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Transient recovery voltages of circuit breakers in UHV transmission system

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Circuit breakers are an important element in a substation, which is used for coupling of busbars, transformers, transmission lines, switching of shunt reactors, capacitor banks etc. The most important task of a circuit breaker is to interrupt fault currents and thereby protect various power system components. This task requires operation of the circuit breaker under different making and breaking conditions such as - faults in the vicinity of the circuit breaker, short-line faults, out-of-phase closing/ opening, switching of - capacitor /shunt reactor banks, no-load transformers/lines etc. During opening operation, after the arc extinction, the insulating medium between the breaker contacts has to withstand the rapidly increasing recovery voltage. This recovery voltage has a transient component (transient recovery voltage, TRV) caused by the system when current is interrupted. The TRV of the Circuit Breaker is a decisive parameter that limits the interrupting capability of the Circuit Breaker. The TRV to be adopted for system voltages of 1200 kV, towards which our country is migrating, needs to be estimated by transient studies as they cannot be extrapolated from lower voltage systems. This paper deals with the modeling and study results of TRV for typical 1200 kV networks and a sample 1200 kV Indian system using Electromagnetic Transient Programs (EMTP).

Keywords: *Transient Recovery Voltage (TRV), Rate of Rise of Recovery Voltage (RRRV), Electromagnetic Transient Program (EMTP), Circuit Breaker (CB).*

1.0 INTRODUCTION

When the circuit breaker contacts separate, an electric arc will be established, and current will continue to flow through the arc. Interruption will take place at an instant when the alternating current reaches zero and the arc has quenched. After the arc extinction, the insulating medium between the contacts must withstand the rapidly increasing recovery voltage. This recovery voltage has a transient component referred to as the Transient Recovery Voltage, (TRV) caused by the system when current is interrupted. The interruption is successful if the circuit breaker is able to withstand the TRV and the power frequency recovery voltage following current zero. The final value of this voltage equals the source voltage while the initial value is equal to the low arc voltage which may be very low. There exists an oscillatory condition involving single frequency or may contain multiple frequencies, depending upon the connected network.

The rate of rise of the recovery voltage (RRRV) determines the ability of the quenching medium to interrupt the arc, since the rate of rise of dielectric strength must exceed the RRRV. In systems having low natural frequency, use of oil circuit breakers is adequate, while systems with high natural frequency necessitate the use of air-blast and SF_6 breakers due to high RRRV.

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A TRV stress similar to that which occurs for a short-line fault occurs due to the busbar connections on the supply side of the circuit breaker. This TRV stress is referred to as the Initial Transient Recovery Voltage (ITRV).Because of the relatively short distances involved, the time to first peak will be short,typically less than 1 μs. Thus, the system's TRV characteristic is often complex, and a computer simulation is generally done for evaluation.

The TRV to be adopted for system voltages of 1200 kV, towards which our country is migrating, needs to be estimated by performing transient studies as they cannot be extrapolated from lower voltage systems. Thus computations have been made for a typical 1200 kV Transmission System for determining the TRV parameters associated with Terminal Fault test Duties (T10, T30, T60, and T100), Transformer Limited Fault (TLF), Short Line Fault (SLF), Out-of-Phase, Capacitive Current Switching, Reactor Terminal Fault cases etc. for 1200 kV Circuit Breaker. The results of these studies have been presented in this paper.

2.0 TRV IN SINGLE PHASE AND THREE-PHASE NETWORKS

2.1 Single Phase system

Figure 1(A) shows the equivalent of a typical system network with L representing the fault level of the network behind the circuit breaker CB, R - losses in the network and C –total stray capacitance on the source side. Figure 1(B) shows the voltage V and the fault current that is to be interrupted by the CB for a fault at its terminals.

The current interruption takes place only at current zero and at this instant the source voltage will be at its peak value (as the circuit is purely inductive). The voltage across the circuit breaker will be (a) equal to the arc voltage, as long as the current has not been interrupted (b) approaches the value of supply voltage through a noscillation with a frequency determined by inductance - L and capacitance-C of the network after interruption. The voltage across the CB after interruption is called the recovery voltage. The initial oscillatory part of this recovery voltage is referred to as the Transient Recovery Voltage(TRV), while the later part is called power frequency recovery voltage.

