Sensitivity Analysis of TRV in TCSC Compensated Transmission Lines during Fault Clearing by Line CB

A. Parvizi* , M. Rostami and A. Majzoob Ghadiri*****

*Engineering Faculty of Shahed University, Tehran, Iran. Email: ahmadparvizi@yahoo.com

**Engineering Faculty of Shahed University, Tehran, Iran. Email: rostami@shahed.ac.ir

***Engineering Faculty of Shahed University, Tehran, Iran. Email: majzoob_ghadiri@yahoo.com

***Abstract*—Thyristor Controlled Series Capacitors (TCSC) are effective devices for transmission lines power delivery enhancement in power systems. Before installation of TCSCs, it is necessary to study side effects of their integration in power system. One of these studies is the effect of series compensation on Transient Recovery Voltage (TRV) of line circuit breaker when clearing a fault. The amplitude and rate of rise of TRV are two parameters which can affect the CB's capability to interrupt a fault current successfully.**

In this paper, first, different factors and conditions which can affect TRV in the line CB of a thyristor controlled series compensated transmission line, have been analyzed and then, the dependence of TRV on protective operation of TCSC in different fault conditions has been illustrated and discussed through simulation of a thyristor controlled series compensated transmission system in PSCAD/EMTDC Program.

***Keywords*—Circuit Breakers; Transmission Lines; Transient Recovery Voltage (TRV); Thyristor Controlled Series Capacitor (TCSC); series compensation; Rate of Rise of Recovery Voltage (RRRV).**

I. Introduction

Transient Recovery Voltage (TRV) is the voltage across circuit breaker contacts immediately after current interruption. The circuit breaker has to withstand both the amplitude and rate of rise of TRV, (demonstrated in figure 1), for successful current interruption [1]. It is therefore an essential task to study the TRV for a certain switching operation.

TCSCs are effective and economical devices for increasing power transfer capability of transmission lines, improving power system stability, mitigation of subsynchronous resonance (SSR) and damping power oscillations [2].However, their integration in transmission lines will affect the TRV of line circuit breaker and it is necessary to perform a TRV analysis under the new system configuration to evaluate breaking capability of existing circuit breakers.

F. Iliceto et al [3] have provided a simplified formula for a quick approximate estimation of TRVs across circuit breakers of EHV lines, compensated with fixed series capacitors protected by Metal Oxide Varistors (MOVs). The authors have proposed several ways to limit TRVs in

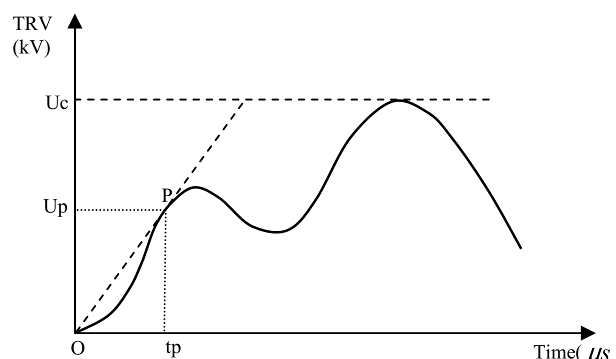

Figure 1. Demonstration of amplitude (Uc) and rate of rise (Slope of OP) of TRV

these circuit breakers.

G. Jianbo et al[6] have discussed the TRV across circuit breaker of 220kV Chengxian substation of Bikou-Chengxian-Tianshui transmission system (china), after installation of TCSC. A general and qualitative analysis of TRV variation after TCSC installation, has done by the authors.

S. Henschel et al [7], have discussed and analyzed the effect of fixed series compensation on line CB's TRV in transmission system of Piauí, Brazil. The evaluation of existing circuit breakers to withstand TRVs after installation of series capacitors has been performed.

In this work we will study the TRV across the circuit breaker when interrupting fault current in a transmission line compensated with thyristor controlled series capacitor (TCSC). The effect of different protection strategies of TCSC, in different fault conditions, on both the amplitude and rate of rise of TRV across the line circuit breaker will be discussed and analyzed. The relation between TRV and different fault conditions and protective operations of TCSC is illustrated and discussed through simulation in the PSCAD/EMTDC program.

II. TCSC Configuration and Protection Schemes

The basic module of TCSC contains a fixed capacitor, C, in parallel with a thyristor controlled reactor, L, as shown in figure 2.

