21, rue d'Artois, F-75008 PARIS
http : //www.cigre.org

CIGRE US National Committee
2017 Grid of the Future Symposium

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

P. DATKA
GE Energy
USA

K. NARENDRA
ERL PPTech
Canada

H. ERIKSSON
Svenska Kraftnat
Sweden

A. HARJULA
Fingrid
Finland

R. LE ROUX
ESB International
Ireland

S. SRIVASTAVA
ABB
India

P. MARKEN
GE Energy
USA

SUMMARY

As the grid of the future is becoming more complex, and many countries have issues with adding extra overhead transmission lines, a solution are to add series compensation to the existing lines. This allows the Transmission System Owner / Operator to increase the amount of power transmitted without adding additional lines. It 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 it increases the effect of TRV on Circuit Breakers. Where over compensation are selected, this might make this effect even worse.

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.

KEYWORDS

Series Compensation, Transient Recovery Voltage (TRV), Rate of Rise of Recovery Voltage (RRRV), Over compensation, Mitigation

robert.leroux@esbi.ie

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.

Transient Recovery Voltage:

The Transient Recovery Voltage (TRV) is the 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.

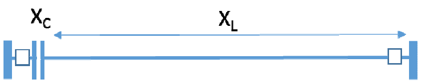
The basic function of a circuit breaker is to clear system faults. The Transient Recovery Voltage (TRV) is the voltage that appears between the contacts of the circuit breaker after arc extinction during opening process while clearing a fault. The Rate of Rise of Recovery Voltage (RRRV) is defined as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

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 a fault, the series capacitor compensates the transmission line reactance, lowering the overall fault impedance and increasing the fault current flowing through the line. This in turn increases the voltage rise from the faulted end to the far end of the line, charging the 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, and if the series capacitor is not bypassed this will leave a trapped DC charge on the series capacitor 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, typically expressed as a percentage of the overall line reactance, affects the level of trapped DC charge. The higher the compensation level, typically the higher the level of trapped DC charge and therefore the higher the TRV. When selecting the level of level of compensation this a key parameter that should be considered in the overall system and equipment planning stage.

Overcompensation:

The degree of compensation is defined in terms of the capacitive reactance of the series capacitor compared to the inductive reactance of the line. A simple transmission line with series compensation is presented in figure X.



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

$$K_C = \frac{X_C}{X_L} * 100 \qquad (1.1)$$

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

A transmission line is overcompensated when the compensation degree KC is greater than 100% as shown in equation (1.1).

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.

Study system and methodology:

- EHV transmission lines typically stretch over hundreds of kilometres. In China some of these lines 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 Series Compensation as just a capacitor, is over simplifying the actual details, as 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. Their response has a tremendous impact on the TRV levels: e.g. a bypassed series capacitor 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. The fault location also influences the fault currents and the contributing currents across the line breakers, and therefore has an effect on TRV. At the same time it is 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.
- A very important effect is whether the faulted line is interrupted in all three phases or in only one phase. Opening of the line breakers at one substation may not start at exactly the same time as at the other terminal. A difference of milliseconds may result because of different protection equipment, different types / manufacturers of breakers and due to communication signals – propagation delay etc.
- Faults on EHV transmission systems are seldom a solid metal connection, but a fault that results in arcing occurring – breakdown of insulation or tracking due to partial discharge etc. The arc will dissipate energy (I^2t) and through its nature adds resistive damping to high frequency oscillations. The arc produced in the interrupter chamber also contributes to damping, and correct modelling / representation of the arc will have an impact on the TRV levels experienced by the CB.
- When the fault occurs the complete power system around the fault is affected and in a state of transient oscillation with the result that when isolation of the fault has taken place, oscillations will continue until a steady post-fault state is gained. As TRV occurs across the line breakers, the level of TRV will be affected by these system

> oscillations. Thus, it is important to consider the power system in the vicinity for analysing the TRV effect on transmission line breaker.

A generic series compensation transmission system was developed in PSCAD to study the impact of the compensation degree on the TRV after the fault clearance. Three compensation levels, in addition to no compensation, were studied in the system. For each compensation level, 3-phase faults were created at different locations on the line and the peak TRV recorded for the affected line circuit breakers after clearing.

