Transient Recovery Voltage Analysis on a Series Power Flow Control Device

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***Abstract*-- In the frame of the Seventh Framework Program, TWENTIES project [1], it´s being developed to demonstrate by early 2014 through real life, large scale demonstrations, the benefits and impacts of several critical technologies required to improve the pan-European transmission network, thus giving Europe a capability of responding to the increasing share of renewables in its energy mix by 2020 and beyond, while keeping its present level of reliability performance.**

In this context, Red Eléctrica de España and ABB are willing to install equipment for the power flow control in a 220 kV overhead line in order to facilitate the power injection generated by renewable sources. The device under study comprises, for each phase, three reactors connected in series each one equipped with a parallel circuit-breaker. With the aim to insert the desired impedance in series with the line, each set of circuit-breaker-reactor forms a step of reactance which can be independently included or excluded in varied combinations.

Since the addition of series inductive elements to the network can alter the transient recovery voltage characteristics of circuit breakers in the vicinity of the same reactors, the rate of rise of the recovery voltage (RRRV) may increase to the extent that it could exceed the allowable limits for successful breaker operation during faults. If the above mentioned limits are violated, it is necessary to find out appropriate mitigation methods to address the issue. Investigation of the TRV across the circuit-breakers, with and without the proposed device were carried out. This permitted to identify the impact of adding the device on TRVs across the breakers.

***Keywords*: TRV, EMTP, Series reactors, RRRV, Circuit-breaker, Terminal Fault, Short-line fault.**

I. Preparation of the Final Manuscript

THE recovery voltage is the voltage that appears across the terminals of a pole of a circuit breaker after interruption. This voltage may be considered in two successive time intervals: one during which a transient voltage exists (TRV), followed by a second during which a power frequency voltage alone exists [4], [13].

The TRV ratings define a withstand boundary. A circuit TRV that exceeds this boundary at rated short-circuit current, or the modified boundary for currents other than rated, is in excess of the rated or related capabilities of the circuit breaker [4]. If the withstand boundary of the circuit breaker is exceeded, either a different circuit breaker should be used, or the system should be modified in such a manner as to change its TRV characteristics.

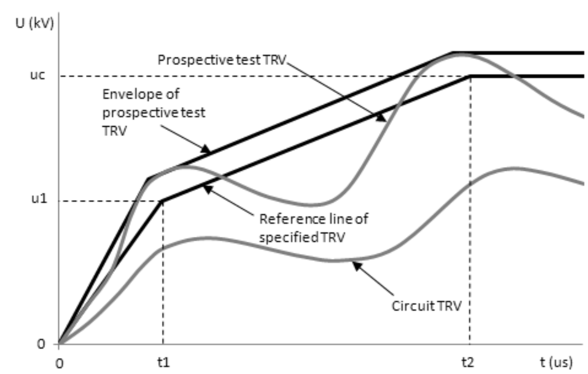

Fig. 1. Example Specified TRV, prospective test TRV and circuit TRV.

Since series reactors have very small stray capacitance, if involved in transients can lead in very high frequencies. Circuit-breakers when installed in the vicinity of such devices, will probably be affected of those TRV high frequencies when clearing faults. The resulting TRV frequencies often exceed the standardized TRV values. In those cases, mitigation measures should be adopted [2].

II. System Representation

There are different ways to approach a TRV study, the one chosen here was the representation of the real network in different, actual and future configurations.

A. System modelling

The starting point for the network representation was the definition of a kind of electrical border (see Fig. 2). Inside that border, the representation was made by models that considered the frequency range of the TRV phenomenon, while outside, an equivalent circuit to deliver correct results from the contribution of the short circuit current was used. The station where the power-flow control device will be installed was

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identified as Station A. The selected boundary corresponds to the end of each interconnection 220 kV line with the other substations, the 400 kV terminals of the autotransformers and 66 kV terminals of the transformers of Station A.

The “external” model consisted in a matrix of “self” and “mutual” impedances that allow the reduction of the system without lacking the necessary information of the short-circuit contributions (Fig. 3). For the “internal” model, the indications given in [6] were followed. In particular, the topology of the Station A and each 220 kV interconnection line was represented by appropriated sections of frequency-dependent lines. Moreover, special attention was paid in the simulation of the transformers and autotransformers of the Station A to consider their frequency dependency [10], [11].

