Impact on Superconducting Fault Current Limiters on Circuit Breaker Capability

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***Abstract*—There has been significant capacity addition to the power system leading to increased fault current at substations buses. This call for costly equipment upgrades and replacements. In order to defer investments utilities are exploring use of superconducting fault current limiters (SCFCL) and current limiting reactors (CLR).**

The SCFCL can be built with either resistive or inductive shunts. Also, it might be possible to include a recovery switch in series with the superconducting element. The choice of shunt is likely to have significant impact on the current limiting capability of the SCFCL. Also, for correct application design the circuit breaker transient recovery voltage (TRV) should be within its capability limits. It is expected that the TRV will be impacted by the choice of shunt and use of the recovery switch. The paper analyzes the effect of type of shunt on efficacy of limiting fault current and impact on TRV using EMTP-ATP.

It is observed that the use of resistive shunt may be better for limiting first peak of the current and limiting TRV values. The inductive shunt reduces the steady state fault current effectively. The use of recovery device has adverse impact on the TRV characteristics of the system.

***Index Terms*—Fault Currents,Circuit Breakers, TRV, Superconducting Fault Current Limiters,EMTP-ATP .**

I. Introduction

In recent years, there has been a rapid expansion in the grid and the fault current levels at the substation buses are increasing. The increase in fault current levels has a direct impact on the circuit breakers that are called upon to interrupt this fault currents. Since, the fault currents observed at the substation buses exceeds the rated interruption capacity of circuit breakers these will have to be replaced. Also, the busbar reinforcements has to be evaluated in order to ascertain if the short circuit forces can be withstood [1], [2]. All of these steps means costly upgrades or equipment replacements. Thus, many utilities are exploring the options of using current limiting reactors (CLR) or superconducting fault current limiters (SCFCL) in their system [3]. This paper explores the impact of the use of CLR and SCFCL on circuit breakers.

II. Background

The use of CLR and SCFCL reduces the fault current to be less than equal to the rated interruption capability of circuit breaker. In most of the reported literature the efficacy of the CLR and SCFCL in limiting the fault current is generally evaluated [2], [4], [1], [5]. The application of CLR and SCFCL should also consider other aspects of system design like impact on protection and transient recovery voltage (TRV) of circuit breakers [3], [2].

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The impact of SCFCL on the protection in marine power systems and future power networks is presented in [5]. From the perspective of a circuit breaker, the TRV capability should also be evaluated to ensure that a correct selection [6]. The TRV appears across the circuit breaker contacts immediately after interruption and imposes severe stress on the interrupting medium [6], [7]. A proper design ensures that TRV capability of the circuit breaker is not exceeded as evaluated on the basis of two and four parameter TRV envelopes [8], [9], [6], [10].

A CLR installed in a power system is known to adversely impact the TRV and is considered a severe duty by standards [9], [6]. The impact on TRV capability of circuit breaker from the point of view of short line faults is presented in [11]. A method for determining the resistance of fault current limiter (FCL) to ensure rate of rise of recovery voltage (RRRV) is within the breaker capability is presented in [12]. The impact of inductive FCL or CLR on short lines faults and out of phase switching is analyzed in [13] [14] respectively.

The effect of location of FCL on severity of TRV is analyzed in [15]. The authors of [15] conclude that the severity of TRV is reduced with resistive FCLs. In [16] also considers MgB_2 based resistive SCFCL and its impact on TRV in medium voltage distribution network. The authors of [16] also conclude that the resistive SCFCL reduces severity of TRV. A similar conclusion is drawn by the authors of [17], [18] in their respective papers.

The circuit breaker application in a system not only requires evaluation of fault current but also of the transient recovery voltage characteristics. The SCFCL models considered in the literature for TRV studies are resistive SCFCL designs. Also, most of studies consider only CLRs for analysis of TRV. But, a SCFCL can be designed with an inductive or resistive shunt, the paper proposes to investigate the choice a shunt in SCFCL with respect to effectiveness in limiting fault current. The paper also aims to investigate the impact of different shunts used in a SCFCL on the TRV of the system and the ascertain correctness of the circuit breaker application.

