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Fusion TRV Limiter a Solution to Modify Interrupting Characteristics of CBs with Presence of Resonance Type SFCL

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***Abstract*— Applying FCLs in power system lead to suppress short-circuit level and burden of CBs. Alongside with their astounding advantages; it is possible that the FCLs have destructive effects on interrupting characteristics of CBs such as TRV characteristics. Among various topologies introduced for FCLs, Resonance type SFCL affects incredibly on TRV characteristics and causes severe interrupting conditions for CB. In this paper to modify TRV characteristics of CBs with presence resonance type SFCL, Fusion TRV Limiter which consists of parallel metal oxide surge arrester and capacitor between CB terminals is proposed. Proposed method is evaluated under different conditions in EMTP-RV® environment with selecting of reliable parameters for FCL and system. The proposed method is finally compared with other methods; obtained results show that the simple proposed method has high performance to modify TRV characteristics.**

Keywords—Fault Current Limiter (FCL); Circuit Breaker (CB); Transient Recovery Voltage (TRV); Rate of Rise Recovery Voltage (RRRV); Metal Oxide Surge Arrester

I. INTRODUCTION

Increasing demand for electricity continuously and consequently, the growth of power grids and distributed generation resources, have caused short-circuit level to be risen in power system drastically. Increasing of this destructive phenomenon can impose irrecoverable damages on the power system. Increasing of nominal and thermal stresses on equipment, reducing of the sensitivity of protective system, failing in circuit breakers (CBs) operation, and generally the suppressing in stability and reliability of power system are examples of serious problems after fault occurrence. Hence, effort to suppress short-circuit level in power system has been caused proposing of different approaches by researchers from the past to the present. For instance, change in topology of system by updating CBs and other power apparatus, splitting the power grid into smaller sectors, introducing a system with higher voltage level, applying high voltage fuses or series reactors, and etc [1]. However, each of aforementioned approaches has restrictions from technical and economic aspects. Using of fault current limiters (FCLs) is an appropriate solution to avoid above-mentioned problems. FCLs have very low voltage drop and loss under normal conditions. Under fault conditions, suppress current drastically decrease in just a millisecond by entering impedance with considerable value to the power system or applying special characteristics of resonance circuit. The type of impedance can be resistive, inductive or composite [1-3]. Effort to reach such operation with the lowest delay has been caused development of various FCLs with different technologies such as liquid metals, superconducting material, and semiconductors. Nowadays, superconducting FCLs (SFCLs) is more common than others due to the high performance, negligible losses at normal operation, and limitation of fault current at first cycle without external fault detector system. However, with neglecting utilized technology in this device, FCLs such as other equipment affect on system parameters. In [3], some of the positive and negative effects have been reported. One of these problems is impact of FCLs on the transient recovery voltage (TRV) characteristics of CBs. Rate of rise of recovery voltage (RRRV) and the magnitude of TRV can be considered as two the most important parameters of TRV characteristics in successful/unsuccessful operation of CB. Depending on type of FCL, TRV characteristics can be experienced various conditions [4-7]. However, among different topologies, the FCLs with resonance principle seriously increase the TRV characteristics of CB so that it grapples with severe conditions to interrupt [7].

A solution for this problem is updating of CB by higher withstand TRV peak value and RRRV, but it is not economical, especially, reconfiguration is impossible in some of power systems. Also, adding external phase to ground capacitor, adding an external capacitor in parallel between CB terminals, and increasing stray capacitance of the FCL by adding a parallel capacitor are other scenarios to modify TRV characteristics of CB. Aforementioned scenarios only modify RRRV parameter and do not have tangible effect on the peak of TRV [4, 8, and 9].

