Effect of Superconducting Fault Current Limiter on Short Line Faults

Himanshu J. Bahirat, Shrikrishna A. Khaparde, Shankar Kodle, and Vikas Dabeer

***Abstract*—The fault currents at substation buses increase due capacity addition and relieving of transmission bottlenecks. In some cases significant changes are observed to warrant remedial actions like breaker upgrades or installation of additional equipment. In order to defer investments utilities are exploring use of superconducting fault current limiters (SCFCL) and current limiting reactors (CLR).**

A superconducting fault current limiter uses material properties to rapidly transition from low to high resistance state when current through it exceeds a critical value thus commutating current into a shunt path. 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 paper analyzes the impact of SCFCL on the short line fault (SLF) capability of the circuit breaker. More specifically the effect of the choice of shunt (inductive or resistive) and stray capacitance on the SLF are investigated. The effects of recovery switch and variation of fault distance on SLF are also investigated.

The SCFCL and SLF simulations are conducted using EMT simulation package with detailed model of the SCFCL. The simulation studies indicate that the nature of the TRV changes to oscillatory with the use of inductive shunt. The triangular waveform is obtained on the line side of the circuit breaker with the use of resistive shunt. The first peak of the line side voltages appears to reduce with the use of resistive shunt.

***Index Terms*—Fault Currents,Circuit Breakers, TRV, Superconducting Fault Current Limiters, EMT, Short Line Faults, SLF.**

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].

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. In [19] the impact of different designs of SCFCL on the TRV is analyzed for terminals. It is found that the use resistive shunt may lead to better application design [19]. 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

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H. J. Bahirat is with the Department of Electrical Engineering, Indian Institute of Technology, Bombay, , India. (e-mail of corresponding author: hjbahirat@ee.iitb.ac.in)

S. A. Khaparde is with the Department of Electrical Engineering, Indian Institute of Technology, Bombay, , India. (e-mail: sak@ee.iitb.ac.in)

S. Kodle is with Applied Materials Inc., Bengaluru, India, , (e-mail: shankar_kodle@amat.com)

V. Dabeer is with Applied Materials Inc., Bengaluru, India, (e-mail:vikas_dabeer@amat.com).

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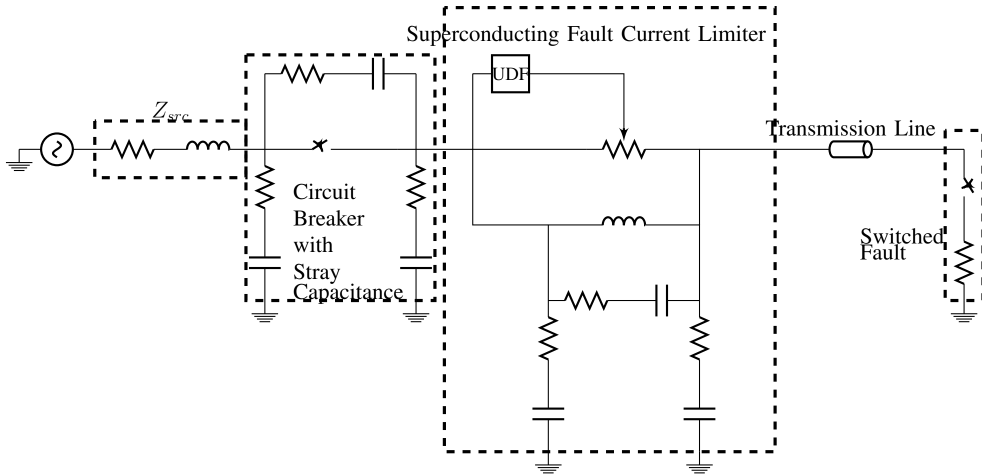


Fig. 1. System Model for EMT Simulation

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 of a shunt in SCFCL with respect to short line faults. The nature of TRV is investigated by varying the SCFCL parameters and fault distances. The paper brings out the change in nature of TRV when shunts are changed.