III. System: Description and Modeling

Fig. 1 shows the system model used for studying the effect of SCFCL on the TRV capabilities of the circuit breakers.

The system is energized by a 115-kV three phase ideal source and has a short circuit current of 63 kA. The system model is derived by reduction from a real power system presented in [10]. The entire system is modeled and simulated using EMTP-ATP. The system assumes a ideal circuit breaker directly connected to the bus with current interruption rating of 63kA. For TRV studies it is important to include stray and bus capacitances of the system. The values of the stray capacitances for various equipment are given in [9].

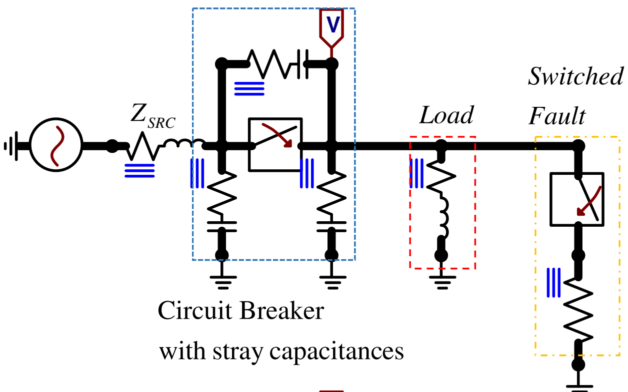
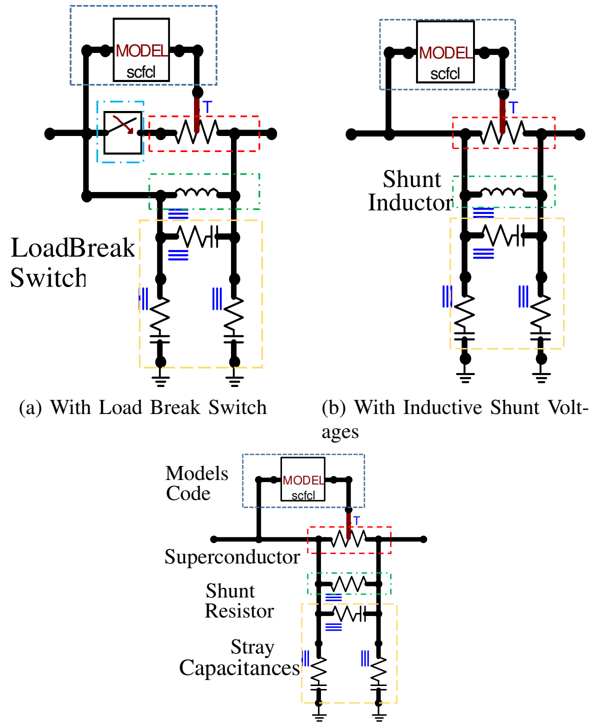


Fig. 1. System Model in EMTP-ATP

Fig. 1 shows a simplified model of a large system with load represented as a lumped load connected at the terminals of the circuit breaker. The lumped load results in a line current of approximately 760 A rms. A fault is created at the load terminals by closing a switch connected in series with a very value of resistance. This is depicted as *switched fault* in Fig. 1. The instant of fault initiation can be controlled precisely by closing the switch at desired point on wave.

The superconducting fault current limiter (SCFCL) (not shown in Fig. 1) can be directly connected to the circuit breaker terminals. The SCFCL can be connected on the source or load side of the circuit breaker. Fig. 2 shows an different SCFCL implementations. The SCFCL model consists of variable resistance i.e. the superconducting element and the shunt impedance branch. The values of the variable resistance are determined by an algorithm written using MODELS code. The modeling details of the SCFCL are discussed in Section IV. The shunt element, also called as bypass path, of the SCFCL can be realized using a resistor or an inductor. Some installations of the SCFCL, as shown in Fig. 2a a circuit breaker or a load break switch, might be used in series with superconducting element. The load break switch interrupts the residual current and facilitates fast recovery of the superconducting element. An objective of this paper is bring out the factors governing the choice of the shunt element and its impact on circuit breaker capability. The size of shunt element is governed by the desired fault current reduction and is calculated using a method described in Section IV.



