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# TRV Evaluation in Advanced Series Compensated System

Mohsen Niasati
Electrical and Computer Engineering Faculty, Semnan University, Semnan, Iran

Mohammad Pazoki
Electrical and Computer Engineering Faculty, Semnan University, Semnan, Iran

Mehdi Gholamzadeh
Electrical and Computer Engineering Faculty, Semnan University, Semnan, Iran

## ABSTRACT

The amplitude and rate of rise of transient recovery voltage (TRV and RRRV) are two parameters which affect the circuit breaker's capability to interrupt a fault current. It is important to evaluate the impact of series compensation on operation of circuit breaker (CB) and TRV when clearing a fault. This paper intends to analyze the TRV and RRRV across a CB of the line in presence of Thyristor-Controlled Series Compensator (TCSC), as one of the series compensation devices. This paper investigates the effect of several factors and different conditions on the TRV. Fault type, fault ignition time, fault location, and fault duration are the most important factors. Moreover, in this study the new aspects of the TRV analysis by considering the impact of various system configurations and the TCSC device are presented.

## Keywords

Transient Recovery Voltage, Rate of Rise Recovery Voltage, Series Compensation, Circuit Breaker.

## 1. INTRODUCTION

The electricity supply industry is undergoing rapid evolution, driven by deregulation and privatization. Years of underinvestment in the transmission grid in many markets has turned attention to increasing the utilization of existing transmission lines, cross-border cooperation and the issue of power quality. This has dramatically increased interest in new and classical solutions. FACTS (Flexible AC Transmission Systems), such as thyristor-controlled series capacitor and others are just such solutions. FACTS is defined by the IEEE as "a power electronic based system and other static equipment that provide control of one or more AC transmission system parameters to enhance controllability and increase power transfer capability". Controllable series line compensation is a cornerstone of FACTS technology [1-4]. The TCSC is one of the main FACTS devices, which has the ability to improve the utilization of the existing transmission system.

Despite the benefits of the series compensation devices, one of the concerns in the implementation of these devices is their influence on the line circuit breakers due to high level of transient recovery voltage and rate of rise of recovery voltage [5-7]. Therefore, it is necessary to perform a TRV analysis under the new system configuration to evaluate breaking capability of the existing circuit breakers. The TRV is a decisive parameter that limits the interrupting capability of the circuit breaker [8]. TRV and RRRV are a function of the system parameters, primarily the source side inductance, as well as the capacitance to ground in the near vicinity of the CB. The CB itself plays little or no role in making the TRV. Rather, the CB has to be able to withstand the TRV in order to sustain a successful interruption. Therefore in designing and applying CB in substations, the TRV peak and RRRV must be investigated [9-12]. The effect of fixed series compensation on TRV across line CB is considered in [13, 14] and the analytical results are presented.

In this paper most important factors that affect the TRV levels and RRRV, in high voltage TCSC based transmission network, are considered. These factors are as follows:

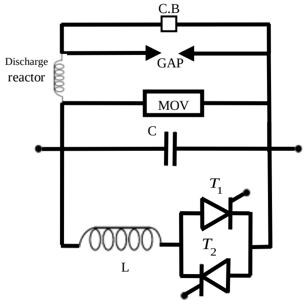
- Fault type
- Fault inception time
- Fault location
- Fault duration
- System configuration
- Compensation based TCSC.

The influence of each factors are simulated by PSCAD/EMTDC [15] software. This paper is the outcome of a study for the evaluation of one CB at the 230 kV transmission line which compensated with TCSC. TRV parameters are analyzed for line breakers which the TCSC as located in middle of line. Generally, CBs in a system are applied based on available short circuit capability at that point in the circuit. But, when circuit is interrupted it results in a TRV, this has harmful effects on the CB. TRV show clearly in different way depending on network configuration, hence the objective of this paper is to study the various parameters causing and affecting the TRV. In different situations, the obtained voltage across CB is compared with each other.

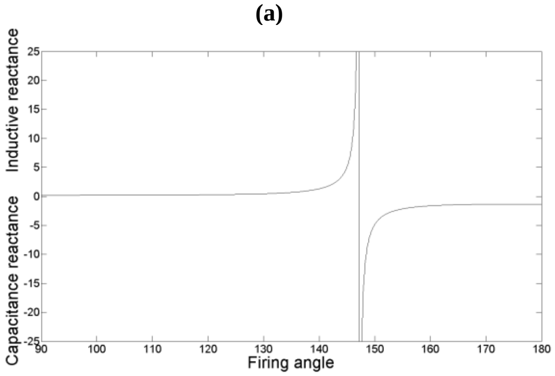
## 2. THE TCSC MODEL

The TCSC basically includes a capacitor bank placed into series with the transmission line, a parallel Metal Oxide Varistor (MOV) to protect the capacitor against over voltage and a branch with a thyristor valve in series with a reactor in parallel with the capacitor.