B. *Description of the power flow control device*

The power flow control device consists in reactors installed in series to one of the 220 kV lines in Station A.

The series reactors comprises three different air reactors: X1, X2 and X3 where X3=2*X2=4*X1. All the combinations of these three reactors can be connected by means of the circuit-breakers connected in parallel with each reactor. However, only two circuit-breakers have to operate during short-circuits, they are indicated as CB1 and CB2 (Fig. 2).

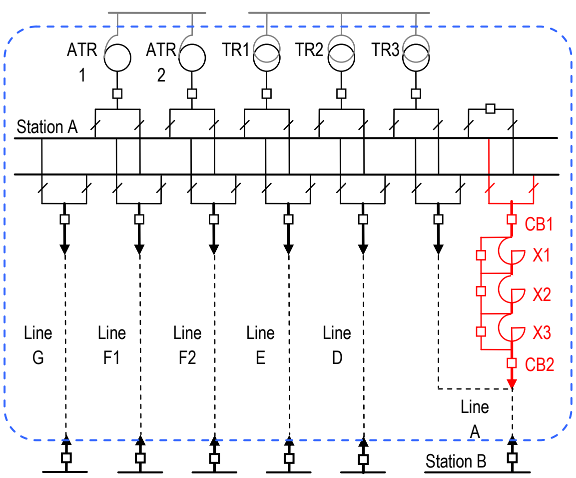

Fig. 2. Single line diagram of the detailed model implemented in EMTP; the model external boundary is evidenced by the dashed blue line.

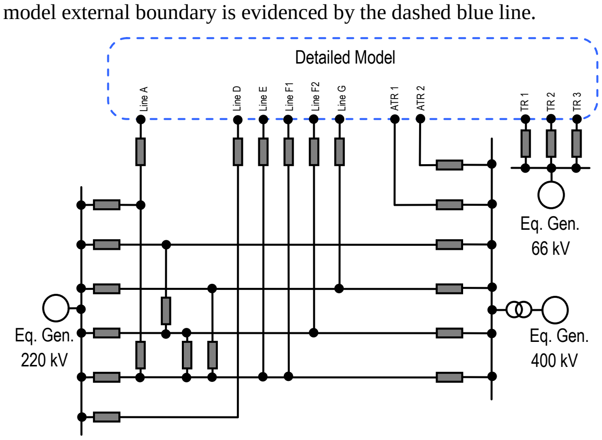

Fig. 3. Short circuit equivalent network model connected to the external boundary of the detailed model

C. *Network configurations considered*

Three different network configurations were studied. The following Table I shows them.

TABLE I
NETWORK CONFIGURATIONS STUDIED

Equipment connected	Network configuration N°1	Network configuration N°2	Network configuration N°3
Line A	X	X	X
Line B			X
Line C		X	X
Line D			X
Line E			X
Line F		X	X
AT1 400/220		X	X
AT2 400/220			X
TR1 220/66	X		X
TR2 220/66	X		X
TR3 220/66		X	X

D. *TRV cases studied*

The TRV during terminal faults, faults in presence of series reactors and short-line fault were studied.

The following five different short-circuit locations were considered:

- CB1 terminals (busbar side)
- CB1 terminals (reactor side)
- CB2 terminals (reactor side)
- CB2 terminals (line side)
- Short-line fault

III. STANDARD ADOPTED

The standard adopted was the IEC 62271-100:2009-04 [2]. However, some guidelines indicated in IEEE Std C37.011™-2005 [4] were also followed. In particular, the RRRV for a certain breaking current value (different from the specified ones) was found by interpolation between two standardized values. The following TABLE II shows the standardized values of TRV and RRRV for breaking currents equal and less than nominal.

TABLE II
STANDARDIZED VALUES FOR 245KV CIRCUIT-BREAKERS

Test duty	First ref. voltage (pu)	Time (μs)	TRV peak value (kV)	Time (μs)	Rate-of-rise (kV/μs)
T100	195	98	364	392	2
T60	195	65	390	390	3
T30	-	-	400	80	5
T10	-	-	459	66	7

IV. NETWORK SIMULATIONS

More than one hundred different simulations were carried out in order to detect critical situations. Some of them are showed below.