(a) With Load Break Switch

(b) With Inductive Shunt Voltages

(c) With Resistive Shunt

Fig. 2. SCFCL Implementation in EMTP-ATP

IV. SCFCL: Modeling and Sizing

A. Modeling

Fig. 2 shows different implementations of SCFCL. An SCFCL is a cryogenics based system with two distinct impedance states i.e. a low impedance or a superconducting state and a high impedance state followed by a recovery stage [2], [19]. The superconducting element carries current during the normal circuit conditions offering very low resistance to the flow of current.

The physics of superconductivity indicates that the low resistance state depends on critical current, critical magnetic field and critical temperature [2]. A superconductor quenches if there is a change in the ambient conditions or if current increases to a value beyond critical current. The quenching results in rapid increase of the resistance the superconductor [2]. The resistance characteristics of a superconductor can be modeled in several ways [19]:

- $R(t)$ with transition time of 1ms
- $R(I,T)$, $R(I)$ based on V-I characteristics
- $\rho(J,T)$, $\rho(J)$ based on E-J characteristics

However, it is typical to model the SCFCL as function of current only and not model the thermal characteristics [19]. Fig. 3 shows the nonlinear resistance transition for the superconductor element of SCFCL as modeled in this paper. The resistance offered by the superconducting element has three distinct regions. Region-I with very low resistance, Region-II with nonlinear increase of the resistance and Region-

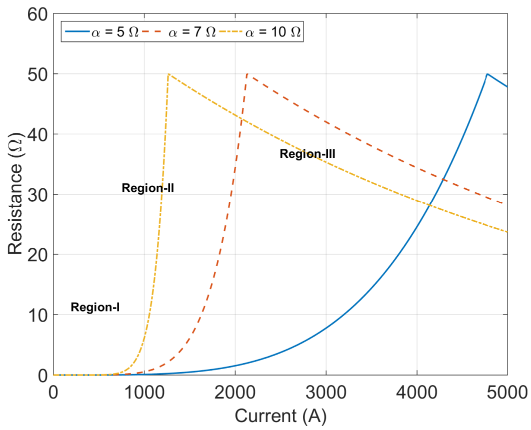


Fig. 3. SCFCL: Superconductor Resistance Characteristics

III is recovery region where resistance exponentially reduces to zero.

$$V = V_c \left(\frac{I}{I_c}\right)^{\alpha} \tag{1}$$

The critical current flowing through a superconductor produces an electric field of 1 μV/cm. The V-I characteristics of a superconductor is given by (1) and depends on transition index (α) and current through the superconductor. The value of V_c depends on the construction of the SCFCL and is assumed to be 0.6 V in this paper. The value of α influences the rate of transition of the superconductor with high values indicating faster transition.

The nonlinear resistance of the superconductor is modeled as current dependent characteristics. The three regions depicted in Fig. 3 are modeled using MODELS code in EMTP-ATP.

- **Region-I**: The region is seen below the critical current level and the value is set to zero.
- **Region-II**: The region above the critical current (I_c) value and is modeled as current dependent resistance given by 2

$$R_{sc}(I) = \frac{dV}{dI} = \alpha V_c \frac{I^{(\alpha-1)}}{I_c^{\alpha}} \tag{2}$$

- **Region-III**: The region of recovery modeled as exponentially reducing resistance given by (3). The value of R_{max} is arbitrarily chosen to be 500 Ω. The value of τ i.e. the recovery time constant is dependent on the cryogenics system. For simulations reported in this paper the value of τ is assumed to be 1s.

$$R_{sc} = R_{max} e^{-t/\tau} \tag{3}$$

Fig. 2 shows various ways in which an EMTP-ATP model of SCFCL can be implemented. The superconducting element is modeled as controlled resistor that assumes values depending on different regions of operation. The equations defining different operating regions are included in simulation as an user defined function (UDF). Fig. 2 shows UDF as MOODELS code. The bypass path of the SCFCL can physically realized using resistor (shunt resistor in Fig. 2a) or an inductor (shunt inductor in Figs. 2c and 2b). During fault $R_{sc} >> R_{shunt}$ hence current is commutated into the parallel path which limits the fault current. The impedance of the shunt is determined based on desired limited value of fault current.