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 with thevenin impedance of $0.9 + j4.713\Omega$. The system model is derived by reduction from a real power system presented in [10]. The entire system is modeled and simulated using EMT simulation tool. The system assumes a ideal circuit breaker directly connected to the bus. 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]. Table.I gives the system parameters.

Fig. 1 shows a simplified model of a large system with a distributed parameter transmission line connected at the terminals of the circuit breaker. The model parameters of the transmission line are given in Table. I. A fault is created on the transmission line at a distance of 1 km from the circuit breaker terminals by closing a switch connected in series with a very small 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 SCFCL is assumed to be connected on the line side of the circuit breaker.

An investigation of the impact of the frequency dependent transmission line model indicated little impact on nature of TRV. Hence, a simple model of transmission line suitable to reproduce traveling wave behavior is considered.

TABLE I
System and Transmission Line Parameters

Parameter	Value	Parameter	Value
V_{src}	115 kV	Z_+	350 Ω
Z_{src}	0.9+j4.713 Ω	Z_0	500 Ω
I_{fault}	20-kA	v_+	$3 \times 10^8 m/s$
t_{open}	0.2 s	v_0	$2.88 \times 10^8 m/s$

IV. Superconducting Fault Current Limiters

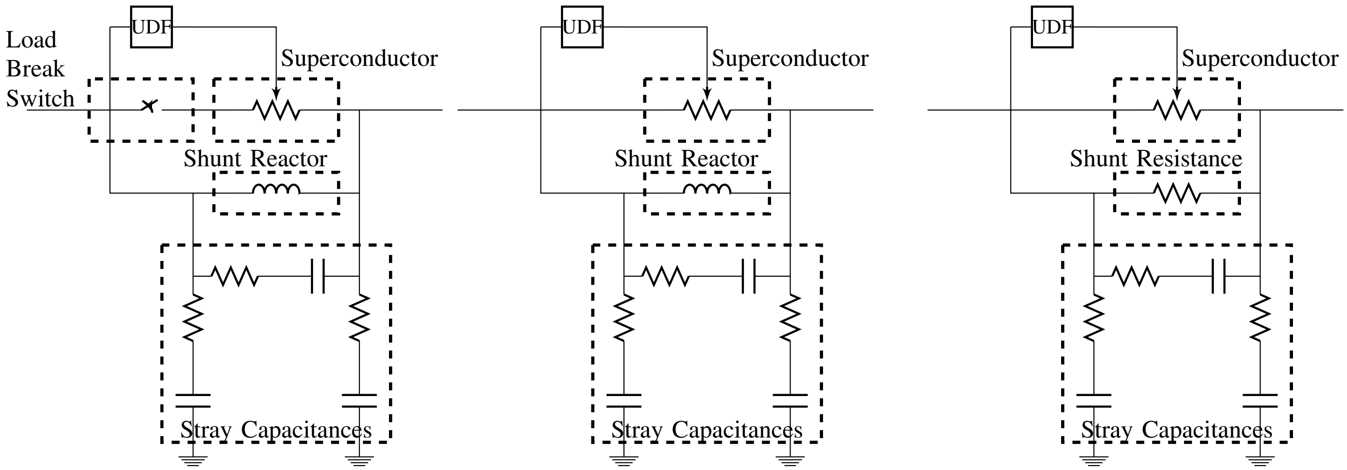
Fig. 2 shows the different SCFCL implementations. The SCFCL model consists of variable resistance i.e. the superconducting element and the shunt impedance branch. The values of the variable resistance are determined by an algorithm written using FORTRAN-like program. The modeling details of the SCFCL are discussed in Section V. 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 impact of the choice of the shunt element on short line fault and identify suitable design choices for future installations. The size of shunt element is governed by the desired fault current reduction and is calculated using a method described in Section V.