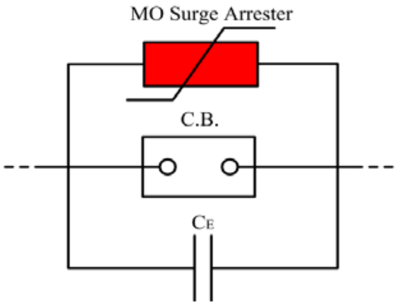


Fig. 1. Fusion TRV limiter

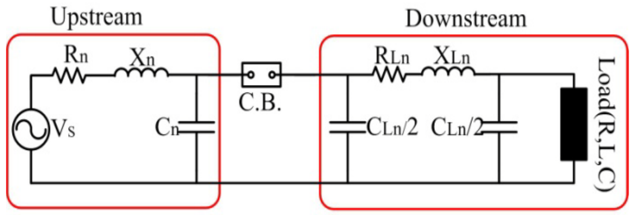


Fig. 2. Overall schematic of power system in TRV studies

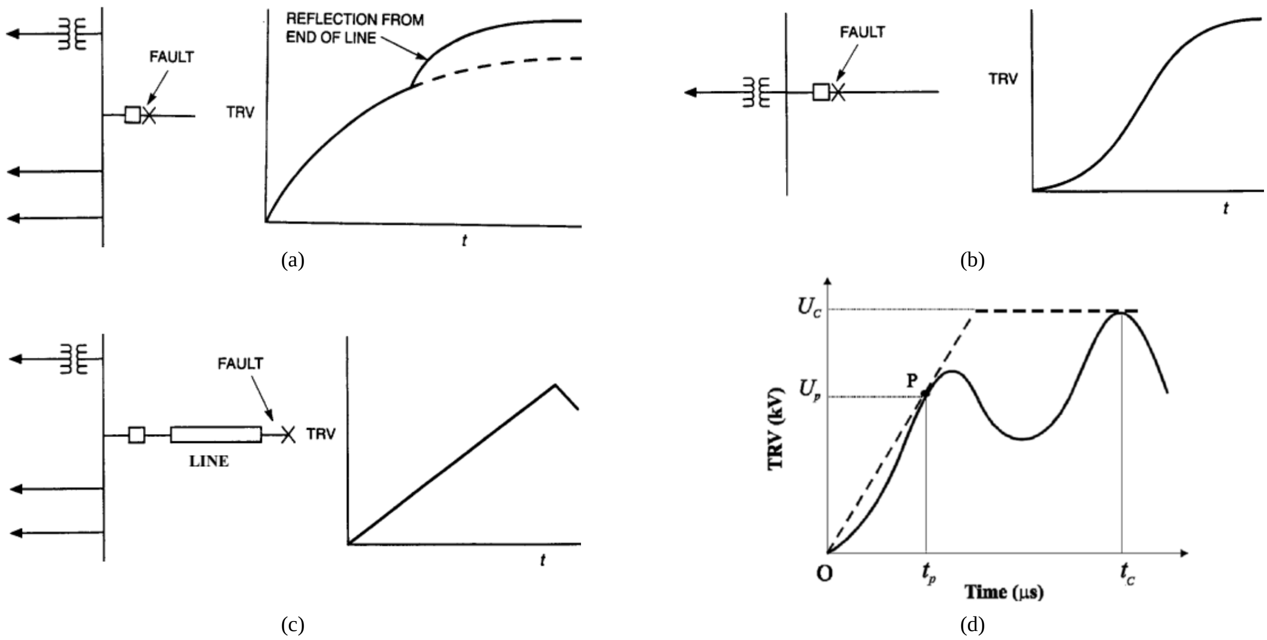


Fig. 3. The waveforms of TRV under different conditions, (a) Exponential TRV, (b) Oscillatory TRV, (c) Triangular TRV, (d) Waveforms of the TRV with four parameter envelope [10, 12]

In this paper, Fusion TRV limiter consisting of parallel metal oxide surge arrester and capacitor between CB terminals is proposed to modify TRV characteristics of CBs with presence resonance type SFCL, as shown in Fig. 1. The simulation results confirm proposed scheme is simple and effective to modify TRV and RRRV in comparison to other methods.

II. Review of Transient Recovery Voltage (TRV)

According to standard IEEE-C37.011, transient recovery voltage is the voltage that appears across the breaker contacts upon interrupting of the current [10]. The nature of this phenomenon is rooted the transient response of RLC circuits. After the arc extinguishes between contacts, power system is divided to two sections of downstream and upstream of CB. In this moment, due to intrinsic resistance, inductance and stray capacitance of equipment and transmission lines; each section forms the series RLC circuit which exchange energy among inductor and capacitor. Different natural frequency and damping each section creates transient voltage with high frequency and magnitude that is named TRV. Figure 2 shows the overall schematic of system in TRV studies.