For all compensation levels the per unit protective level voltage of the MOVs was held constant resulting in higher protective level voltages as the compensation level was increased. For all cases the series capacitors were prevented from bypassing. This was done to keep the transient conditions consistent across all simulations.

The study system is shown in the following figure:

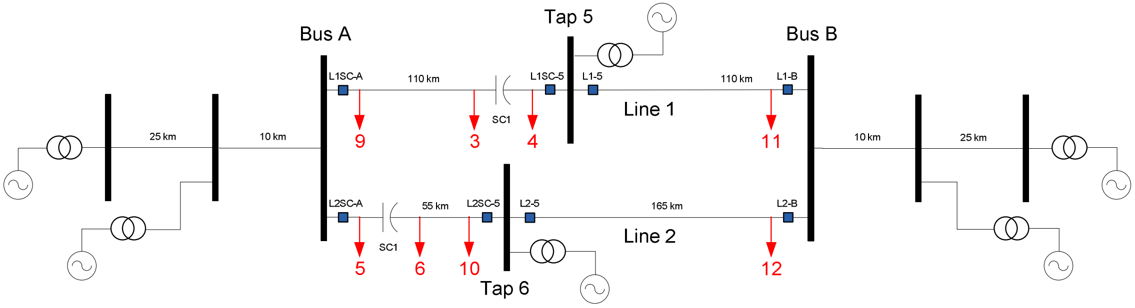


Figure 01 *– Fault Location and Line Circuit Breaker (LCB) Identification*

Sample of results and simulations:

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

Table 01 *– Worst Case TRV Results*

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
L**2**SC-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*