The bypass breakers are provided in parallel with the capacitor bank and in parallel with the thyristor valve. The arrangement of TCSC and its protective device is depicted in Figure 1(a).



**(a)**



**(b)**

**Figure 1. (a). TCSC arrangement (b). reactance variation versus firing angle characteristic**

The MOV comprise of a number of zinc oxide discs electrically connected in series and parallel. MOV basically is a nonlinear resistor to prevent the occurrence of high capacitor over voltage. MOV current could be represented according to its voltage. The MOV characteristics used in this work is the characteristics of the ASEA XAP-A metal oxide varistor provided in PSCAD [15].

The operation of the MOV depends on the seriousness of the fault. It may continue to operate until the air-gap is triggered cycles later. When the energy level in the MOV increases the air-gap is fired. A bypass circuit breaker in parallel with the gap automatically closes for abnormal system conditions that cause prolonged current flow through the gap [4]. The discharge reactor in the TCSC device limits the current through the air-gap or circuit breaker circuit. The impedance versus firing angle $\alpha$ characteristic of the simulated TCSC is shown in Figure 1(b). For a practical implementation of TCSC, $X_L / X_C$ ratio is between 0.1 to 0.3 range [1]. In the simulated TCSC this ratio is 0.1333 and in the reactance variation versus firing angle, there is one resonant point between $90° - 180°$, as shown in Figure 1 (b). Series compensation is used in multiple applications and locations in the power system. The principal applications of series compensations are [1, 4]:

- Improves voltage regulation
- Improves power transfer capability of the transmission line
- Improves system stability.

For the TRV study, different location of TCSC in transmission line with maximum compensation is considered.

## 3. TRANSIENT RECOVERY VOLTAGE (TRV)

TRV is defined in ANSI/IEEE STD-100 as the voltage transient that occurred across the terminals of a pole of a switching device upon interruption of the current [7]. When the CB contacts open they draw an arc between the poles. In the current zero crossing of AC current, the arc extinguishes. The capability of the breaker to withstand the opening transient is dependent on the magnitude of the TRV peak and the RRRV. The wave-shape of TRV is specified by two characteristic; firstly, values peak TRV (Uc) and secondly, RRRV slope which depends on several influences. Figure 2 illustrates how to achieve TRV parameters in general states. The slope of the OP line segment, as shown in Figure 2, is defined as the RRRV [6, 12].

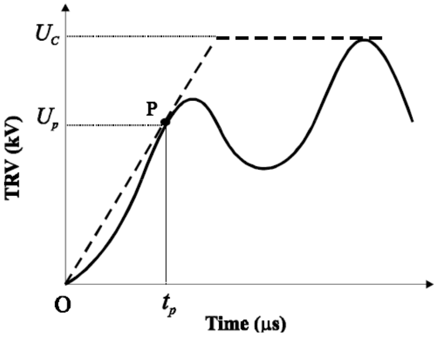


**Figure 2. The wave-shape of TRV and its parameters**

The presence of series compensated device such as TCSC usually causes rise of the TRV in the CBs of the transmission networks. The following is a list of most important reasons that affect TRV levels in high voltage TCSC based transmission network:

- TCSC compensation: The presence of series capacitor of TCSC on the transmission lines substantially increases TRV stresses across line CB due to the presence of trapped charges on series capacitor.

- Fault type: it is important to consider the fault type, i.e. single phase to ground, three-phase, phase-to-phase with or without ground. Obviously, there are multiple possibilities of fault occurrence, e.g. a single phase fault that develops into a three phase fault.
- Fault inception time: different fault inception time changes the severity of fault, and therefore the wave shape of TRV is affected.
-  Fault duration: how long a fault lasts before the CB start opening their contacts is another reason which affects TRV.
- Fault location: the peak of TRV and RRRV is related to fault distance from CB.
- Number of parallel transmission line: transmission lines, depending upon number of lines in parallel, are known to add damping to the system and hence produce less peak value of TRV waveform than single transmission line.

In the present study, all of the aforementioned factors are considered and their impacts on TRV and RRRV are evaluated. Summarize of the most important factors that affect the TRV level is depicted in Figure 3.