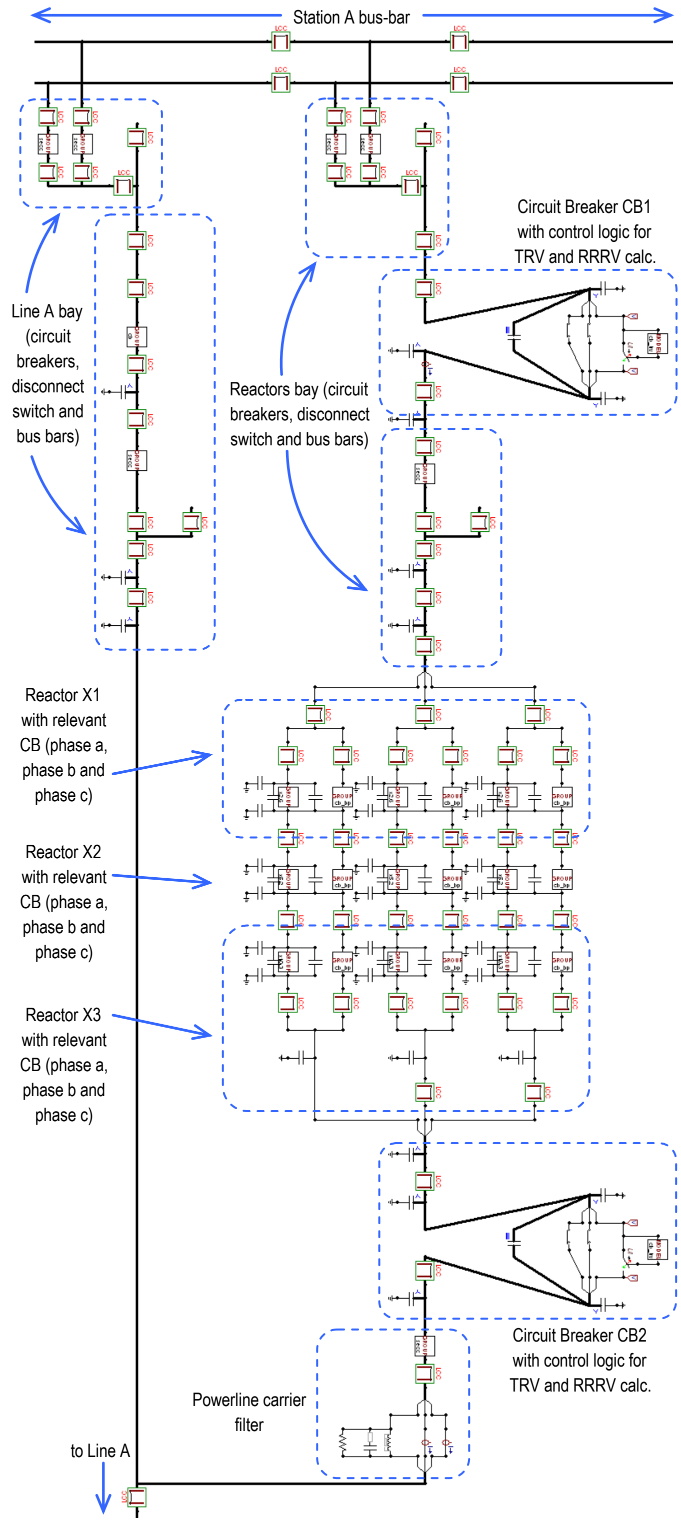

Fig. 4: Power-flow control device portion of the EMTP model.

A. *Terminal faults*

A total of 12 different short-circuits at circuit-breaker terminals were calculated (3 Network configurations per 4 fault locations). Each of this short-circuit currents were analyzed in both circuit-breakers (for a total of 24 cases).

Simulation results shows that no terminal faults exceed the standardized TRV boundaries. Fig. 5 shows a case of a terminal fault.

B. *Short-line faults*

Additionally to the terminal fault cases, nine "Short-Line-Faults" were studied. The IEC Standard [2] foresee three different Short-line fault cases:

- 60% of the rated Short-circuit, that correspond to voltage at the instant of current interruption of: 80kV.
- 75% of the rated Short-circuit, that correspond to voltage at the instant of current interruption of: 50kV.
- 90% of the rated Short-circuit, that correspond to voltage at the instant of current interruption of: 20kV.