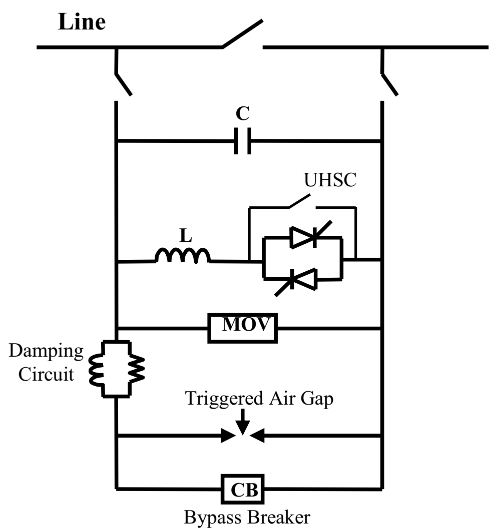

Figure 2. TCSC Main Circuit

If the thyristors are required to operate in fully on mode for prolonged duration, the conduction losses will be minimized by installing an ultra high-speed contact (UHSC) across the valve.

The metal oxide varistor (MOV) provides protection against overvoltages caused by high through current due to transmission line faults. These overvoltages may persist until the opening of the line circuit breakers clears the fault. Modern series capacitors banks use MOVs to limit the voltage across the series capacitor to a desired protective level. This protective level typically ranges between 2 and 2.5 per unit, based on the capacitor voltage drop at the rated line current. When limiting the voltage across the series capacitor to the protective level during fault conditions, the MOV must conduct excess fault current and thereby absorb the energy.

If the current or energy absorbed by MOV exceeds the maximum allowable limits, the air gap will be triggered immediately and the bypass breaker will close after about 1ms. The damping circuit is installed to limit and damp the discharge current of capacitor in this condition. This protection scheme is similar to Fixed Series Compensation (FSC) overvoltage protection [2].

In another protection scheme, when the current or energy absorbed by MOV exceed the maximum allowable limits, the thyristors of TCR branch will be fired to operate in fully conducted mode to perform bypass operation instead of the spark gap and bypass breaker. In this case, the inductive impedance of TCSC, will partly limit the fault current [6].

From a system performance point of view, bypass operation of a series capacitor increases the impedance of the circuit. This may, in turn, decrease system stability. The effect is not significant for internal faults (i.e. faults located on the line section in which the series capacitor is installed), since the line section containing the series capacitor bank is removed from service to allow fault clearing. For external faults, however, the impact on system stability can be significant. Therefore the overvoltage protection scheme is usually designed not to bypass the capacitor bank during external faults. Protective bypassing is normally restricted by design to act only for the more severe internal faults exceeding the maximum energy and fault current limitations determined for MOV.

III. TRV ANALYSIS FOR A LINE CIRCUIT BREAKER OF A THYRISTOR CONTROLLED SERIES COMPENSATED TRANSMISSION LINE

The opening of circuit breaker contacts, produce an arc between the poles, which extinguishes at zero cross of AC current. Whether or not the arc reoccurs is determined by the breaker's capability to quickly de-ionize arc chambers and the gap between the poles. This is partly influenced by breaker specifications such as the speed of the contacts departing, SF6 gas pressure, the mechanism of extinguishing the arc within the chamber[3], but it also depends on the initial voltage builds up across breaker contacts, as it can affect the dielectric strength of the gap. The objective of TRV analysis therefore is to determine the fastest initial build-up wave-shape of the voltage across breaker contacts and the maximum level of this voltage, after current interruption.

The wave-shape of TRV and hence the two characteristic values peak TRV and RRRV slope depend on many factors. A list of some factors that affect TRV levels in a high-voltage thyristor controlled series compensated transmission system are as follows:

- Transmission lines: High-voltage transmission systems typically involve long transmission lines that extend over hundreds of kilometers. Due to traveling of voltage waves, TRV travels forth and back along the line, affecting the TRV wave-shape across the line breaker.
- Thyristor Controlled Series Capacitor (TCSC): the series capacitor is equipped with protective devices such as spark gap, metal-oxide varistors, bypassing TCR branch and a bypass breaker. Since TRV appears during fault clearing, these protective devices have already responded to the 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 [4].
- Fault conditions: The time of fault occurrence and the location of fault influence the fault currents and the contributing currents across the line breakers, and therefore have an effect on TRV. By the same argument, it is important to consider the fault type, i.e. single-phase-to-ground, three-phase, phase-to-phase with or without ground.