TRV appears in all of CBs from low voltage to high voltage, however, the type of fault, power factor, the CB type, and grounding arrangement are parameters which can affect on the severity of TRV. Performed studied shows the three-phase ungrounded fault at terminal and the faults that occur in isolated system create severe interrupting conditions. However, IEEE-C37.011 suggests three-phase grounded fault for TRV studies, because the contingency of mentioned faults is very low [10]. Also, in line faults, short line faults (SLF) have dominant effect on TRV characteristics. Despite the in line, faults the fault current is lower than terminal fault and it seems the CB can interrupt current in convenient conditions, but travelling waves with saw-tooth waveform and extra high frequency significantly influence on RRRV value.

Waveform of TRV relying on location of fault can be oscillatory, exponential, triangular (saw-tooth shape) or combinations of them. A typical exponential TRV is shown in Fig. 3a. This exponential TRV typically occurs when at least one transformer and one line are on the unfaulted side of the CB and a three-phase fault is cleared at the CB terminals. The oscillatory TRV shown in Fig. 3b occurs when a fault is limited by a transformer or a series reactor and no transmission line or cable surge impedance is presented to provide damping. SLF exhibit the characteristic shown in Fig. 3c. The transmission line surge impedance, Z, determines the nature of the TRV. The rate of rise of the saw-tooth shaped TRV is generally higher than that of exponential or oscillatory TRV [10].

To facilitate for comparison between obtained test result with an allowable TRV, or to compare a CB specified TRV capability and a system TRV obtained by calculation, IEEE STD C37.04b have introduced “two-parameter” and “four-parameter” envelopes [10-11]. Figure 3d illustrates an example of a TRV with four parameters envelope, U_c and the slope of the OP line is defined as the TRV peak value and RRRV respectively [10, 12].

III. Power System Description

A. Modeling of System with Presence FCL

Figure 4 shows the single line equivalent of under study system. FCL model considered in the study is a simple series LC resonance circuit consists of a capacitor C_{FCL} and superconducting reactor L_{FCL} which resonance frequency tuned at the line frequency (50Hz or 60 Hz) [13, 14]. In the normal state, resonance circuit has a negligible losses and voltage sag. As a fault occurs, a particular characteristic of the resonance circuit causes fault current to be increased gradually. The metal oxide varistor (MOV) protects the capacitor from considerable high voltage generated by LC resonance circuit at the instant of a fault clearing. When the capacitor voltage exceeds of protective level of MOV, it operates and clips capacitor voltage. The varistor protective voltage (VPV) level is normally set about 2 p.u of crest voltage across capacitor at rated conditions. This concept has been verified in [13] by experimental testing and mathematically equation.

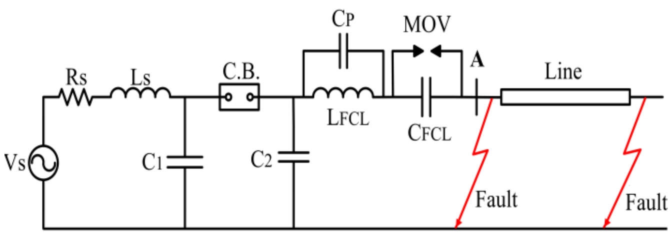


Fig. 4. Single line equivalent of system under study

The stray capacitances C_1, C_2 and C_P correspond to the source side capacitor-to-ground, the capacitor-to-ground of the FCL and stray capacitance of the reactor, respectively. System data has been expressed in Table I.

It should be noted that the value of R_S and L_S, short-circuit impedance has been calculated according to IEC60909-0 by assuming that the short-circuit level is 650 MVA [15].

TABLE I. System Data

	Parameters	Values
Source Side	V_S	20kv
	F	50 Hz
	L_S	1.95 mH
	R_S	61.53 mΩ
	C_1	0.775 µF
FCL	C_2	10 nF
	C_P	50 nF
	L_{FCL}	7.5 mH
	C_{FCL}	937.759 µF

The transmission line has been modeled using frequency dependent (FD) model in EMTP-RV. Transmission line data are as followed:
Conductor: mink, Length: 30 km, Ruling span: 80 m

B. Model of surge arrester

With respect to the nature of the TRV, a frequency dependent model of surge arrester should be used which is suitable for fast transient waves [15]. The proposed arrester model has been shown in Fig. 5 [16]. This model is known as Pinceti model which has been derived from an IEEE model for arrester.