The test conditions cannot be reproduced because [2] considers the tests current equal to the 100% of the CB rated braking current (40kA). In this case the maximum short-circuit current is always lower than the CB rated braking current. With the scope of reproduce the three test conditions stated above, with a voltage at the instant of current interruption respectively of 80kV, 50kV and 20kV, the fault distances (impedances) were adapted. The resulting currents for each case were thus smaller than the tests condition ones (90% = 36kA; 75% = 30kA; 60% = 24kA) due to the higher actual source impedance than the test condition. This represents a conservative assumption due to the fact that the actual short-circuit currents are lower than the ones stated in the Standard.

As the terminal faults, the SLF cases did not exceed the standardized boundaries. Fig. 6 shows a case of short-line fault; the source side and the line side are inside the boundaries withstand of the circuit-breaker.

A. *Faults with series reactors*

Unlike the Short-line fault where source and line side boundaries are specified, in these cases, the rate-of-rise of the TRV for the fault current should comply with the standard values given in TABLE II.

The simulation of the different cases shows that some of them exceed the standardized TRV boundaries. As it clearly seen in Fig. 7, the TRV of the circuit exceeds the withstand boundary of the circuit breaker. On the contrary, Fig. 8 shows a case were the RRRV of the circuit is lesser than the standardized one.

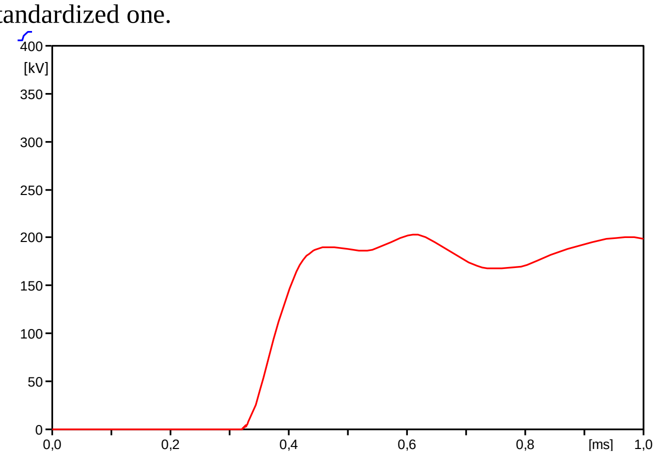

Fig. 5: Fault at CB1 terminals – Network configuration 3 (max short-circuit current).

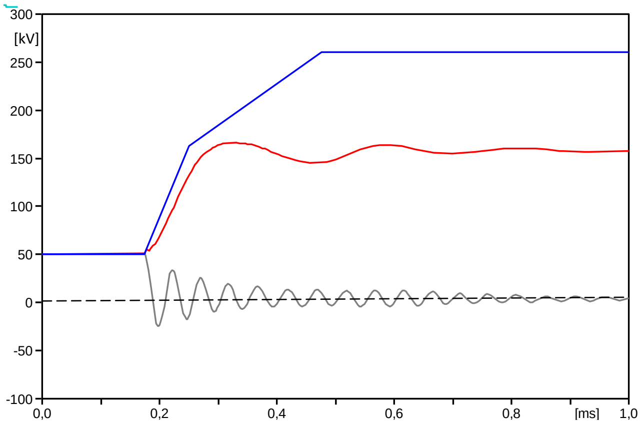

Fig. 6: Short line fault (75% - CB1) – Network configuration 3 (max short-circuit current).

V. SIMPLIFIED METHOD FOR RRRV COMPLIANCE VERIFICATION

It is interesting to point out that the worst situations were found for the cases of the smallest series reactors connected. This can be explained by means of frequency scans. In fact as it can be seen from Fig. 9, the smaller reactors shows higher resonance frequency but lower amplitude. In other words, it will be faster but the oscillations will be of lower amplitude.

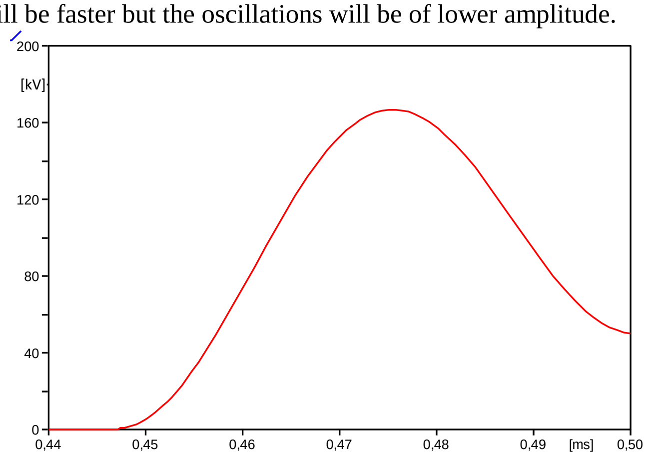

Fig. 7: CB1 TRV - fault at X1 reactor terminals – Network configuration III (max short-circuit current).

