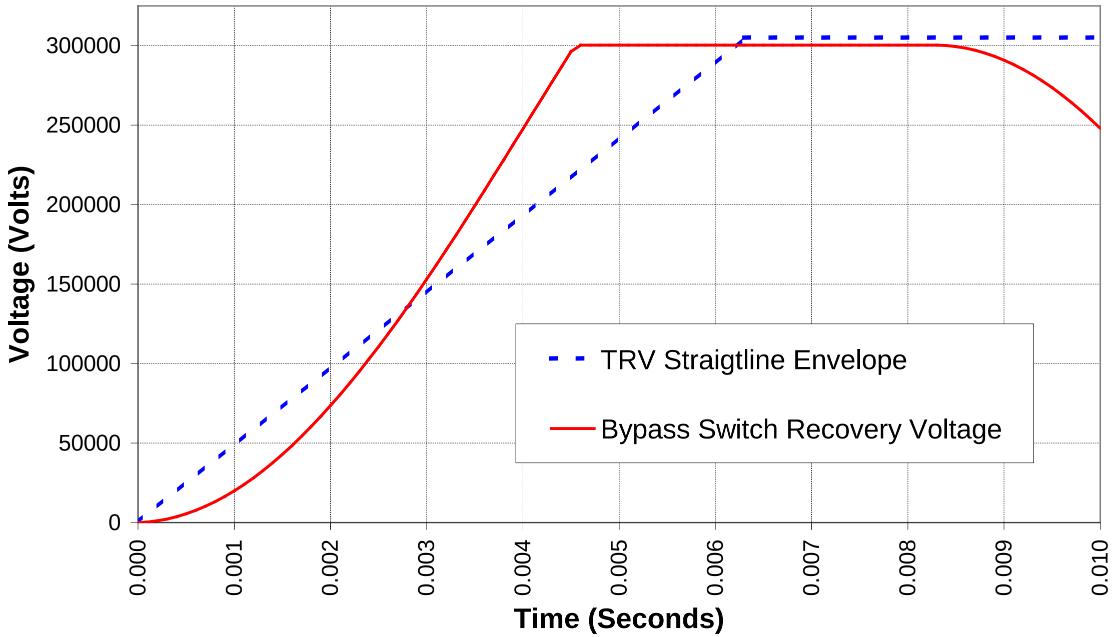
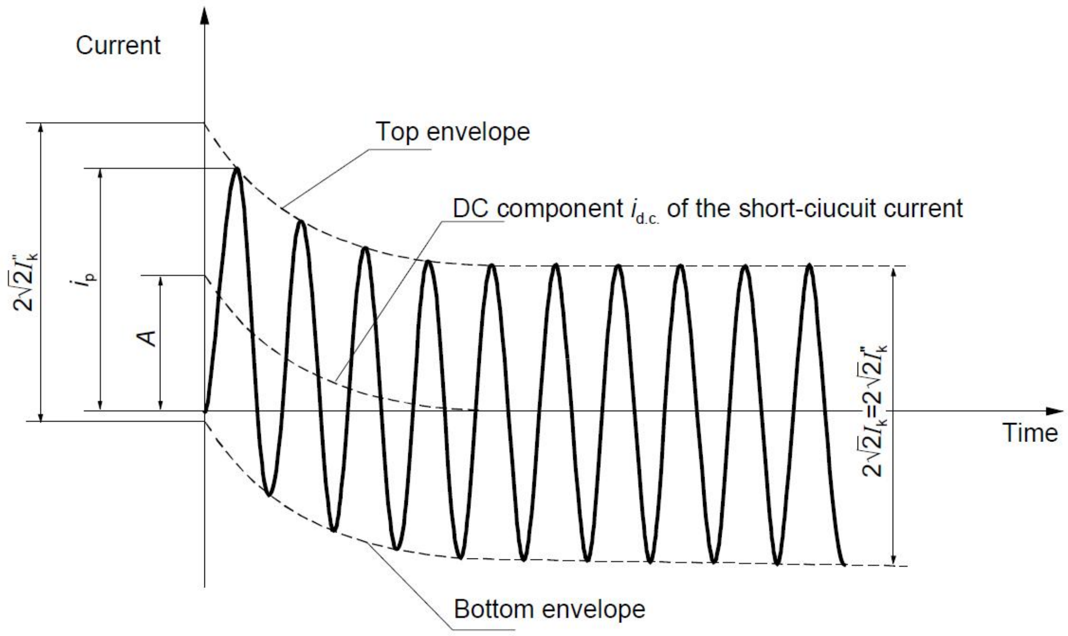
The addition of series capacitors in a transmission line may affect the Transient Recovery Voltage (TRV) of Line Circuit Breakers (LCB) in multiple ways:

- During fault, series capacitor compensates the transmission line reactance,
- Lowering the overall fault impedance
- Increasing the fault current flowing through the line. Increases the voltage rise from faulted end to far end of line, changing line Susceptance to higher voltage levels just before current break, increasing the TRV on the line-side of the LCB.
- The LCB will normally break current at a zero-current crossing,
    - If S/C not bypassed, will leave trapped DC charge on the S/C bank which will offset the line-side TRV by the amount of that trapped voltage, increasing the peak TRV across the opening contacts of the LCB.
- The level of series compensation, expressed as a percentage of the overall line reactance, affects the level of trapped DC charge.
    - Higher compensation level, higher level of trapped DC charge thus higher TRV.

TRV Recover Voltage Of Bypass Breaker



DC Offset During Faults



Study system and methodology:

- EHV transmission lines stretch over hundreds of kilometres.
  - In China they reach up to 2000 km.
  - Due to finite wave traveling times, **distinct voltage shapes** such as TRV may travel forth and back a line, producing a harmonic /subharmonic oscillation on its own (e.g. trapped line charge).
- Representing S/C as just a capacitor, is over simplifying the actual details,
  - it can be various types eg FSC or TPSC with all methods being equipped with further protective devices like MOV's, a spark gap and a bypass breaker.
  - As TRV occurs during the process of fault clearing, most of these protective devices have already responded to the fault situation – depending on level and location of fault.
  - Response has tremendous impact on the TRV levels: e.g. a bypassed S/C does not interact with the harmonics in the circuit.
- Fault sequence:
  - Time of fault occurring, instantaneous voltages and currents in the system prior to the fault need to be considered.
  - Fault location also influences the fault currents and the contributing currents across the line breakers, therefore effects TRV.
  - Important to consider the fault type, i.e. single-phase-to ground, three-phase, phase-to-phase with or without ground.
  - Multiple types of fault development can occur, e.g. a single-phase fault that evolves into a three phase fault.
  - Duration of the fault before the circuit breaker contacts start opening also have an effect.

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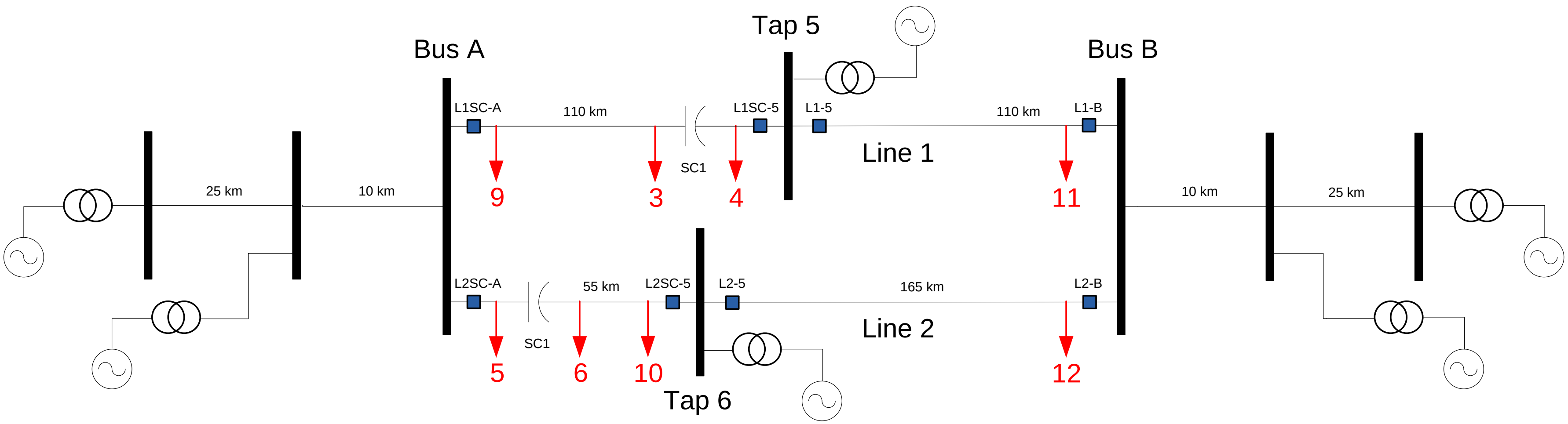

Sample of results and simulations:

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- A sample of the simulations results is below. From the table and figures, as the level of compensation is increased, the peak TRV also increased.
- It can also be seen is that the average RRRV is relatively consistent as the level of compensation is increased.