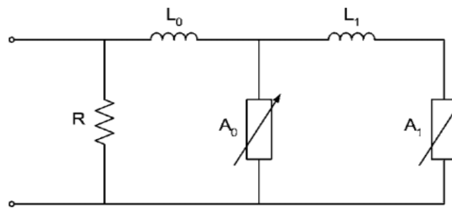


Fig. 5. Pinceti model [16]

Where R is set to 1MΩ to avoid numerical instabilities and the nonlinear characteristics of the A_0 and A_1 have been presented in Table II.

The parameters L_0 and L_1 of the recommended model are obtained by following equations:

$$L_0 = \frac{1}{4}.\frac{V_{r1/T_2} - V_{r8/20}}{V_{r8/20}}.V_n \tag{1}$$

$$L_1 = \frac{1}{12}.\frac{V_{r1/T_2} - V_{r8/20}}{V_{r8/20}}.V_n \tag{2}$$

Where V_n represents the arrester rated voltage, V_{r1/T_2} is the residual voltage for a 10 kA fast front current surge ($1/T_2$) and $V_{r8/20}$ is the residual voltage for a 10 kA current surge with 8/20 µs shape. The manufacturer’s data of used surge arrester has been given in Table III.

TABLE II. U-I CHARACTERISTICS FOR A_0 AND A_1 [17]

I (kA)	U (p.u)	
	A_0	A_1
0.01	0.8750	-
0.1	0.963	0.769
1	1.05	0.850
2	1.088	0.894
4	1.125	0.925
6	1.138	0.938
8	1.169	0.956
10	1.188	0.969
12	1.206	0.975
14	1.231	0.988
16	1.250	0.994
18	1.281	1
20	1.313	1.006

TABLE III. MANUFACTURER'S DATA OF THE METAL OXIDE SURGE ARRESTER U_r = 12.5KV [18]

Discharge Current (kA)	(1/…)μs		(8/20)μs		
	5	10	2.5	5	10
Residual Voltage (kV)	31.7	33.5	27.7	29	30.7

IV. SIMULATION RESULTS

The above mentioned typical system for three types of faults, three-phase ungrounded (severe TRV), three-phase grounded (ANSI suggested), and single line to ground (most common fault) at different distance of installation location of FCL has been simulated. In all cases, it has been assumed that the fault occurs at t=60ms after the beginning of simulation and the CB clears the fault after 3 cycles. Figure 6, shows fault current before and after installation of FCL during three-phase grounded fault at bus A (terminal fault). It can be seen that the installation of FCL suppressed fault current at its first peak.

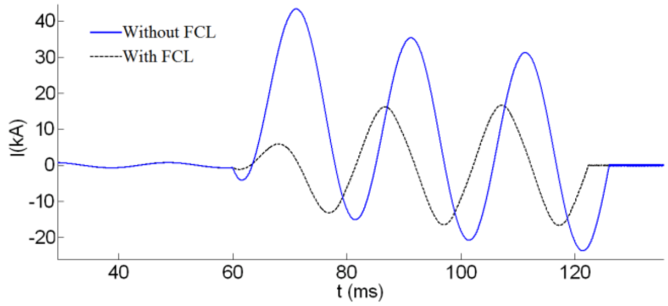


Fig. 6. Fault current before and after installation FCL during three-phase grounded fault at bus A

Figures 7-8 shows TRV across breaker contacts before and after installation of FCL during three-phase grounded fault at bus A, respectively. It can be observed that the highest TRV peak occurs in three-phase ungrounded. For each of two cases, values of TRV and RRRV have exceeded by significant margin than standard rating due to the presence of FCL. Corresponding to international standard IEC62271-100, values of TRV and RRRV for 20kV network are 45.3 kV and 1.05 kV/μs, respectively [19].