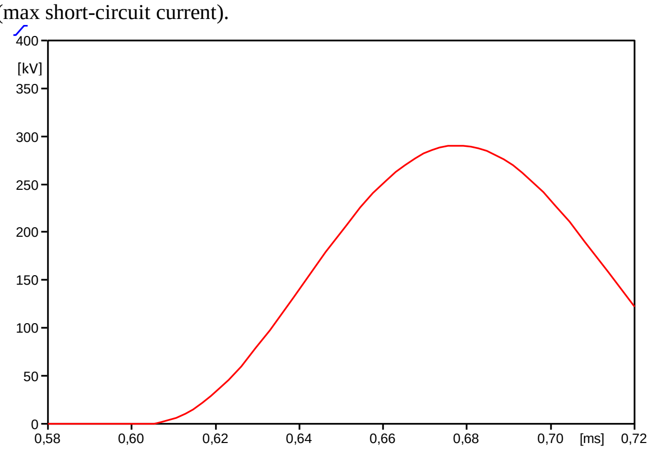

Fig. 8: CB1 TRV - fault at X3 reactor terminals – Network configuration III (max short-circuit current).

Fig. 10 shows the transient recovery voltages of three different series reactor values, where it can be seen the difference of the frequencies involved in the phenomenon and also the difference in the amplitudes. It is important to point out also the difference in the max slope observed (indicated in the Fig. 10 with dotted lines).

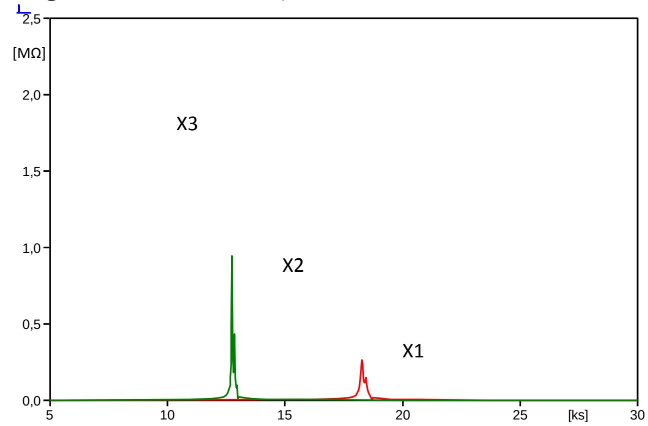

Fig. 9: frequency scan for three different series reactors connected.

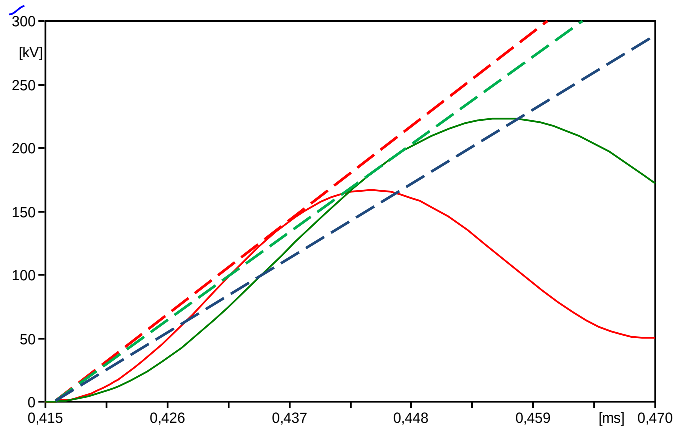

Fig. 10: TRVs for three different series reactors connected.