V. 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], [20]. 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



(a) With Load Break Switch (b) With Inductive Shunt Voltages (c) With Resistive Shunt

Fig. 2. SCFCL Implementation in EMT Simulation

[2]. The resistance characteristics of a superconductor can be modeled in several ways [20]:

- $R(t)$ 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

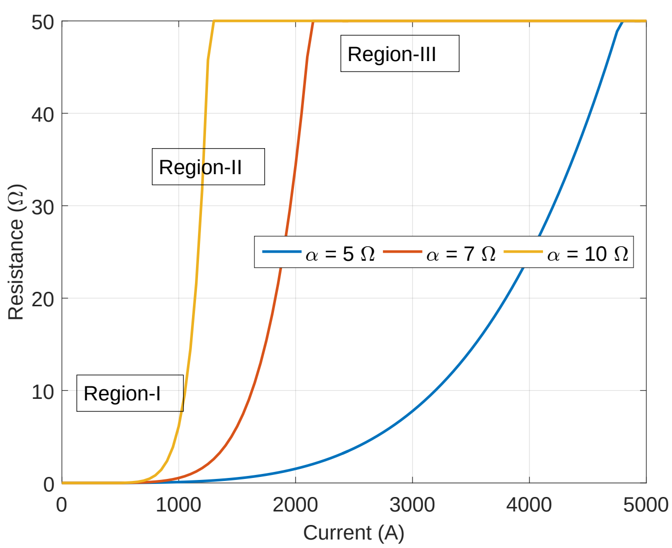


Fig. 3. SCFCL: Superconductor Resistance Characteristics

However, it is typical to model the SCFCL as function of current only and not model the thermal characteristics [20]. 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-III is recovery region where resistance exponentially reduces to zero. The resistance in the Region-III is independent of the current flowing through the circuit.

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

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 user defined function in simulation tool.

- **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 chosen to be 50 Ω based on the material properties and transition index. 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 a simulation 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). 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

TABLE II
SCFCL SIMULATION PARAMETERS

Parameter	Value
τ	1s
α	20
R_{max}	50 Ω
I_{crit}	2500 A

TABLE III
STRAY CAPACITANCE VALUES

Parameter	Value
$C_{phase-gnd}$	100 pF
$C_{term-term}$	100 pF

the shunt is determined based on desired limited value of fault current. Table. II gives the SCFCL modeling parameters.

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).

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

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. Table .III gives the values of stray capacitance for shunt reactors as obtained from IEEE C37.011 [9].

VI. TEST CASES

Table IV gives the list of test cases enumerated in order to investigate the effect of the FCL on SLF. Case-01 is a base case with no fault current limiter in the circuit. The distance of the fault from the breaker location is assumed to be 1 km for all the enumerated cases. The parametric sensitivity analysis considers different fault distances. Case-02 considers a situation when a current limiting reactor is used to limit the fault current. The value of the CLR is determined using (4). Case-03 uses a a CLR to limit the current and a large resistance is connected in parallel with the CLR. It has to be considered that the presence of CLR will reduce the power flow during normal operating conditions.

Case-04 uses a SCFCL the shunt path that limits the fault current is considered to be resistive. The value of the shunt resistance is obtained using (4). Case-05 uses a SCFCL with an inductive shunt to limit the fault current. In this case the superconductor is assumed to be continuously in circuit even after quenching. This results in increased heat dissipation in the superconductor and has important design impact on SCFCL. In certain implementation a switch may be used to interrupt the residual current in the superconductor. In oder to understand the impact of such operation on the main circuit breaker Case-06 is defined. The current limiting element is still a inductor in this case. The series connected switch is opened immediately after the superconductor has quenched.