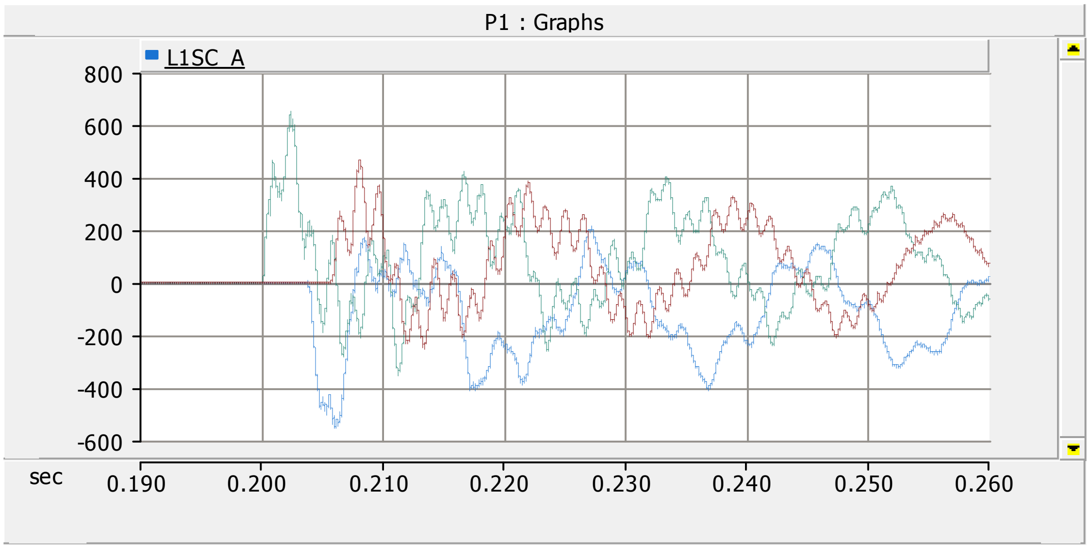


Figure 03 – *L1SC-A TRV Plot – 60% Compensation*

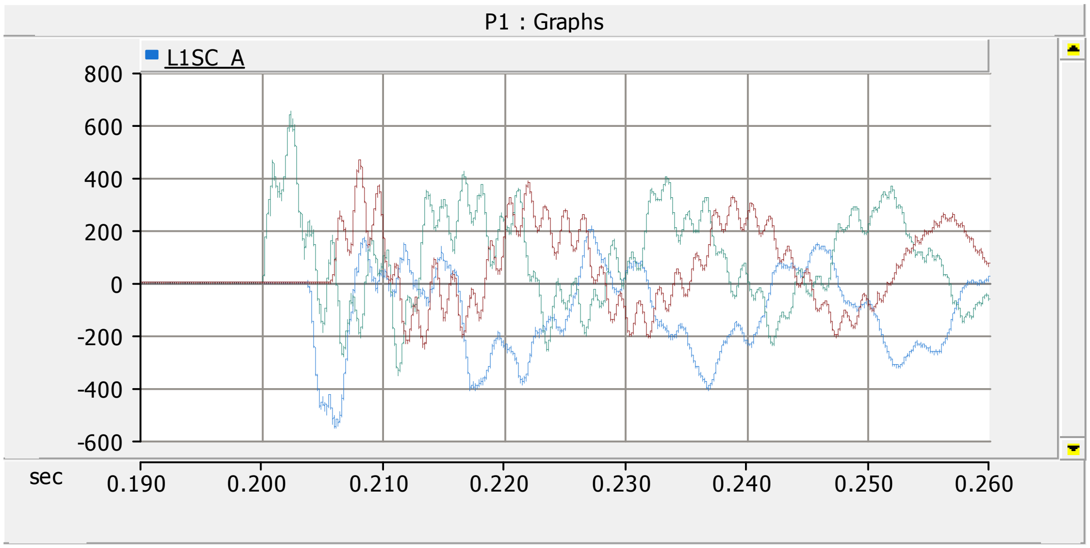


***Figure 04** – L1SC-A TRV Plot – 100% Compensation*

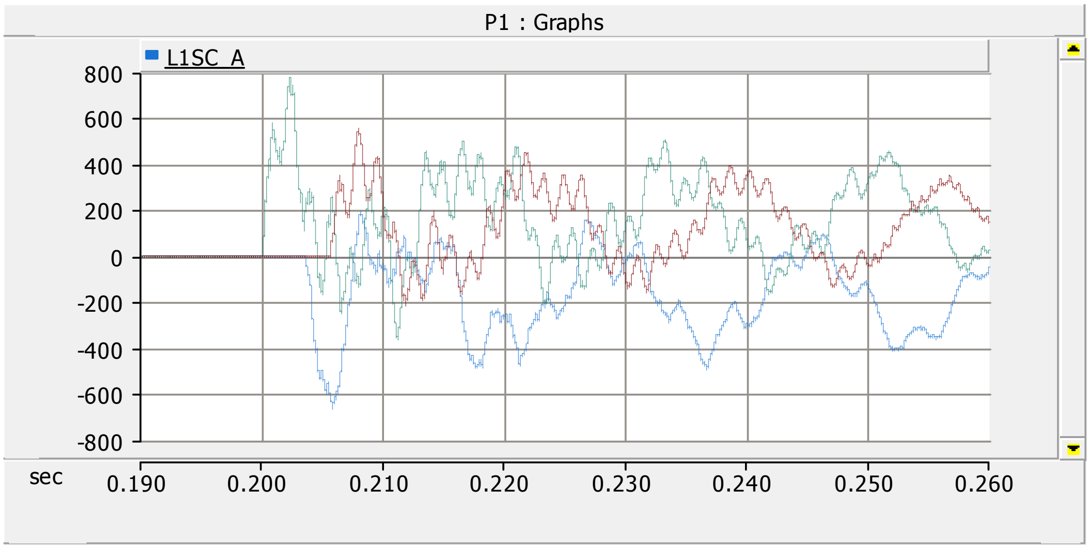
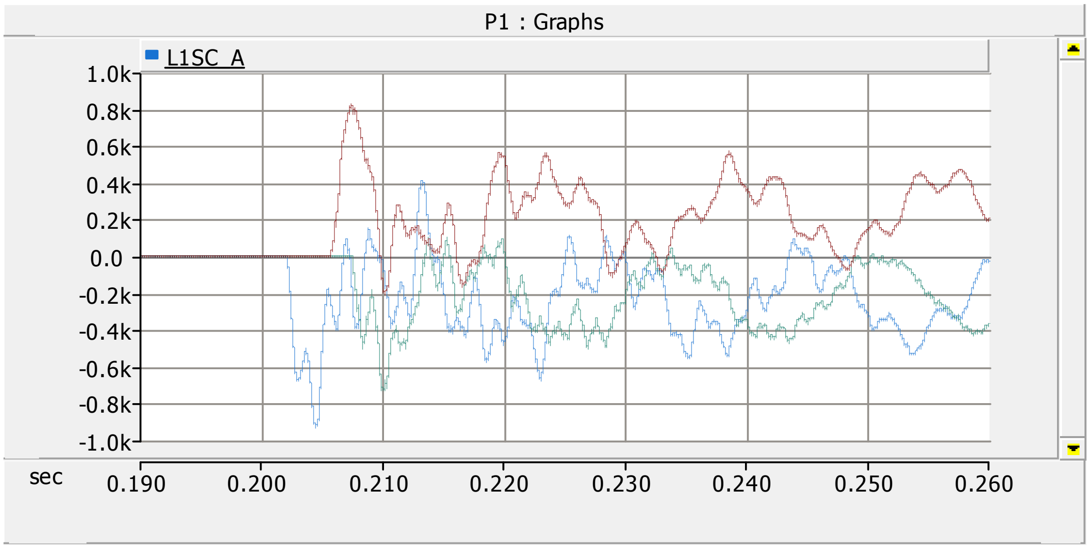