B. Sizing

The fault current is commutated to the bypass impedance as soon as the superconducting element quenches. The impedance value can be determined using (4).

$$Z_{shunt} = \frac{V_{sys_L G}}{I_{scd}} - Z_{src} \tag{4}$$

From (4) it can be seen that the impedance value depends on the desired fault current level. The desired fault current typically is selected such that the resultant fault current level is below the switchgear capability. The shunt used in SCFCL carries the limited fault current whereas the superconducting element limits the first peak value.

C. Stray Capacitances

The stray capacitances are assumed to be lumped at the shunt element terminals to ground and from terminal to terminal. The stray capacitances are extremely important for investigating the TRV characteristics of the system. The stray capacitance values for shunt reactors are obtained from IEEE C37.011 [9].

V. Case Studies

The simplified system of Fig. 1 is modeled in EMTP-ATP. In order to fully investigate the effect of SCFCL on the interruption duty of the circuit breaker and for application design several case studies were defined. The test case definition is given in Table I. The bypass shunt in SCFCL and current limiting reactor (CLR) are assumed to be 2.75Ω. Since, it possible to connect the SCFCL and CLR on the source side or the load side, test cases were also defined. The results for test cases pertaining to source side connection have not been presented due to space limitation.

TABLE I
TEST CASES

FCL Type	Case No.
No FCL	BaseCase
SCFCL Resistive Shunt	Case01-LS
SCFCL Inductive Shunt	Case02-LS
SCFCL Inductive Shunt and Recovery Switch	Case03-LS
CLR	Case04-LS
CLR with Damping Resistance	Case05-LS

VI. Results

A. Choice of Shunt for SCFCL

Fig. 4 shows the fault current obtained from the simulation of the system of Fig. 1. The fault current are presented for the cases with FCL connected on the source side of the circuit breaker. The fault is initiated at 0.25 s and interrupted by the circuit breaker at 0.4 s.

The BaseCase condition gives worst fault current with the first peak value of about 150 kA and steady state peak of about 89 kA. The fault current waveforms for Case02-SS, Case03-SS and Case04-SS are almost identical and thus overlapping each other in Fig. 4. The first peak value for Case02-SS, Case03-SS and Case04-SS is restricted to 45 kA whereas for Case01-SS the first peak is restricted to 30 kA. Thus, from the perspective of first peak a SCFCL with resistive shunt provides better performance.

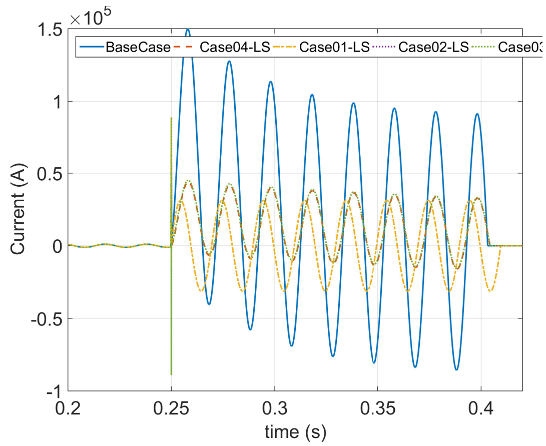


Fig. 4. Fault Current Waveforms

The peak values of steady state fault current are noted 24.5 kA for Case02-SS, Case03-SS and Case04-SS whereas for Case01-SS it is noted to be 30 kA. The reduction in steady state fault current is more significant when an inductive shunt or CLR is used. This is expected since high voltage power systems are highly inductive with large X/R ratios. Thus, an addition of inductor results in direct reduction of the fault current value. The resistive shunt addition however has a significant impact on the phase angle of the current. Thus, it may be inferred that the inductive shunt reduces the steady state fault current value significantly whereas a resistive impacts the circuit asymmetry. Fig. 5 shows instances of fault current interruption for various cases considered in this paper.