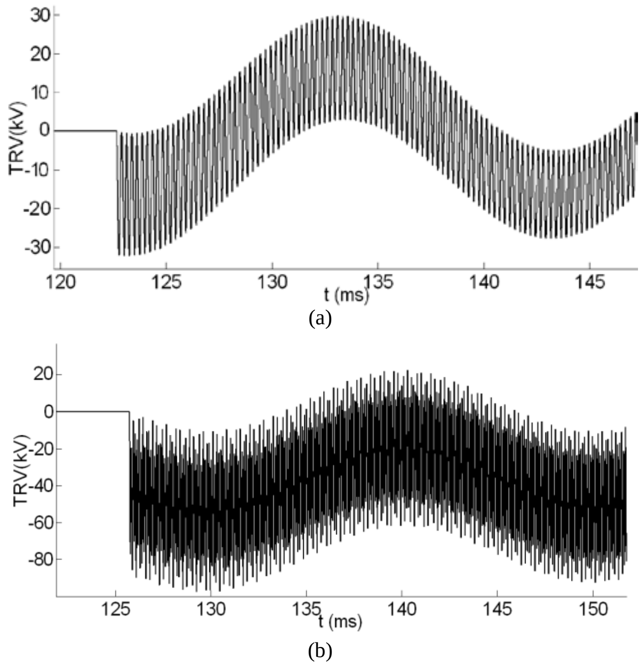


Fig. 7. Voltage across circuit breaker contacts for a three-phase grounded fault at bus A, (a) without FCL, (b) with FCL

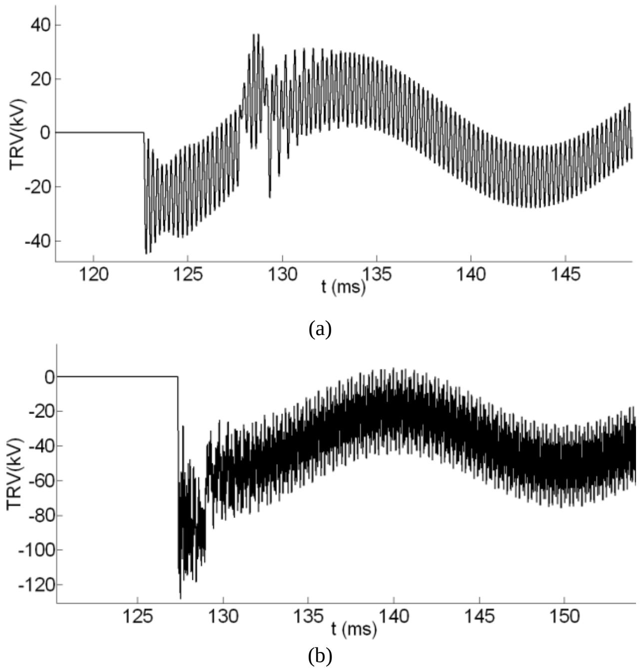


Fig. 8. Voltage across circuit breaker contacts for a three-phase ungrounded fault at bus A, (a) without FCL, (b) with FCL

Increasing of TRV and RRRV can establish arc across breaker poles and prevent successful interruption. To solve this problem, in this paper, Fusion TRV limiter between CB terminals is proposed. Figure 9 shows the TRV and RRRV during three-phase grounded and ungrounded fault in 2 states of single surge arrester and Fusion structure, respectively. It can be observed that single surge arrester modifies TRV and RRRV (TRV=29.3kV, RRRV=0.98 kV/µs in grounded fault), but it cannot provide safety margin for RRRV. Adding capacitor or same Fusion state reduce RRRV significantly (TRV=29.23kV, RRRV=0.44 kV/µs). It has been assumed that C=100nf is true for above simulation. As the capacitance of C would be increased, the RRRV would be decreased more.

Also, it can be observed from Fig. 10 that three-phase ungrounded fault type is the most severe case to examine the energy absorbed by metal oxide surge arrester.

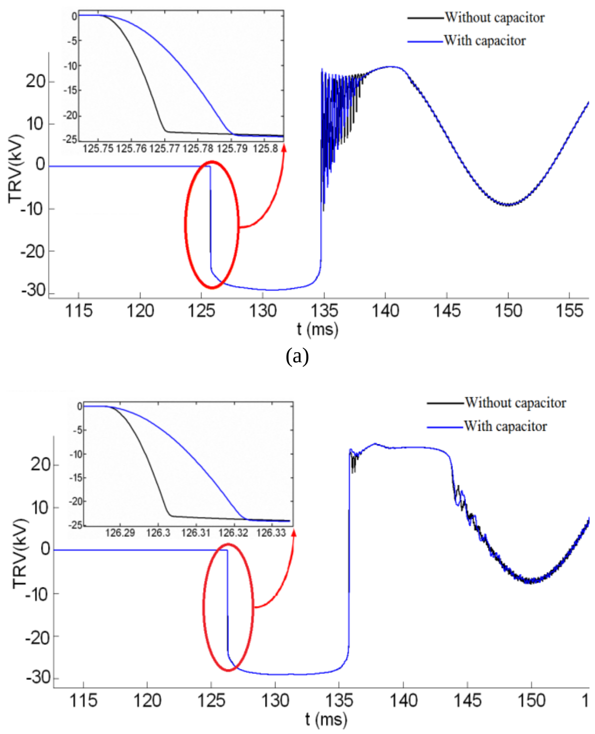


Fig. 9. Voltage across circuit breaker contacts for three-phase grounded fault and three-phase ungrounded fault at bus A with FCL after installation surge arrester with or without capacitor, (a) three-phase grounded fault, (b) three-phase ungrounded fault