Breaker	Compensation Level	Max TRV (kVpk)
L1SC-A	0%	396.8
	60%	648.9
	100%	777.5
	140%	931.9
L1SC-5	0%	374.0
	60%	519.0
	100%	550.1
	140%	831.4
L2SC-A	0%	467.4
	120%	755.3
	200%	922.8
	280%	1001.1
L2SC-5	0%	356.1
	120%	455.7
	200%	626.8
	280%	797.3

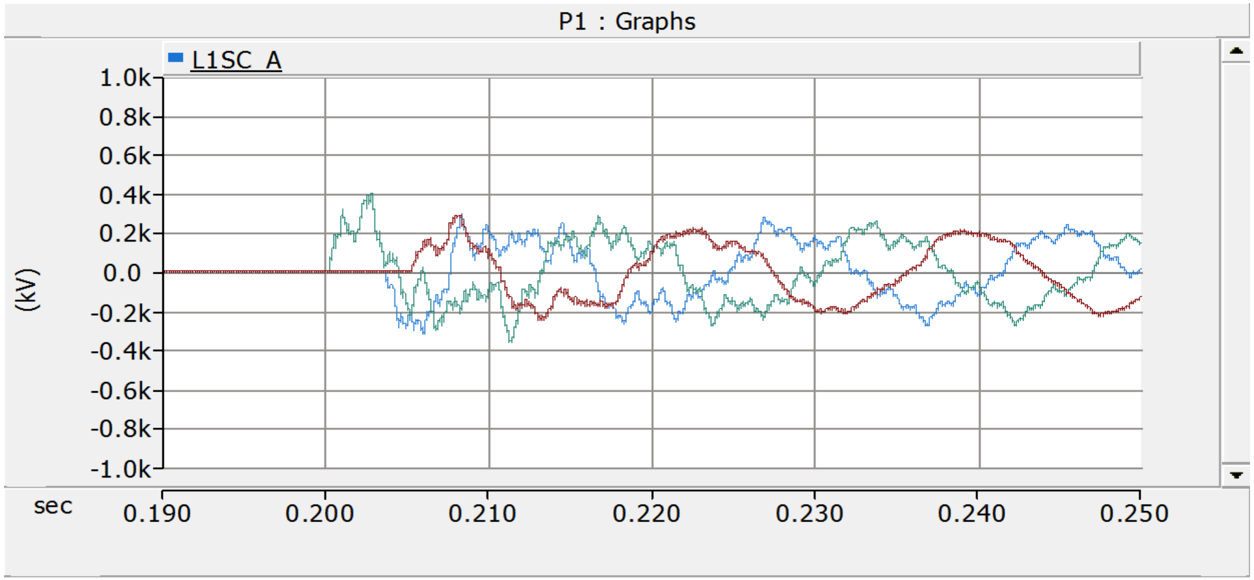


***Figure 02 –** L1SC-A TRV Plot – 0% Compensation*

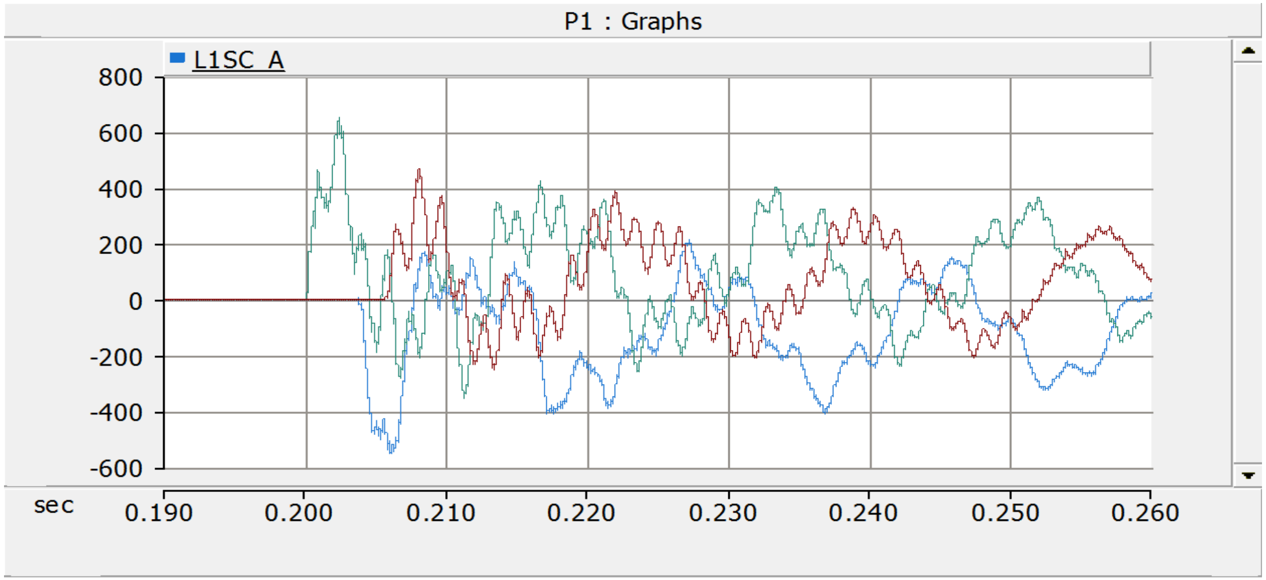


***Figure 03 –** L1SC-A TRV Plot – 60% Compensation*

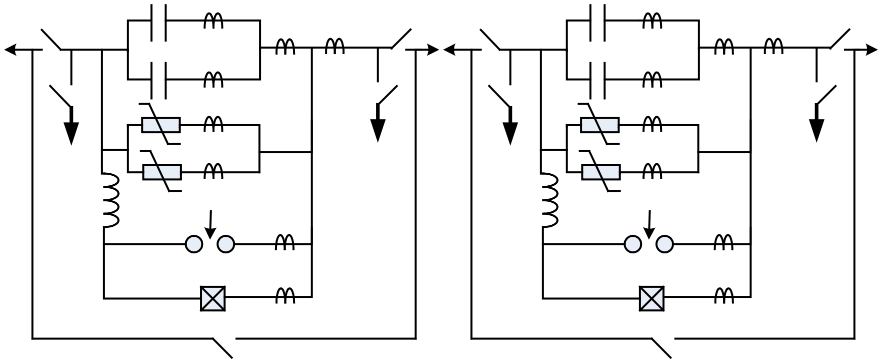
Recommendations and Mitigation:

1. **Fast bypass of SC**
   - When fault detected by the protection system, a command to the CB to open and simultaneously to the SC equipment to perform a fast SC bypass operation.
   - Upon receiving the bypass command, SC gap would be triggered to perform the bypass – this would occur if the voltage between Gap contacts are high enough.