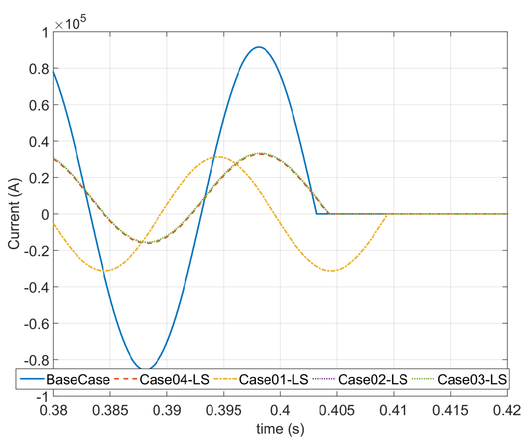


Fig. 5. Current Interuption Instances

The circuit breakers are given command to interrupt at 0.4 s. It is well known that the circuit breakers interrupt at current zeros after the open command has been received [8]. The circuit breaker in the model is assumed as ideal device and arcing is not simulated in the paper. Hence the circuit breaker interrupts immediately at the first current zero it encounters once the open command is received. It can be seen clearly from the Fig. 5 that the choice of shunt has an impact on the interruption instances. The circuit breaker with resistive shunt interrupted first for the cases under consideration in this paper. This result is expected since the resistive shunt reduces the phase difference between the voltage and current along with significant impact on reduction of system asymmetry.

B. Transient Recovery Voltage

As soon as the fault current is interrupted by a circuit breaker the system voltage starts to recover and approaches the rated voltage level rapidly. This rapid increase in the system voltage is termed as the transient recovery voltage (TRV) [6], [7]. The TRV withstand capability of the circuit breaker is extremely critical for successful interruption of the fault current [7].

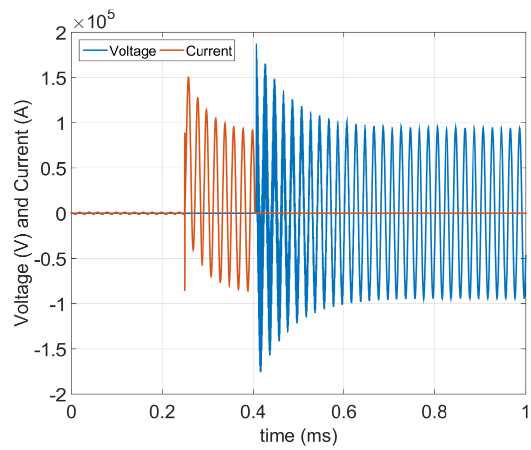


Fig. 6. Voltage and Current during Fault and after Interuption

Fig. 6 shows the current through the circuit breaker and voltage across its terminals for Case04-LS. It can clearly seen that voltage across the circuit breaker is zero when the contacts are closed and also when the fault current is flowing. The circuit breaker is modeled as an ideal device in this simulation hence the arcing voltage is not produced.

The circuit breaker used in the system is a 115 kV 63 kA circuit breaker. The expectation is to limit the fault current to approximately 19 kA which represents a T30 duty for the circuit breaker. The description of various interruption duties is given in IEEE C37.06 [8] and IEEE C37.011 [9]. In this paper, the source side of the circuit breaker is modeled such that the TRV for circuit breaker terminal fault without CLR is within the capabilities of the circuit breaker. Fig. 7 shows the TRV obtained for BaseCase. The TRV waveform is oscillatory because a lumped equivalent circuit of the system is considered. The circuit parameters on source side are selected