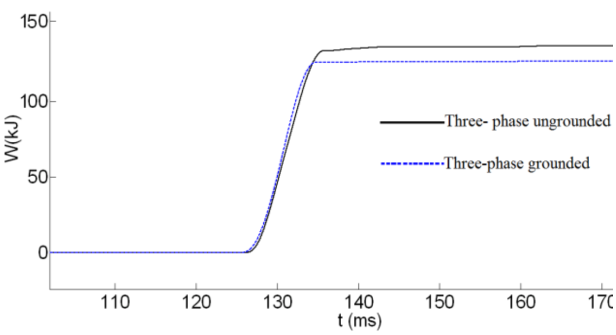


Fig. 10. Energy absorbed by metal oxide surge arrester

In Table IV, effect of fault location on TRV and RRRV in different cases has been provided. In all cases with installing of FCL, TRV and RRRV have been increased. Three-phase ungrounded fault and short line fault have the highest TRV peak and RRRV, respectively. But with installing single surge arrester parallel with CB, the values of TRV and RRRV decrease. However, RRRV still has no suitable safety margin at the nearest fault to terminal. This problem can be solved by fusion scheme and decreased interrupting characteristics of CB to appropriate value.

At the end, proposed method is compared to other presented scenarios in [6, 9, and 10]. Figure 11 shows the effect of adding the capacitor in parallel with CB. As can be observed, adding capacitor significantly reduces RRRV, but it increases the TRV peak in three- phase ungrounded fault.

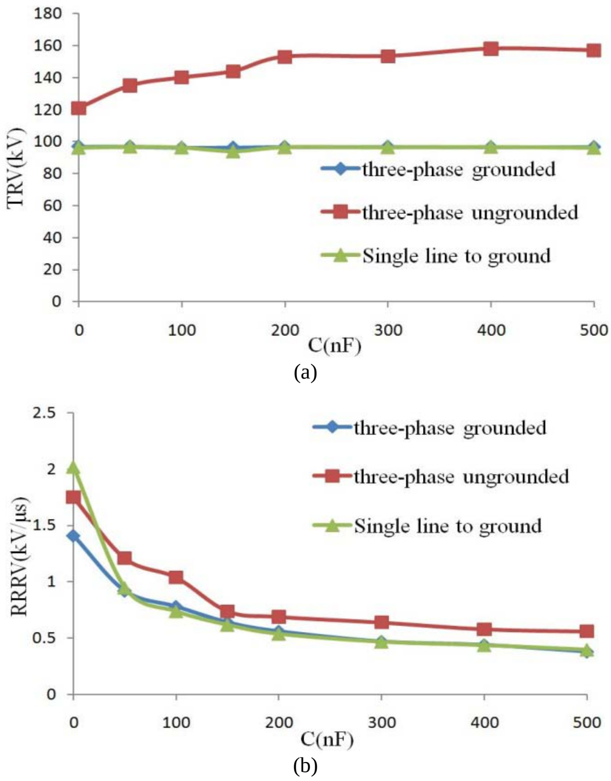
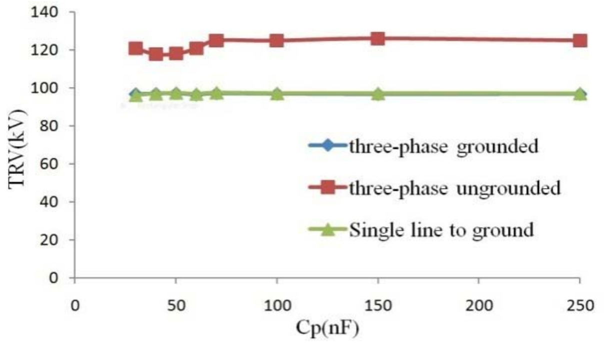


Fig. 11. The effect of adding the capacitor in parallel with CB on TRV peak and RRRV values. (a) TRV peak value, (b) RRRV value