## 4. CASE STUDY

To assess the impact of TCSC on the operation of CB, a test system is simulated in PSCAD/EMTDC environment. The case study is a double feed transmission system. 100 km, 230 kV transmission line and TCSC device placed in line are considered to evaluate different influences of TRV in the line CB which is shown in Figure 4.

## 5. SIMULATION AND RESULTS

### 5.1 Simulation Conditions

In order to determine worst-case stresses by TRV on the line CB, several simulations have been performed. The different system configuration is utilized for simulations. Also, the impact of TCSC on characteristics of TRV (across CB1 in Figure 4), during fault clearing, is investigated. Simulations are carried out by PSCAD/EMTDC software in full detail in several conditions. The factors which affect the TRV and RRRV corresponding to CB1 are presented in Figure 3. The simulations are performed using a time step of 2 microseconds. The all cases which are investigated for TRV and RRRV analysis are categorized in two main parts as follows:

- Transmission line without TCSC
- Transmission line with TCSC

In the first part, in order to find the most severe impact on TRV and RRRV, different fault type (i.e. single phase to ground, two phase, two phase to ground, three phase, three phase to ground) are considered. Moreover, the different simulated faults have been categorized as “near-end faults” and “far-end faults”. Near-end faults are short circuits that occur on the transmission line in the surrounding area of the CBs, while far-end faults are faults located at greater distances from CB. In the case of near-end faults the fault location is varied at 1, 2, 3, 4, and 5 km from CB1. In other case, different faults are occurred at 55 and 80 km distance from CB1.

The instant of fault occurrence is varied with 5.5 mSec. increments between 100 and 111 mSec.. The fault duration is evaluated for 2 and 5 cycles that the TRV worst-case is determined in greater fault duration.

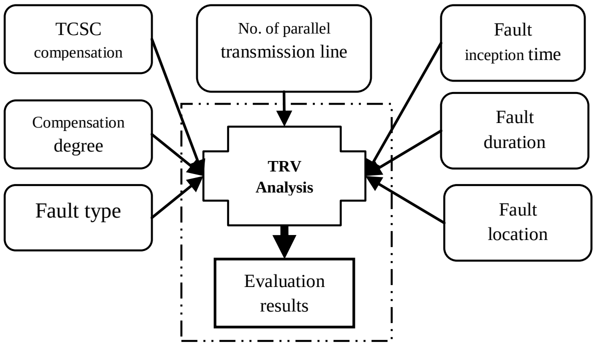


**Figure 3. Summarize of TRV analysis**

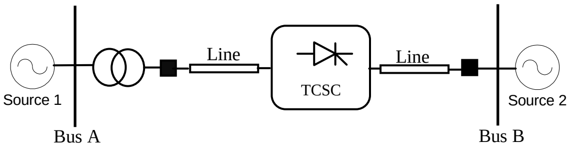


**Figure 4. The case study configuration**

In simulation it is assumed the breaker open at once in the first current zero crossing. Moreover, in comprehensive TRV analysis which is presented in this paper the impact of parallel transmission line is investigated. The worst-case of TRV level are determined by simulation of the above numerous case scenarios. In order to assessment the TRV of CB in the transmission line with TCSC these worst-case are simulated and related results are obtained.

### 5.2 Simulation Results

As stated in above, according to different scenarios, TRV and RRRV of the CB1 for the phase A are shown as follows:

TRV wave shape across the CB1 due to current interruption of different fault types are shown in Figure 5. In this case the simulation has performed for the 5 cycles of power frequency after occurrence of different fault types at 0.1 msec. The TRV wave-shapes for 5 cycle fault duration have a greater peak than the wave-shape of these faults with duration of 2 cycle of power frequency. Therefore in order to evaluating the simulation results and comparing them with each other, the fault duration is assumed to be 5 cycle.

It can be seen from Figure 5, the worst TRV and RRRV is produce in three phase fault without ground.

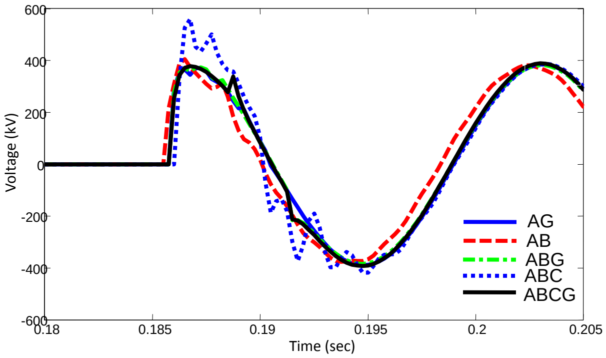


**Figure 5. TRV and RRRV for different fault type at circuit breaker terminal with 0.1 fault inception time (without TCSC)**