   - In the event of bypassing the SC through GAP triggering TRV caused by capacitor impact can be reduced.
   - This measure is only effective if the fault is large or close to the SC banks.

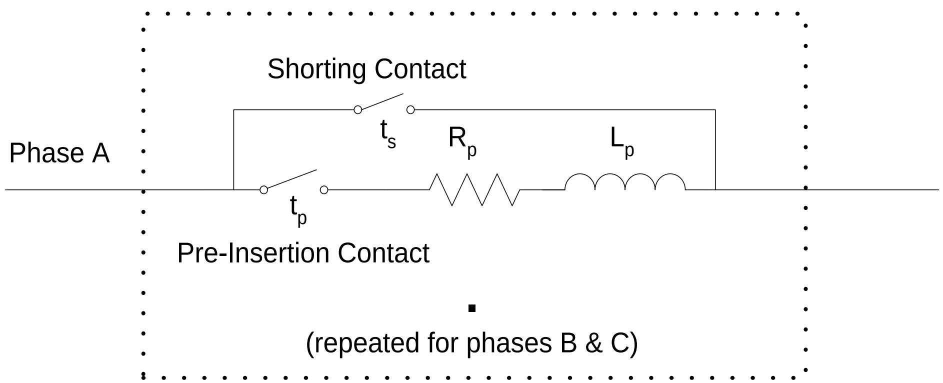
2. **Reducing the degree of Compensation**
   - Calculations and tests shows that reducing degree of compensation will restrict the peak value of TRV.
   - One example of this during opening of a single phase to ground fault at Beijingdong Substation, reducing compensation from 40 % to 25 % and use of the fast bypass measure, the TRV peak at Ximeng CB was reduced from 2440kV to 2171kV.
   - The breaking current is below 1/4 of the rated CB breaking current of 50 kA_{rms} and the RRRV is below 1.54kV/µs.