***Figure 05** – L1SC-A TRV Plot – 140% Compensation*



Recommendations and Mitigation:

- **Fast bypass of SC**
  - When a fault is 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.
- **Reducing the degree of Compensation**
  - Calculations and tests have shown that reducing the 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.

- **Dividing the SC into two parts – one SC at every terminal**
    - Because the remaining charge voltage of SC capacitor increases TRV peak value, implementing measures to reduce the service level voltage of SC capacitor can help to reduce the TRV level. This is achieved by splitting the line into two lines and building the SC at the two line terminals. Test result have shown that the worst case condition is when a single phase to ground fault occurs somewhere along the line, the maximum TRV peak of the CB would be up to 2.127 MV while the breaking current would be only ¼ of CB rated breaking current of 50 kA_{rms}. RRRV is below the level of 1.54 kV/µs. Thus, in a situation where land is not an issue – like in China, having the SC at the two line ends would reduce the TRV level.
- **Use of opening resistors on the CB**
    - With resistors having a damping effect, the use of CB's with opening resistors will help reduce TRV peak value over the CB contacts. Application of a 600 Ω opening resistor on the Chinese 1100 kV line CB's, the TRV peak between main and auxiliary contacts were limited to 1.93 p.u. and 1.58 p.u. respectively while clearing a single phase to ground fault. Cost and reliability of the CB with opening resistor is a factor and should be considered. Research have also shown that TRV over the auxiliary contact may in certain cases be very high. TRV for various fault conditions like clearing a terminal fault, long-line fault or close-in fault or out of phase fault have to be analysed.
- **MOV and CB in parallel**
    - Turkey adopted the measure of having CB and MOV in parallel in 1995 on their 420 kV system. This principle was analysed while clearing a single line to ground fault on the Chinese UHC SC line. When applying a 1.85 p.u. MOV with the CB, the TRV peak is limited to 2.2 MV where 1 p.u.= 1.1 MV.
    - During extreme system conditions such as out of phase conditions, the energy to be absorbed by the MOV paralleled with CB may be very large. To solve this may add to the complexity of the system, but can be achieved by co-ordination between CB disconnectors.
- **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.

BIBLIOGRAPHY

[1] Cigre TB336 Changing Network Conditions and System Requirements Part II, Impact of long distance transmission on HV Equipment – pp 38-40, 105-107

[2] AJF Keri et al, ‘ Improving Transmission System Performance using Controlled Series Capacitors’. Cigre session 1992 14/37/38-07

[3] TRV Analysis in 765 kV model network wit Series Capacitor A3-12 WG28

[4] B Khodabakchian et al ‘TRV and non-zero crossing phenomenon in Hydro-Quebec’s projected 735 kV series compensated system’ Cigre sesión 13-303, 1992