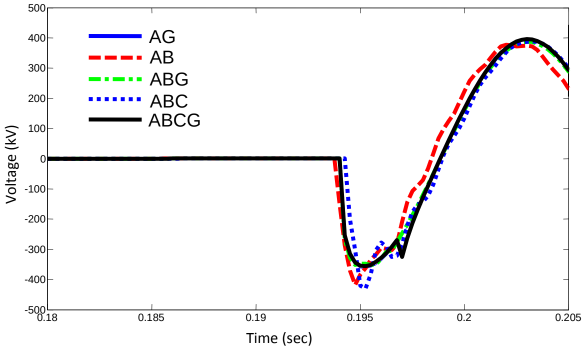


**Figure 6. TRV and RRRV for different fault type at circuit breaker terminal with 0.1055 fault inception time (without TCSC)**

The peak voltage level for this fault exceeds 550 kV, which is approximately 2.3 times the nominal voltage.

The TRV and RRV are affected by different fault inception time. The wave-shape of TRV for 0.1055 and 0.111 fault inception times for different fault types are depicted in Figures 6 and 7 respectively. Similar to Figure 5 the three phase fault has a worst influence on TRV.

For the better comparison of impact of different fault inception time and fault types the amplitude of TRV peak are depicted in a bar diagram as shown in Figure 8. The represented results by bar diagram are in case of the transmission line without TCSC. The TRV peak is related to 0.111 fault inception time is greater than two other times.

Simulation results for various faults location in the near-end fault case are depicted in Figure 9. The fault inception time and fault type are assumed 0.111 and three phase fault respectively that cause to worst case TRV level. The TRV and RRRV of the ABC (three phase) fault, in different fault location (1, 2, 3, 4, and 5 km), approximately are same. It is clearly shown, in zoomed area of Figure 9, the magnitude of TRV level is decreased due to increasing fault distance from CB1.

The impact of presence of TCSC, in the middle of transmission line, on TRV for far-end fault (at 55 and 80 km from CB1) is shown in Figure 10. In this Figure, the TRV and RRRV of three phase fault across CB1, in the transmission line with and without TCSC, are depicted together. Maximum compensation degree with TCSC by $180^{\circ}$ firing angle is assumed. It can be seen from Figure 10 that the peak of TRV and RRRV is related to fault distance from CB1. The peak of TRV and RRRV is reduced when fault is occurred far away from CB1. The comparison among TRV wave- shapes of CB1, in Figure 10, shows the presence of TCSC increase the peak of TRV. Consequently, the redesign of CB in transmission line with TCSC is essential task.

Parallel transmission lines cause to add damping to the system and hence produce less peak value of TRV waveform than single transmission line. In this paper two parallel transmission lines which one line is compensated with TCSC is considered. The length of second line is 100 km and the all fault types are occurred in first line at 55 km distance from CB1. The TRV and RRRV across CB1, related to three phase to ground fault, is illustrated in two cases simultaneously in Figure 11:

- One transmission line compensated with TCSC
- Two parallel transmission line which one line is compensated with TCSC.

It can be seen from Figure 11, when another line is added to system, the TRV peak is reduced in greater network. In order to comprehensive evaluating of TRV and RRRV in CB1 different fault types are simulated for two above cases.

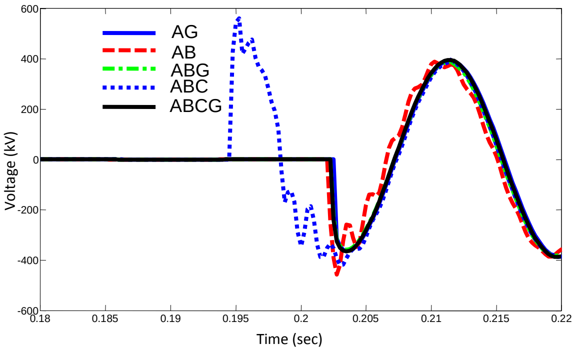


**Figure 7. TRV and RRRV for different fault type at circuit breaker terminal with 0.111 fault inception time (without TCSC)**

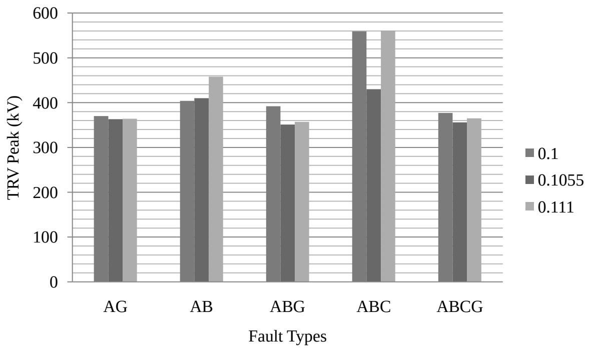


**Figure 8. The bar diagram of all obtained results related to different fault inception time and fault types (without TCSC)**

The obtained results, TRV peak and RRRV, are shown in Table 1. The comparison between TRV peak between one and two transmission line is confirmed that the TRV peak in larger network is less.