Recommendations and Mitigation:

- Dividing the SC into two parts – one SC at every terminal

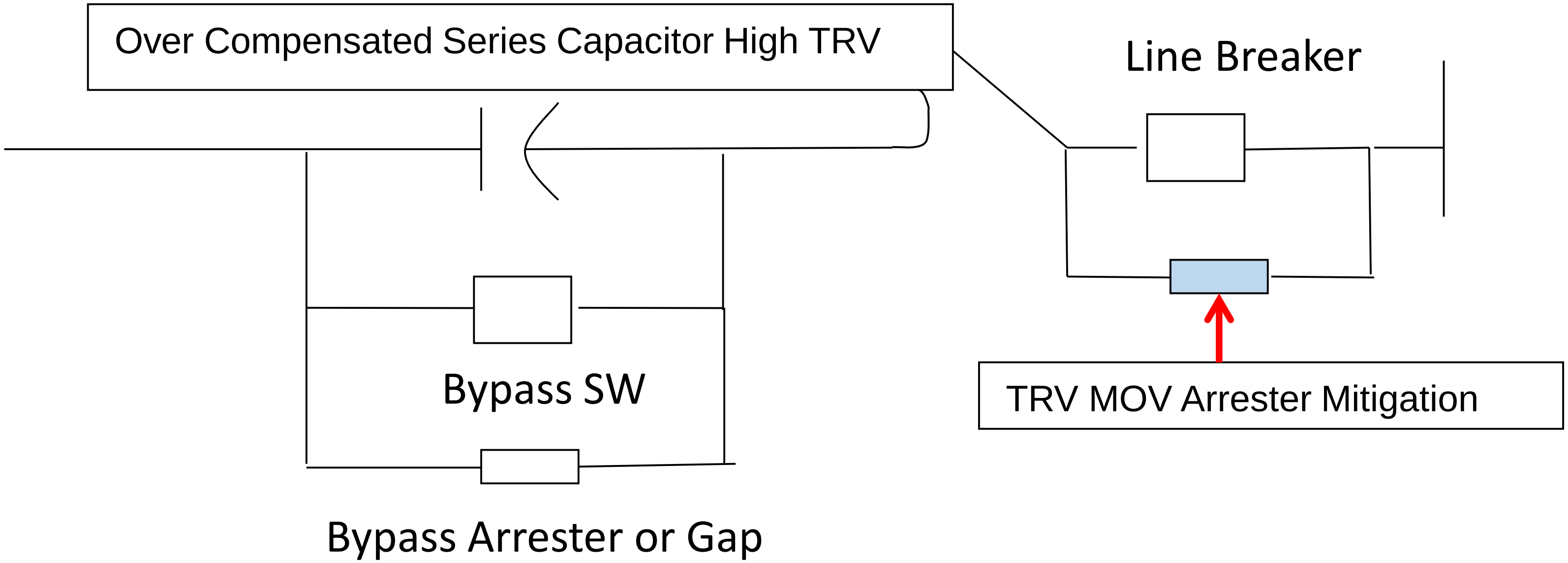


- Use of opening resistors on the CB



Recommendations and Mitigation:

MOV and CB in Parallel



Recommendations and Mitigation:

Changing test requirements of CB TRV amplitude

- Current Chinese and IEC EHV/UHV CB standard, requires CB's to withstand a TRV peak value of 2.5 p.u. and RRRV of 1.54 kV/μs when interrupting 25 % of rated breaking current. For SC line CB's, the TRV peak value across CB may exceed 2.5 p.u. during certain fault conditions.
- Some CB manufactures designed CB's with higher TRV withstand capability and applied it. Eg. in Turkey some CB's TRV capability are enhanced to withstand the TRV peak value of 3.2 p.u. and RRRV of 1.54 kV/μs for breaking current of 12.5 kA_{rms}. In Canada's 735 kV SC system, CB's are able to withstand 2.8 p.u. TRV peak value in order to satisfy the systems operational requirements, which is higher than IEC standards. In western Canada's 500 kV system, several 500 kV SC line CB's can withstand TRV peak value of 3.3 p.u. for breaking current of 6 kA_{rms}.
- For the Chinese UHV SC lines CB's, when clearing a single line to ground fault, the maximum TRV peak value is 2.5 p.u., RRRV is 1.3 kV/μs and steady state breaking current is less than 8.5 kA_{rms}.
- With reference to the above simulation results, the higher TRV test condition for EHV CB's are suggested for CB's used in series compensated transmission lines.

Conclusions and future work:

As the level of series compensation increases on a given transmission line segment the severity of the TRV also increases proportionally and may exceed the circuit breaker capability leading to damage or failure of the breaker and possibly further damage to the system. Mitigation approaches are available that can successfully limit TRV.

Breaking current will also increase with the increase in degree of compensation. This all needs to be included in the design of the series compensated system

Extensive research on this subject has been performed by Hydro Quebec and suggestions were made to included modified Class B circuit breaker TRV specifications w.r.t. test duties for circuit breakers used in series compensated lines.

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