Another factor is how long a fault lasts before the circuit breaker starts opening its contacts.

- Arc: Most faults on a high voltage transmission lines are not solid connections between phases but result in arcs. An arc dissipates electric energy and, therefore, increases resistive damping of high-frequency oscillations. Accurate representation of the arc model bears an effect on the TRV levels that can be experienced by the circuit breakers. Similarly, the arc produced within the breaker chambers also contributes to the damping.

• Power system: During the fault, the entire power system in the vicinity is affected and in a state of transient oscillation so that, when the faulted line is isolated, the oscillations continue until a steady post-fault state is gained. Since TRV are voltages across the line breakers, the system oscillations also affect the level of TRV. As a consequence: not only is it important to analyze the affected transmission line with regards to TRV but also to consider the entire power system in the vicinity in all its details[5],[6].

From this list it can be concluded that it is tedious task, if not impossible, to determine worst-case TRV levels for a circuit breaker. Particularly since the task involves minute representations of stochastic phenomena such as the arcs at the fault location or in the breaker chambers. In practice therefore a number of these parameters are varied in an iterative approach to include as many scenarios as possible.

Upon fault current interruption, the line voltage rings down to zero and the bus side voltage rises to approximately prefault level, with both voltages overshooting their final value. In series capacitors, current interruption leaves a trapped charge on the bank approximately equal to the MOV clipping level. This trapped charge adds substantial voltage to the breaker TRV. The high TRV can exceed the capabilities of installed breaker and even a new breaker with standard ratings [7].

Series capacitors between the breaker and the fault location increase the breaker TRV, in the worst case by the full level of the trapped charge, whereas on the source side of the breaker, other uncompensated lines will attenuate the trapped charge effect. If the MOV is protected by a triggered gap, then the high-TRV faults would be at locations that do not cause the gap to fire. Series capacitors also compensate part of the fault impedance and cause an increase in the fault current. The largest TRVs and fault current are due to multi-phase faults.

IV. STUDY SYSTEM

A single machine connected to the infinite bus (SMIB) through a transmission line compensated with TCSC (figure 3), is considered to study the sensitivity of TRV to different fault conditions and TCSC protection schemes.
System specifications are as follows:
Generator: 500MVA, 13.8kV
Transformer: 500MVA, 13.8kV/220kV
TCSC: L=4.6 mH
C=350 uF (40% compensation)

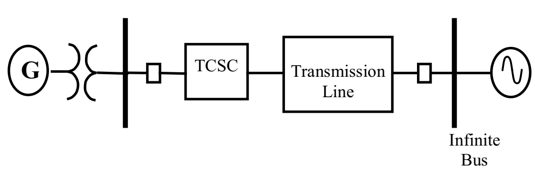

Figure 3. Study system configuration

Rated Capacitor Voltage: 26.3 kV
Overvoltage protective level (2.3 times of the rated peak voltage of the capacitor): 85kV peak
Damping Circuit: R=4 ohms, L=683 uH
Maximum Energy dissipation of MOV: 3.7 MJ/phase
Maximum Current of MOV: 5.4kA peak
Transmission Line Length = 140 km

A. MODELLING

Generator: A detailed model of generator including transient and subtransient impedances, Q-axis damper winding and mechanical model of rotor is considered. The mechanical input power and the excitation voltage are assumed to be constant.

Transformer: Transformer model consists of impedances, losses, core saturation and the capacitance of high voltage and low voltage windings and the capacitance between two windings.

Circuit Breaker: The line circuit breaker is modeled as ideal switches. Its contacts open 5 cycles (100ms) after fault occurrence, resulting current interruption in the zero crossing of the respective phase.

TCSC: The spark gap and bypass breaker is modeled as an ideal switch which closes with 1ms delay when the current or energy in the metal-oxide varistor exceeds the trigger levels. If TCR branch is used to bypass the capacitor, it will be fired to operate in full conduction mode with a maximum of half-cycle delay. The MOV model is the approximated values of the ASEA XAP-A metal oxide surge arrester characteristics which is given in table 1[9]. The voltages in the table are per-unit on the base of capacitor rated voltage.