## 6. CONCLUSIONS

TRV is the voltage across breaker contacts immediately after current interruption. The circuit breaker has to withstand both the amplitude and rate of rise of TRV (RRRV) for a successful current interruption.

Despite the benefits of the series compensation devices, these devices have an impact on the breaker by increasing the stress during fault clearing. In this paper, TRV assessment and analysis for a typical high voltage power system including TCSC has been performed. The levels of TRV and RRRV in case of different fault location, fault types, fault duration, fault inception time and number of transmission lines are investigated.

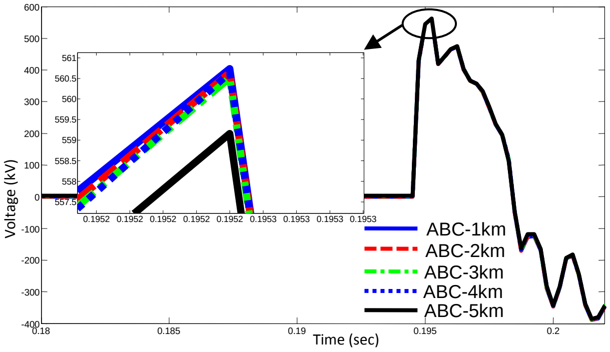


**Figure 9. TRV and RRRV for different fault locations at circuit breaker terminal with 0.111 fault inception time (without TCSC)**

The main results that are observed from extensive transient simulation are summarized as follows:

- Peak values of TRV and RRRV are increased in series compensated transmission line.
- Ungrounded 3-phase faults result is in high TRV across circuit breakers.
- Near-end faults increase the TRV peak much more than far-end faults.
- TRV peak and RRRV across CB in one transmission line is greater than two parallel transmission lines.

**Table 1. TRV peak and RRRV across CB1**

| | One transmission line | | Two parallel transmission line | |
|---|---|---|---|---|
| TRV & RRRV / Fault Type | TRV Peak (kV) | RRRV (kV/µs) | TRV Peak (kV) | RRRV (kV/µs) |
| AG | 411 | 1.26 | 301 | 0.92 |
| AB | 459 | 1.01 | 280 | 0.84 |
| ABG | 414 | 1.44 | 296 | 0.80 |
| ABC | 452 | 1.1 | 436 | 0.94 |
| ABCG | 450 | 1.66 | 308.5 | 0.73 |

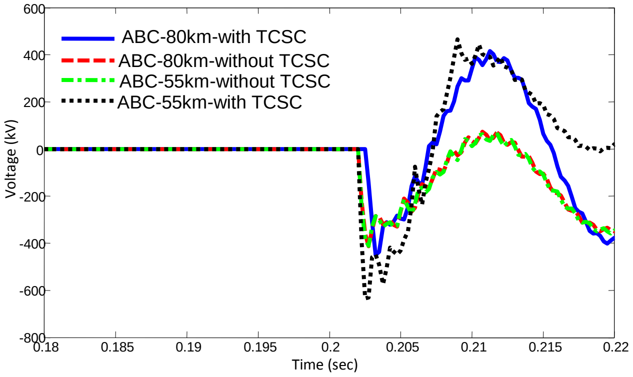


**Figure 10. TRV and RRRV for different fault type at circuit breaker terminal with 0.111 fault inception time**

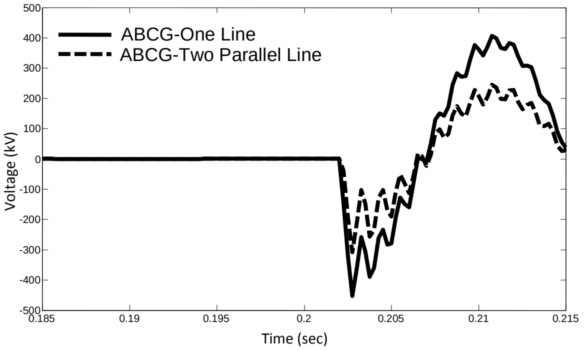


**Figure 11. TRV and RRRV for two system types**

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