TABLE IV
TEST CASES

Case Number	Description	Shunt Type
Case-01	Base Case	No SCFCL
Case-02	With CLR	No Shunt
Case-03	With CLR	Parallel Resistance
Case-04	SCFCL	Resistive Shunt
Case-05	SCFCL	Inductive Shunt
Case-06	SCFCL	Series Switch-Inductive Shunt

VII. RESULTS

Fig. 4 shows the TRV obtained for test cases Case-01, Case-02 and Case-03 respectively. Fig.4-Case-01 clearly shows the characteristic triangular waveform associated with SLF. The TRV exceeds the TRV capability of the circuit breaker. Fig. 4-Case-02 shows the TRV and circuit breaker capability curves obtained when a current limiting reactors (CLR) is used. The nature of the TRV changes from triangular to oscillatory. The circuit breaker capability is exceeded and it may be subjected to very high rate of rise of the recovery voltage. Fig.4-Case-03 shows the TRV waveforms for the case when CLR has a high value damping resistance connected across it. The nature of the TRV changes for such parallel L-R combination. The nature of the resultant TRV appears to dependent on the value of the parallel resistance. The nature changes from triangular to exponential and then to oscillatory for large values. The RRRV also exceeds the circuit breaker capability. The Case-03 facilitates development of simple circuit for the analysis of SLF with SCFCL. This is because the superconductor may remain in the circuit after quenching. The resistance may not change substantially at the point of interruption since the recovery period long and depends on the cryogenic system.

Fig. 5 presents TRV waveforms when different designs of SCFCLs are used to limit fault current. Fig. 5-Case-04 shows the TRV waveforms when a resistive shunt is used. The nature of the TRV is seen to been triangular but the TRV capability of the circuit breaker is not exceeded. The reduction of the TRV peak and the rate of rise can be attributed to the shunt resistor. Fig.5-Case-05 shows the TRV waveforms for the case with SCFCL and a shunt inductor. The results of the case are similar to the Case-03. A triangular TRV is obtained because the resistive FCL is connected in parallel with the shunt inductor. The result of Case-05 is similar to that of Case-03. In addition, it can also be observed that TRV analysis of Case-05 can be performed by considering SCFCL resistance as constant during the period of analysis.

Fig. 5-Case-06 shows TRV waveforms for the SCFCL case with an inductive shunt and a switch for disconnecting super-