The bypass mechanism is operating individually for each phase, so that in the case of a simulated two-phase fault without ground in the vicinity of a capacitor, the bypass would occur in the affected phases but not in the healthy phase. With the exception of single-phase faults, all three

Table 1. V-I characteristics of MOV used in the study

I (kA)	V (pu)
0.001	1.100
0.01	1.600
0.1	1.700
0.2	1.739
0.38	1.777
0.65	1.815
1.11	1.853
1.50	1.881
2.00	1.910
2.80	1.948
200.0	3.200

poles of the bypass breaker close. In the case of a single-phase fault the bypass breaker is closed only for the affected individual phase.

Transmission Line: A frequency dependant distributed model developed in [8] is considered for transient modeling of transmission line. The effect of traveling waves is included in this model.

Fault: The short circuit fault is modeled as a solid connection to ground. The connection to ground remains in place even after the fault is cleared by opening the line circuit breakers. The fault is applied at various places along the thyristor controlled series compensated transmission line.

B. SIMULATION CONDITIONS

Simulation is done by PSCAD/EMTDC program for different fault conditions and TCSC protection schemes. In order to evaluate sensitivity analysis of different conditions on TRV, several simulations has been done for different fault types (single-phase-to-ground, three-phase, phase-to-phase with or without ground), different fault locations(at 2,10,56,100 and 135km away from line CB), different fault occurrence instants within a half cycle of power frequency (at zero-cross of supply voltage and 2, 5 and 8ms after that) , different fault durations (5 and 7 cycles) and two protection schemes of TCSC described in section II.

C. SIMULATION RESULTS

Figure 4 shows the simulation results for TRV waveform when the fault distance varies along the line.
The simulation results are shown in tables 2, 3 and 4. Tables 2 and 3 show the variations of amplitude and rate of rise of recovery voltage for different fault types as the fault distance varies. Fault duration has taken to be 5 and 7 cycles in tables 2 and 3, respectively. When the TCSC protection system performs the bypass operation, two pairs of data has been inserted in the related table cell, the superior data is related to CB bypass operation and the

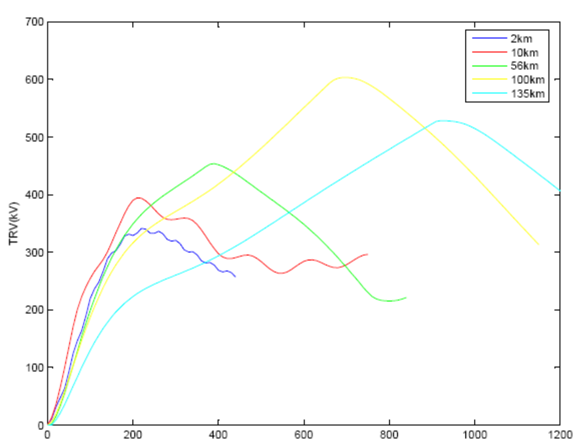

Figure 4. Variation of TRV waveform in different fault distances

Table 2. TRV variations with fault distance
(Fault duration: 5 cycles, t=650ms, CB bypass (up) and TCR bypass (down))

Fault dist. / Fault type	2km	10km	56km	100km	135km
1ph. to ground	354.18kV 1.36kV/us 297.6kV 1.45kV/us	369.61kV 1.23kV/us	435.08kV 1.35kV/us	475.24kV 1.12kV/us	517.66kV 1.28kV/us
2ph. without ground	408.02kV 2.52kV/us 474.63kV 2.69kV/us	429.82kV 2.28kV/us 436.19kV 2.85kV/us	435.1kV 1.96kV/us	684.4kV 1.92kV/us	684.75kV 1.71kV/us
2ph. to ground	395kV 2.66kV/us 439.49kV 2.75kV/us	409.43kV 2.64kV/us 481.82kV 2.86kV/us	418.88kV 1.92kV/us	664.91kV 2.01kV/us	663.8kV 1.55kV/us
3ph. without ground	341.8kV 2.19kV/us 337.97kV 2.41kV/us	367.72kV 2.42kV/us 327.38kV 2.69kV/us	452.9kV 2.02kV/us 529.44kV 2.42kV/us	597.36kV 1.81kV/us	500.26kV 1.25kV/us
3ph. to ground	355.42kV 2.11kV/us 349.14kV 2.15kV/us	375.12kV 2.26kV/us 333.86kV 2.46kV/us	452.88kV 1.88kV/us 530.90kV 2.48kV/us	596.7kV 1.81kV/us	515.35kV 1.25kV/us

inferior is related to TCR bypass operation. The following results can be obtained from tables 2 and 3 :