In the case in which the resonance frequency of the source side of the circuit-breaker under consideration presents a value much lower than the reactor side it can be neglected. Consequently the following equations can be formulated in order to find the max slope from the breaking point:

$$y1 = m \cdot t$$

$$y2 = Uo - Uo \cdot \cos(\omega r \cdot t)$$

Where:
- $y1$: Equation of the max slope from the point of breaking
- $y2$: Simplified equation of the TRV
- $Uo = I_L * X$
- I_L: Reactor fault breaking current
- X: Impedance of the reactor
- $\omega r = 2 \cdot \pi \cdot fr$
- fr: Reactor resonance frequency

Therefore, in order to obtain the maximum slope (from the breaking point) of the TRV function ($y2$), the following equations shall be solved:

$$\begin{cases} y1 = y2 & \Rightarrow \quad m \cdot t = Uo - Uo \cdot \cos(\omega r \cdot t) \\ \dfrac{dy1}{dt} = \dfrac{dy2}{dt} & \Rightarrow \quad m = \omega r \cdot Uo \cdot \sin(\omega r \cdot t) \end{cases}$$

Yields:

$$t = \frac{2.32}{\omega r} \qquad (1)$$

$$m = \frac{2 \cdot Uo \cdot t}{t^2 + \dfrac{1}{\omega r^2}} \qquad (2)$$

Equations (1) and (2) gives a very simple way to determine the max slope from the point of breaking of the circuit transient recovery voltage when the frequency of the source side of the TRV can be neglected.

In the cases in which the source side contribution cannot be neglected, its slope should be considered. In order to calculate the additional slope of the source side that have to be summed to "slope *m*", the approach for SLFs described in Annex A of [2] was followed.

$$(du/dt)_{RF} = \frac{(du/dy)_{TF} \cdot I_L}{I_{SC}} \qquad (3)$$

Where: $(du/dt)_{RF}$: Rate of rise at reactor fault breaking current

$(du/dt)_{TF}$: Rate of rise at rated short-circuit breaking current

I_L: Reactor fault breaking current

Isc: Rated fault current

Therefore, comparing the values of "slope *m*" (2) and "slope *m*" plus the "Rate of rise at reactor fault breaking current" (3) with the standardized RRRV, it is possible to understand if mitigation methods are necessary or not.

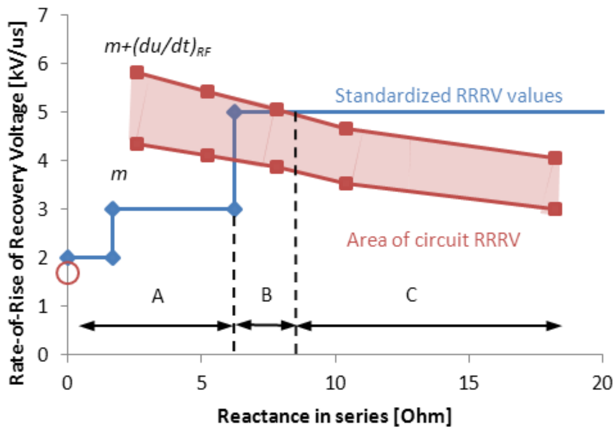

Fig. 11: Simplified method for RRRV compliance verification.

Then comparing the results (see Fig. 11), it is possible to determine which are the series reactance values that needs mitigation solutions. Fig. 11 shows three different ranges of X values; Range A shows the necessity to adopt mitigation methods due to the fact that the circuit RRRV exceeds the standardized RRRV values; Range B, further investigations should be carried out to determine the need of correction actions and Range C where no mitigation is needed.

This method is valid in the cases were the circuit-breaker, without series reactors, complies with the standard values of prospective transient recovery voltage.

It is important to point out that in the above Fig. 11, the Standardized values of the RRRV were left constant up the following test duty (T100, T60, T30 and T10) in order to use a conservative approach. As an alternative, the multipliers for rated parameters given in [4] can be adopted.

VI. Mitigation Methods

As it was shown in Fig. 11, for the smaller reactors, mitigation methods should be adopted.

There are mainly three ways for reduce the RRRV of the circuit TRV, that is the application of (a) capacitors in parallel to the reactors (b) capacitors connected to ground (c) a combination of the previous. One example of the addition of the capacitance in indicated in Fig. 12 which is the same case showed in Fig. 7 but with capacitors connected to ground at CB terminals. It is clear the RRRV reduction due to the capacitors. There is an additional solution that should be considered: the use of circuit-breakers with fast transient recovery voltage rise times. In such case it may be necessary for special TRV characteristics to be agreed between manufacturer and user [5].