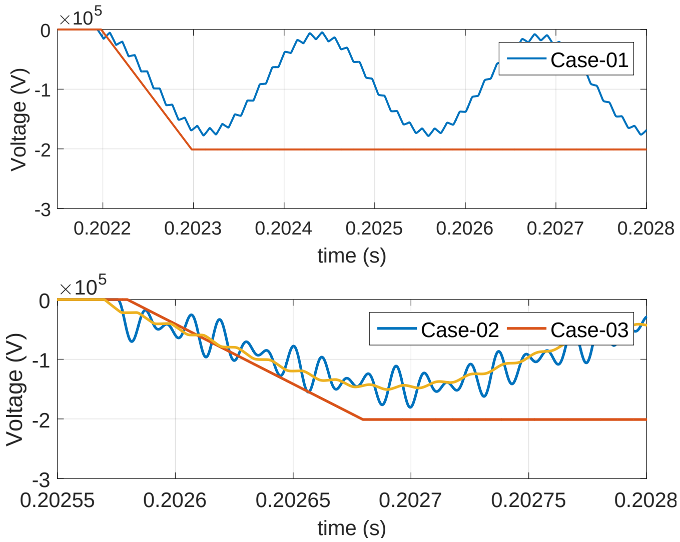


Fig. 4. SLF TRV Response with and without FCL a. Without FCL b. With CLR

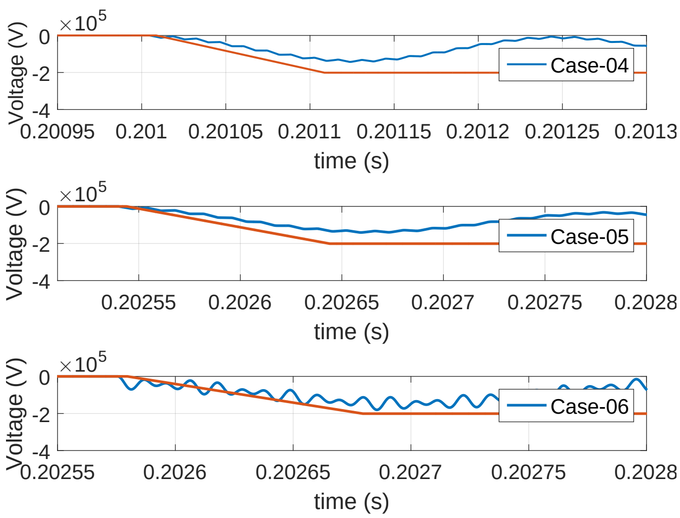


Fig. 5. SLF with different SCFCLs a. With L-Shunt b. With R-Shunt c. With L-Shunt and RUL

conductor. The nature of the TRV changes to being oscillatory since the switch disconnects the resistive superconductor from the circuit. The analysis for Case-06 can thus be performed with assumption of shunt inductance in the circuit. The RRRV and first peak exceed the circuit breaker capability. Thus, mitigation methods may have to be included.

Fig.6 shows the variation of TRV first peak and RRRV with the variation of parallel resistance for Case-03 and R_{max} variation for SCFCL used in Case-04 and Case-05. The variation of parallel resistance indicates that the TRV first peak and RRRV increases with increase in the value of resistance for Case-03. The TRV waveform becomes oscillatory as the value of resistance is increased. The analysis is also valid for R_{max} variation in Case-05. For Case-04, the variation of the value of R_{max} has no impact on the TRV peak and RRRV. Infact, the RRRV and TRV peak is observed to minimum with when a resistive shunt is used. The value of peak and RRRV

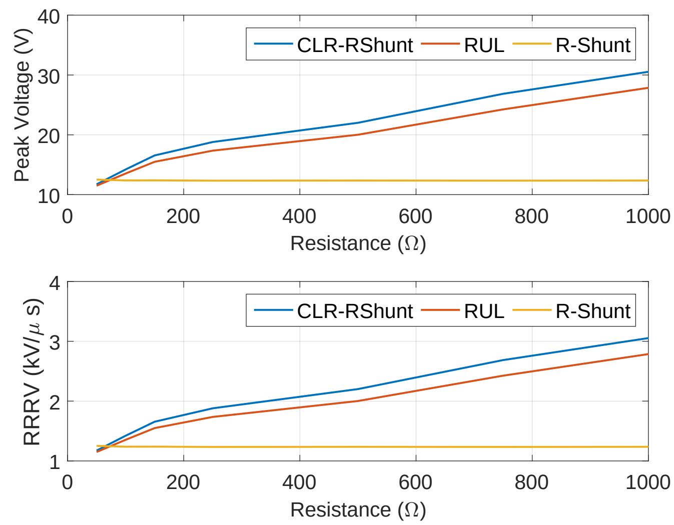


Fig. 6. Impact of R_{max} and R_{PL} variation on SLF Peak and RRRV

will depend on the value of shunt resistance which in turn depends on the desired fault level.

Fig. 7 show the results of the sensitivity analysis performed with the distance of fault from the circuit breaker and R_{max} for Case-04. The results indicate the first peak of the TRV increase with the distance of fault from the circuit breaker. The increase in peak value and the RRRV may be attributed to the higher voltage supported by the faulted line which increases with increase in the fault distance. It was also observed that the TRV peak and RRRV do not vary when R_{max} is varied with fixed fault distance.