- Longer fault distance leads to less fault current and bypass operation will not occur, therefore capacitor is in circuit and TRV level is probably harmful.
- If capacitor does not bypass, TRV amplitude will be high, if it does, RRRV will be high.
- TRV amplitude increases as the fault distance from the line CB increases.
- TRV amplitude is higher when the fault duration is longer.
- RRRV at the beginning of the line is higher than the end of the line.

Table 3. TRV variations with fault distance
(Fault duration: 7 cycles, t=650ms, CB bypass(up) and TCR bypass(down))

Fault dist. / Fault type	2km	10km	56km	100km	135km
1ph. to ground	422.19kV 1.65kV/us 366.01kV 1.89kV/us	421.95kV 1.56kV/us	446.01kV 1.44kV/us	462.38kV 1.44kV/us	561.27kV 1.28kV/us
2ph. without ground	465.08kV 1.95kV/us 476.93kV 2.44kV/us	436.34kV 2.82kV/us 440.93kV 2.96kV/us	508.03kV 1.88kV/us	493.49kV 1.47kV/us	501.83kV 1.55kV/us
2ph. to ground	436.75kV 1.84kV/us 417.28kV 2.58kV/us	458.53kV 2.54kV/us 432.27kV 3.04kV/us	478.11kV 2.00kV/us	483.41kV 1.17kV/us	501.23kV 1.55kV/us
3ph. without ground	353.34kV 2.38kV/us 360.19kV 2.39kV/us	404.91kV 2.82kV/us 424.27kV 2.95kV/us	463.41kV 1.90kV/us 536.45kV 2.57kV/us	505.4kV 1.55kV/us	572.18kV 1.30kV/us
3ph. to ground	368.97kV 2.26kV/us 371.88kV 2.34kV/us	413.79kV 3.06kV/us 431.67kV 3.26kV/us	492.15kV 2.15kV/us 563.15kV 2.52kV/us	508.96kV 1.54kV/us	559.66kV 1.37kV/us

Table 4. TRV variations with fault occurrence instant
(Fault duration: 5 cycles, L=135km)

Fault Type \ Fault Time	600ms	602ms	605ms	608ms
1ph. to ground	514.14kV 1.15kV/us	517.36kV 1.18kV/us	531.75kV 1.21kV/us	527.8kV 1.28kV/us
2ph. without ground	524.95kV 1.73kV/us	348.87kV 1.04kV/us	422.84kV 1.42kV/us	415.43kV 1.52kV/us
2ph. to ground	599.7kV 1.72kV/us	390.2kV 0.84kV/us	378.68kV 1.25kV/us	372.8kV 1.72kV/us
3ph. without ground	524.75kV 1.36kV/us	525.74kV 1.30kV/us	526.43kV 1.36kV/us	527.24kV 1.38kV/us
3ph. to ground	527.26kV 1.38kV/us	527.81kV 1.41kV/us	528.71kV 1.32kV/us	529.39kV 1.36kV/us

- When the capacitor is bypassed, the RRRV is higher than when it is in circuit.
- RRRV in TCR bypass operation is greater than CB bypass operation.

In table 4 the variation of TRV amplitude and RRRV for different fault types is shown when the fault occurrence instant varies within a half cycle. The fault is applied at 135km far from the line CB, so the capacitor will not be bypassed during the fault.

From table 4 it can be seen that TRV level is not so much sensitive to the fault occurrence instant.

V. CONCLUSIONS

In this paper, TRV analysis of a line circuit breaker when clearing a fault in a thyristor controlled series compensated transmission line has been performed. Different conditions and modeling details which is necessary for this analysis, is considered and discussed. Finally, using PSCAD/EMTDC program, the sensitivity of TRV amplitude and RRRV in different conditions such as fault type, fault location, fault occurrence instant and fault duration is tabulated and discussed. The results can give us a rule of thumb to estimate the TRV amplitude and RRRV variations in a thyristor controlled series compensated transmission line and help us to find out the worst case of TRV level and evaluate the required line CB capability to withstand transients in line.

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