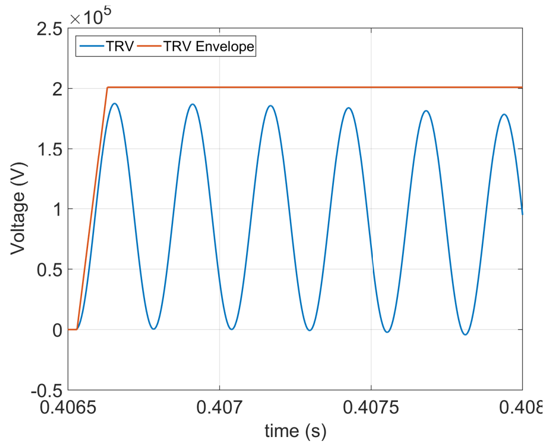


Fig. 7. BaseCase: TRV and Two Parameter TRV Envelope

so as to limit the TRV on source side to within the circuit breaker capability.

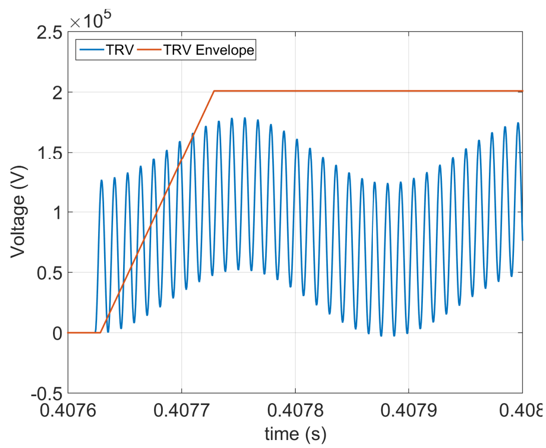


Fig. 8. Case04-LS: TRV and Two Parameter TRV Envelope

Fig. 8 shows the TRV waveforms and two parameter envelope obtained for Case04-LS. The circuit breaker interrupts a fault current of approximately 19 kA because of the limiting action of the CLR. The TRV is oscillatory in nature and is evaluated using the two-parameter envelope given in IEEE C37.06 [8]. Fig. 8 clearly shows the rate of rise of recovery voltage (RRRV) is higher than the T30 duty specified in the standard. This could lead a breakdown in the circuit breaker and fault current will start to flow again in the circuit.

Fig. 9 shows the TRV waveforms and two parameter envelope for Case04-LS. A resistance of 500 Ω is connected in parallel with the CLR in this case. The parallel resistance is connected for equivalencing the SCFCL circuit of Case02-SS where the superconductor remains in the circuit even after enter the quenching state. The TRV waveforms for Case02-LS with an inductive shunt are also shown in Fig. 9. The obtained results are the almost identical for the two cases. It can be seen the parallel resistance provides additional damping resulting in reduced TRV peak. Also, the RRRV is reduced. It can be seen that the TRV capability is exceeded in initial

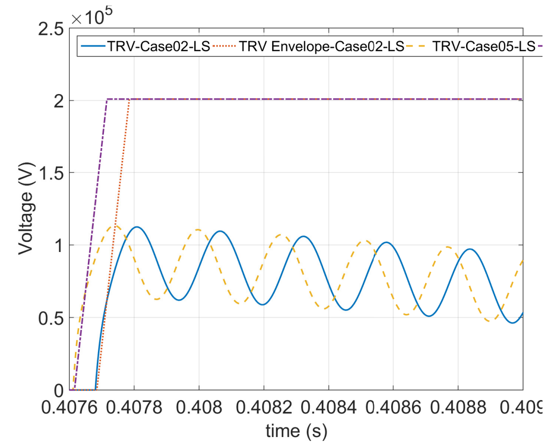


Fig. 9. Case02-LS and Case05-LS: TRV and Two Parameter TRV Envelope

period. This represents a likelihood of failure of the circuit breaker when subjected to this TRV. The application may thus is not correctly designed and mitigation methods will have to be adopted.