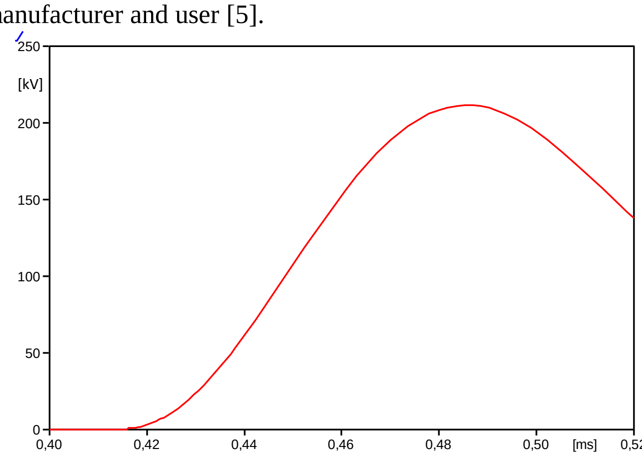

Fig. 12: same as Fig. 7 but with capacitors at CB1 terminals.

VII. Results of the Analysis

It was observed that the cases in which the series reactors are not present (bypassed) do not show any critical situation; that is the circuit-breaker TRV capability is higher than the circuit TRV. On the other side, the addition of the series rectors provokes a high frequency oscillation on one side of the circuit-breaker. The rate of rise of the recovery voltage (RRRV) across the circuit-breaker have, in some cases, exceeds the standardized values.

Short-circuits applied on the bus-bar side do not show any dangerous situation. On the contrary, short-circuits between CB-1 and CB-2 and on the line side show critical conditions for the circuit-breakers. In particular, the circuit-breaker CB-1 shows dangerous situations for both "internal" (between CB-1 and CB-2) and "external" (line side) faults; while the circuit-breaker CB-2 shows critical situations only when short-circuits are applied on the line side.

The worst condition is reached when the X1 series reactor is connected. In fact the frequency of the phenomenon and the standardized RRRV of the circuit-breakers gives the worst possible condition for the cases studied. Therefore, in order to prevent any misoperation of the circuit-breakers, it is necessary to take mitigation measures. The simulations show that for CB-1, it is sufficient to install 30 nF. This capacitance could be connected in parallel to the reactors as well as to ground at the terminal (reactor side) of the CB-1.

As far as the CB-2, the analysis shows that the different modes of possible operation of this circuit-breaker will implies different capacitor sizes.

- CB-2 opens only when internal faults are applied:
  In this case the 30 nF to be installed for the proper operation of CB-1 are sufficient.
- CB-2 opens for both internal and external faults:
  In this case, in addition to the 30 nF for the proper operation of CB-1 (in this case should be in parallel), other 20nF to ground at the terminals (reactor side) of the CB-2 must be added.
  Or in alternative, 30 nF to ground at CB-1 terminals (reactor side) plus 40 nF to ground at CB-2 (reactor side)
- CB-2 does not open neither for internal or external faults:
  In this case, the CB at Station B (the other extreme of the line) should open also for internal faults. This could seem a critical situation for the circuit-breaker at Station B, but due to the length of the line the CB in Station B reaches a dielectric strength enough to afford the TRV. In fact, the time needed for the voltage wave to arrive at Station B is around 200 μs, and thus enough to allow the CB to open.

As it can be noted, the cases in which the Circuit Breaker CB-2 operates only for "internal" short-circuits or does not operate at all during short-circuits, will have the benefit of use less number of capacitors than the case in which the CB-2 should open (only 30 nF are needed).

VIII. Conclusions

When series reactors for power flow control, or more in general, for any purpose must be installed, extensive analysis regarding the TRV should be carried out.

In case when more than one value of the series reactance is available, a very high number of different simulations must be considered; therefore it is recommended to carry out a sensitivity analysis in order to verify the worst cases.

A very simple method to analyze such cases was presented in the paper. The method consists in the evaluation of the range of possible slopes for a specific reactor value to be then compared with the specified rate-of-rise of recovery voltage. The determination of the range of slopes is made by calculating the reactor side recovery voltage, by means of a simple frequency scan of the reactor side, plus adding the rate-of-rise at reactor fault breaking current.

For those cases in which the specified TRV boundary was exceeded, different mitigation alternatives, such as capacitances in parallel to the series reactors and or connected to earth at the circuit-breakers terminals, were calculated. The same simplified method was used to determine the first approximation values of the capacitance. Their optimization was obtained by specific electromagnetic simulations.

A further optimization was recommended adopting some different operational procedures.

IX. Acknowledgment

The authors gratefully acknowledge the contributions of Manuel Marquez for his work on the original version of this document.

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