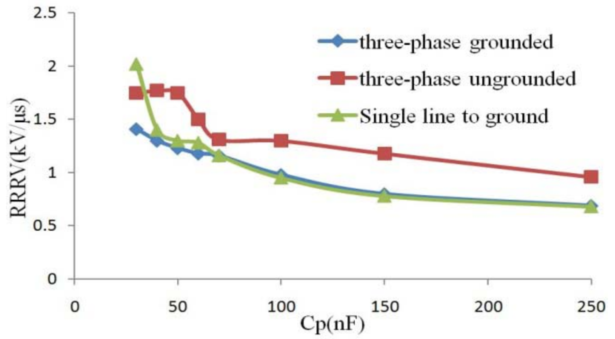
Figures 12-14 show the effect of adding external capacitor to each of stray capacitances on TRV and RRRV. In all the cases, by adding external capacitor RRRV is decreased, however, increase of C_1 has a lower effect on RRRV than other cases. Also, in all the cases increases of stray capacitors do not have a tangible effect on the peak of TRV.

By comparing the previous scenarios, it can be seen that parallel capacitance with CB has the best performance to reduce RRRV.

Table V shows summary simulation results and trade off various TRV limiters from different aspects.

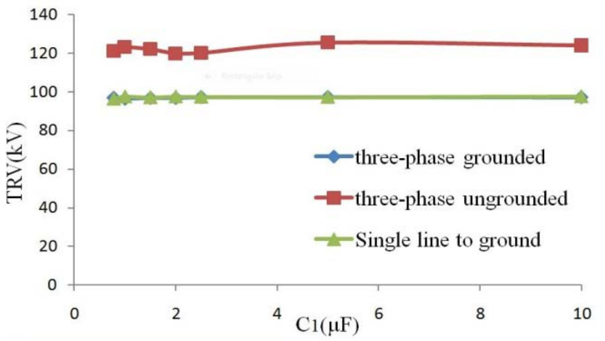


(a)



(b)

Fig. 12. The effect of increasing of stray capacitor of FCL (C_P) on TRV peak and RRRV values, (a) TRV peak value, (b) RRRV value



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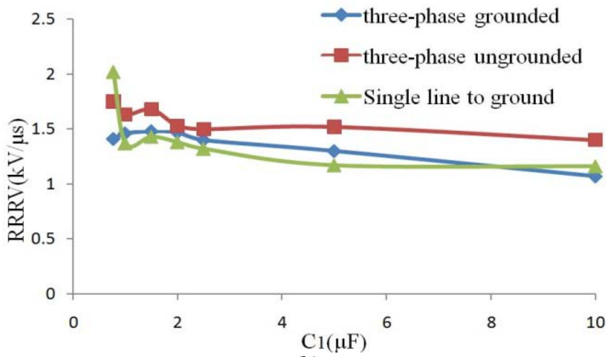
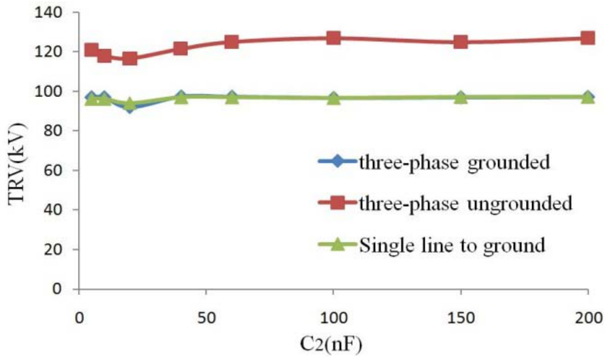
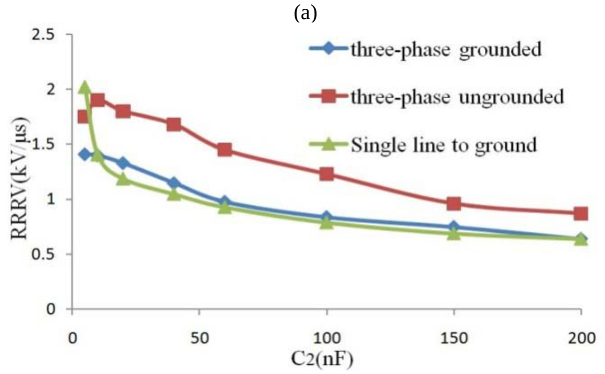