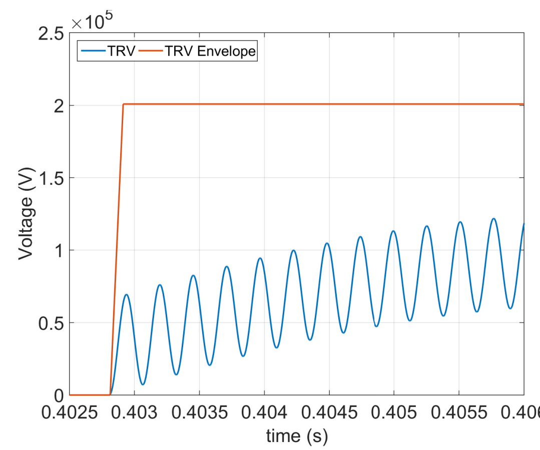


Fig. 10. Case01-LS: TRV and Two Parameter TRV Envelope

Fig. 10 shows the TRV waveforms and the two parameter envelope obtained with SCFCL with resistive shunt i.e. for Case01-LS. As can be interpreted from the figure the TRV capacity will not be exceeded and the application design is correct.

Fig. 11 shows the TRV waveform and the envelope for Case03-SS. In this case a load switch is connected in series with the super conductor as shown in Fig. 2a. The load switch disconnects the superconductor from the circuit as soon as it quenches and fault current in commutated in to the inductive shunt. A comparison of Figs. 8 and 11 shows the results are identical and Case03-LS represents a very severe TRV duty for the circuit breaker.

It can be clearly concluded that connection of CLR can have an adverse impact on the system TRV thus imposing severe interruption duty on the circuit breaker. For the case in which SCFCL is used with inductive shunt and superconductor is not disconnected after it quenches, the TRV is damped

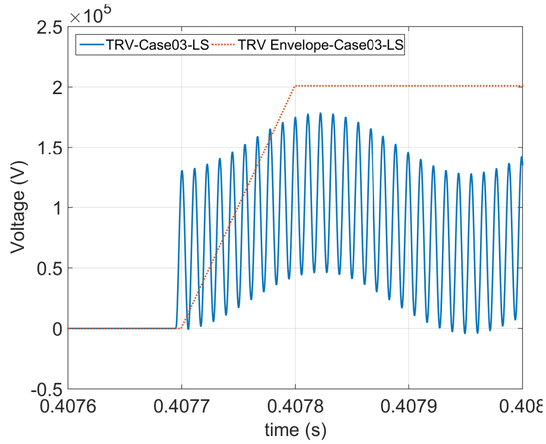


Fig. 11. Case03-LS: TRV and Two Parameter TRV Envelope

and the application may be brought within the circuit breaker capabilities. The case with SCFCL and resistive shunt has TRV which is well within the circuit breaker capabilities. The case with CLR is identical to the case with inductive shunt and recovery switch. The TRV capabilities are exceed for these two cases. A proper application of the circuit breaker will require mitigation methods to be adopted. A possible mitigation method is to connect a capacitor at the inductive shunt terminals or across the shunt.

VII. Conclusions

The SCFCL and CLR are being proposed to be used in the power system to postpone costly upgrades and replacement of equipment in substation due system expansion and increase fault current levels. The paper evaluates different shunts for use in SCFCL as current commutation and limitation path. The SCFCL and CLR are seen to be effective in limiting the fault current values to within limits of the circuit breaker capabilities. It can be concluded that the SCFCL with resistive shunt is very effective in limiting the first peak of the fault current compared to an inductive shunt. The inductive shunt appears to be more effective in limiting the steadu-state fault current value. From the point of view of TRV capability of circuit breakers, a SCFCL with resistive shunt appears to be a good solution. The SCFCL with inductive shunt and recovery switch appears to be similar to CLR from TRV perspective. With the use of SCFCL with inductive shunt the TRV capabilities of the circuit breaker are exceeded. A proper application of the circuit breaker will require mitigation methods to be adopted. A possible mitigation method is to connect a capacitor at the inductive shunt terminals or across the shunt.

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