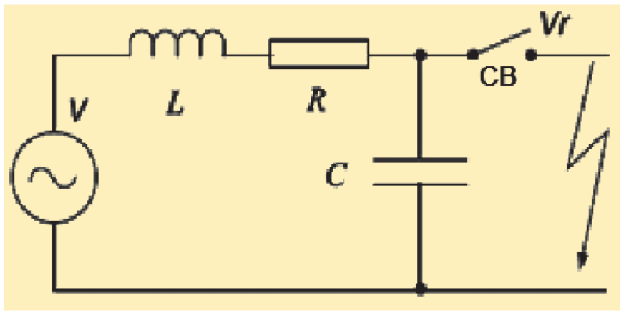

FIG. 1(A) SINGLE PHASE EQUIVALENT -TYPICAL NETWORK

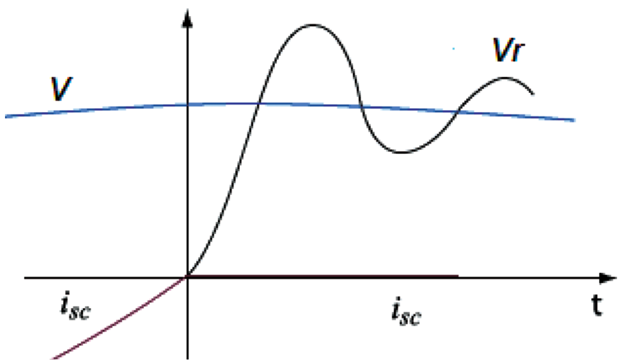

FIG. 1 (B) SHORT CIRCUIT CURRENT AND VOLTAGE

Complicated wave shapes of the TRV are possible depending on the network configuration. An exponential TRV wave shape (Figure 2(A)) is seen in networks having infinitely long lines, and the wave shape shown in Figure 2(B) is seen in network with long lines, as the reflections adds to the TRV shape. EHV networks may have TRV wave shapes that are combinations of the single-frequency response of Figure 1 (B) and the exponential of Figure 2(B).

Both IEC and IEEE standards have almost the same approach for specification of the standard transient recovery voltages. For rated voltages (a) below 100 kV, a TRV waveshape as illustrated in Figure 3(A) is assumed. It is described by means of two parameters, u_c and t_3. This two-parameter method is used for lower breaking currents.(b) For rated voltages 100 kV and above, a TRV waveshape shown in Figure 3(B) is assumed. It is described by means of four parameters, u_1, u_c, t_1 and t_2. This four-parameter method is used for high breaking currents (terminal fault type tests at 100% and 60% of rated breaking current).

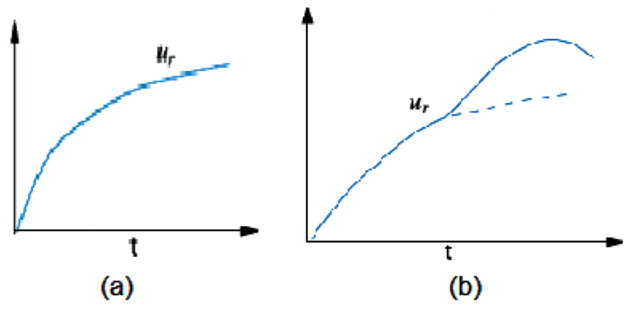

FIG. 2 DIFFERENT TRV WAVE SHAPES

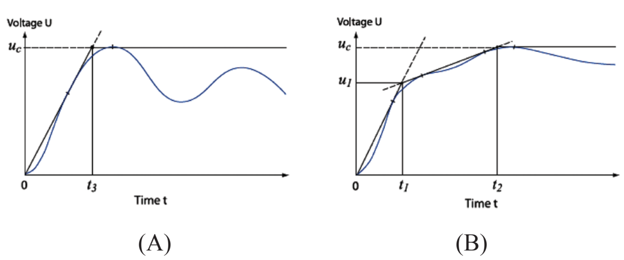

FIG. 3 TRV (A) 2 PARAMETER (B) 4 PARAMETER METHODS

2.2 Three phase system

In a three-phase system, several types of faults can occur, such as - single-phase to ground, two-phase and three-phase (with or without ground).Nearly 80% of all faults in a system are single phase faults and the short circuit current magnitude is lower than for 3-phase faults, which occurs only in ten percent of cases. However, the most severe duty of a breaker occurs under a 3-phase fault and this governs the breaker design.

Consider the three-phase equivalent circuit of a network with effectively earthed neutral as shown in Figure 4(A). The three-phase fault is isolated and has no connection to earth. When the first pole (pole a) of the CB interrupts the fault, symmetry is lost and a two-phase fault remains, causing the potential of the faulted point to shift. The recovery voltage Vna across the breaker poles is given by Va-Vn. The voltage of the faulted point related to earth, $\overline{V_n}$ will attain a value half way between $\overline{V_a}$ and $\overline{V_c}$ after interruption of the current in phase a, due to symmetry in the circuit. The value of the recovery voltage will be 1.5 times the phase to neutral voltage ($1.5\overline{V_a}$).