(b)

Fig. 13. The effect of increasing of source side capacitor-to-ground (C_1) on TRV peak and RRRV values, (a) TRV peak value, (b) RRRV value



(a)



(b)

Fig. 14. The effect of increasing of capacitor-to-ground of FCL (C_2) on TRV peak and RRRV values. (a) TRV peak value, (b) RRRV value

V. CONCLUSION

The use of resonance SFCL to mitigate short-circuit level in power system can have a destructive impact on TRV characteristics of CB. To solve this problem, in this paper, parallel metal oxide surge arrester and capacitor between CB terminals has been proposed. Obtained result, which has been done with the frequency dependent model of surge arrester, shows efficiency of proposed method to modify the highest RRRV and TRV peak that occurs in short line fault and three phase ungrounded fault at the terminal. Finally, with comparing to other methods for limiting TRV, it is shown that proposed method is simple and effective.

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TABLE IV. RELATIONSHIP BETWEEN FAULT LOCATION AND VALUES OF THE TRV AND RRRV AT DIFFERENT FAULT

Type of fault	Fault distance(km)	Without FCL		With FCL						
				Without TRV limiter		With TRV limiter				
						Parallel surge arrester		Parallel surge arrester with capacitance(100nF)		Peak of current surge arrester (kA)
		TRV (kV)	RRRV (kV/μs)	TRV (kV)	RRRV (kV/μs)	TRV (kV)	RRRV (kV/μs)	TRV (kV)	RRRV (kV/μs)	
Three- phase grounded	0	32.052	0.36	96.9	1.41	29.3	0.98	29.23	0.44	8.884
	0.3	33.66	0.44	98.661	1.84	29.4	1.06	29.4	0.49	8.519
	1	34.3	0.58	106.99	1.55	29.264	1	29.23	0.52	7.75
	2.5	31.352	0.52	108.32	1.6	29.038	1.02	29.05	0.54	6.865
	5	30.252	0.47	67.1	1.05	27.848	0.75	26.9	0.25	2.734
	10	26.231	0.39	41.69	0.65	25.34	0.54	25.17	0.2	0.785
	30	26.031	0.13	31.64	0.22	22.81	0.2	22.3	0.09	0.076
Three- phase ungrounded	0	43.199	0.407	121.17	1.75	29.474	0.95	29.41	0.49	8.894
	0.3	43.077	0.486	117.15	1.8	29.313	1	29.35	0.46	8.539
	1	35.037	0.53	109.04	1.83	29.282	1.02	29.23	0.47	7.95
	2.5	29.666	0.73	110.23	1.7	29.04	1.05	29.02	0.41	6.885
	5	27.05	0.617	63.98	1.09	27.88	0.95	27.8	0.3	2.774
	10	26.231	0.33	40.01	0.61	25.6	0.56	25.8	0.19	0.79
	30	26.072	0.13	31.66	0.23	22.95	0.21	22.6	0.1	0.078
Single line to ground	0	32.05	0.38	96.21	2.02	29.23	0.95	29.198	0.44	7.8
	0.3	25.15	0.65	86.36	2.2	21.431	1	28.8	0.4	5.8
	1	29.2	0.73	53.7	0.82	23.96	0.5	26.7	0.27	1.43
	2.5	27	0.42	29.53	0.52	23.61	0.35	23.6	0.18	0.18
	5	26.22	0.15	29.57	0.35	22.68	0.3	21.1	0.14	0.044
	10	24.934	0.11	33.04	0.4	23.42	0.32	23.38	0.16	0.08
	30	24.3	0.12	30.91	0.21	22.33	0.2	22.35	0.08	0.045

TABLE V. TRADE OFF VARIOUS TRV LIMITERS

Type of TRV Limiter	Impact on TRV and RRRV values		Restriction
	TRV	RRRV	
Increase of C_1	Weak	Average	Insulation problems, large volume
Increase of C_2	Weak	Good	Insulation problems, large volume
Increase of C_p	Weak	Good	C_P must be withstand High pulse voltage generated across FCL at inductive type
Increase of C	Weak	Excellent	C must be Withstand peak of TRV during fault clear
Parallel surge arrester	Excellent	Good	Peculiar surge arrester, surge arrester must be designed to withstand the energy absorbed during fault clearing about 1 cycle
Fusion	Excellent	Excellent	Peculiar surge arrester, Large volume