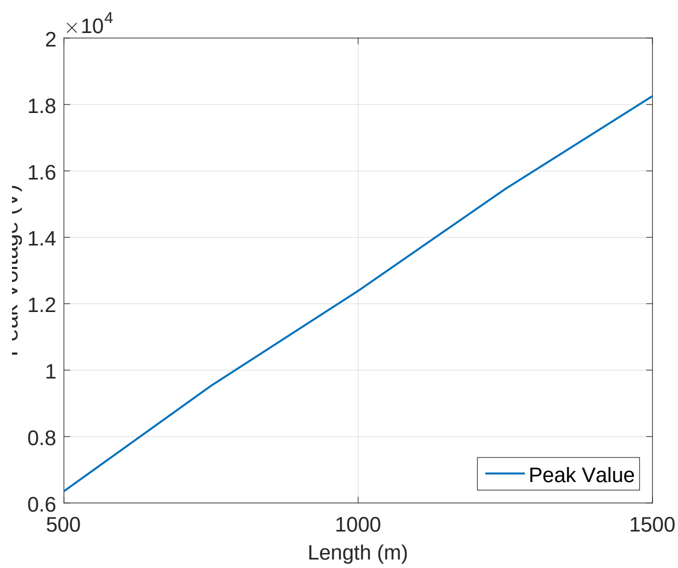


Fig. 7. Impact of R_{max} in Case-04 on variation of SLF Peak

Fig. 8 shows the results of sensitivity analysis for Case-05 where the fault distance from circuit breaker terminals is varied along with variation in R_{max}. It can be clearly seen that the TRV peak increases with increase in distance. This can be attributed to the higher voltage supported by the faulted transmission line. It can also be observed that the RRRV increases with R_{max} and fault distance. It is also clear from the analysis that TRV peak and RRRV increase with the increase in value of R_{max}.

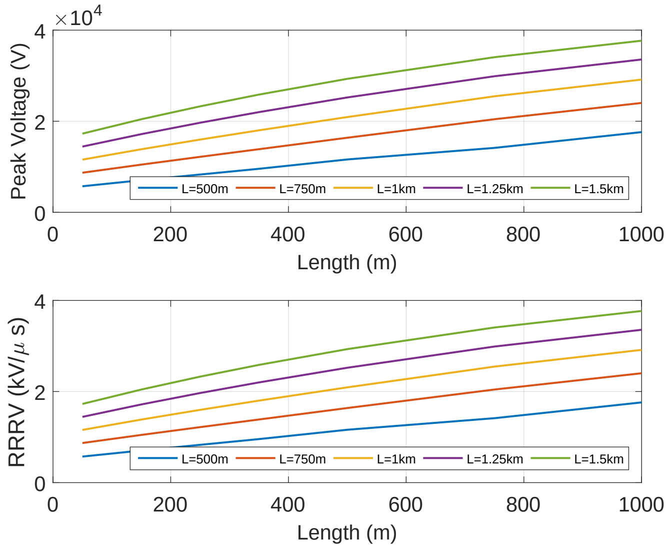


Fig. 8. Impact of R_{max} in Case-05 on variation of SLF Peak and RRRV

VIII. Conclusions

The paper presents the results of investigation related to short line faults in presence of current limiting reactors and SCFCL. The different designs of the SCFCL are presented. It can be concluded that the use of CLR results in triangular TRV changing to oscillatory TRV. In case of CLR with large parallel resistance, the nature of TRV again changes to triangular for relatively smaller values of the parallel resistance. The analysis of systems with SCFCL may be performed with assumption of constant resistance in parallel with the shunt branch because at the instant of interruption the voltage changes faster than the resistance of the superconductor in quenched state. The SCFCL with inductive shunt results in triangular TRV for relatively smaller values of R_{max} but becomes oscillatory as R_{max} is increased. The TRV peak peak value increase with fault distance since higher voltage is supported by the faulted line. The RRRV for SCFCL with inductive shunt also increases with fault distance and value of SCFCL quench resistance. In case of SCFCL with resistive shunt the TRV is triangular. The TRV is within the capabilities of the circuit breaker with small values of the shunt resistor.

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