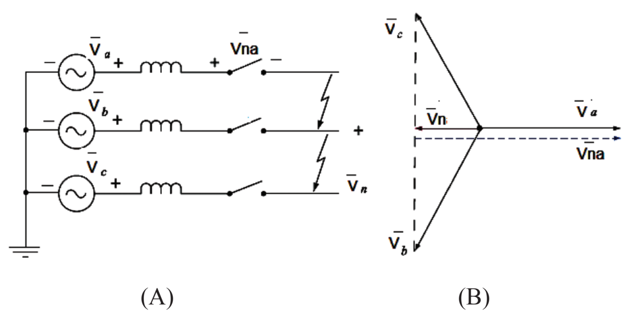

FIG. 4 (A) 3-PHASE NETWORK
(B) VECTOR DIAGRAM

In case of three phase faults, during interruption process of a three pole circuit breaker all the three phases will not open simultaneously, thereby, first pole to clear will experience highest transient recovery voltage compared to other poles. First pole to clear factor is the ratio of the power frequency voltage across the first interrupting pole before current interruption in the other poles, to the power frequency voltage occurring across the pole or the poles after interrupting in all three poles [1]. First pole to clear factor (kpp) of short-circuit fault interruption is one of the important parameters to estimate the maximum stress in service due to the Transient Recovery voltage (as recovery voltage peak increases by this factor). The first-pole-to-clear factor kpp depends on the network conditions. For the case of a three-phase-to-earth fault in a network with earthed neutral, kpp is related to the positive sequence reactance X_1 and zero sequence reactance X_0 of the network as:

$$\text{First Pole to Clear Factor} = \frac{3}{(2+\frac{X_1}{X_0})} \qquad \text{....(1)}$$

IEC standard 62271-100 gives the value for both earthed and unearthed condition and hence uses first-pole-to-clear factors of kpp = 1.5 for non-effectively earthed and kpp = 1.3 for effectively earthed neutral systems.

IEEE standards specify the same first-pole-to-clear factors as IEC. In addition, however, IEEE takes into consideration the possibility that isolated three-phase faults may occur. Therefore, as an option, a first-pole-to-clear factor kpp = 1.5 is specified for rated voltages of 100 kV and above.

3.0 APPLICATIONS

TRV also depends on the application of circuit breaker. Some important switching cases and also the test duties described by the IEC standards are

(a) Terminal faults

(b) Short Line faults

(c) Out of phase switching

(d) Capacitive switching

(e) Shunt reactor current switching

(f) Transformer limited faults

3.1 Terminal faults

Terminal faults are faults located a tor in the vicinity of the circuit breaker terminals. In this case, the total impedance upto the fault point is equal to the impedance on the source side. Thus, the terminal fault is the condition that gives the highest short- circuit current.

IEC requires tests with 10, 30, 60 and 100% of the rated short-circuit breaking current (T10, T30, T60 and T100- described in section 4.0). A first pole to clear factor of 1.3 and 1.5 is specified by IEC depending on the way the system is earthed.

3.2 Short Line Faults (SLF)

Short line faults are faults to ground along the transmission line within a few kilometers of the circuit breaker. The fault current is determined by the source impedance together with the impedance of the line between the circuit breaker and the fault location. As the fault occurs close to the circuit breaker the fault current will be almost as high as the terminal fault current. The rate-of-rise of TRV will be more severe than at corresponding terminal fault resulting in major stresses on the circuit breaker.

The TRV characteristic for the SLF condition has been found to be in the shape of saw-tooth type. It has been experienced that the severity of SLF is mainly dependent on the rate of rise of recovery voltage (RRRV), since it comes higher than from other cases where the waveform was found exponential or oscillatory in general. SLF exhibits the characteristic shown in Figure 5.

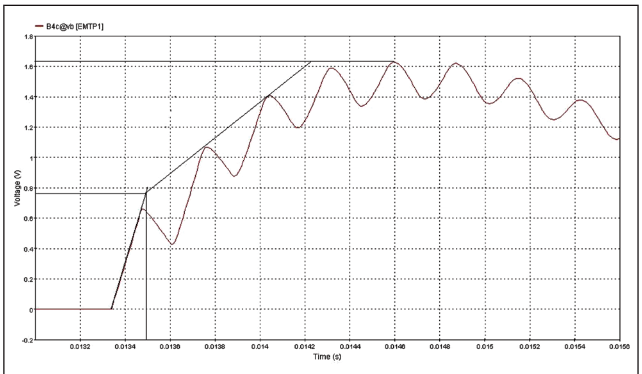

FIG. 5 TRV CHARACTERISTIC DURING SHORT LINE FAULT

The test duties for SLF as per IEC are L90 and L75. Both IEEE and IEC require the SLF tests to be performed at 90 % and 75% of the rated short circuit current.

3.3 Out of Phase Switching

Out-of-phase switching happens when different parts of the network are out of synchronism. The magnitude of TRV for out-of-phase switching is generally higher than that for interruption of short-circuit current, and leads to severe dielectric stress on the circuit breaker.

Out of phase switching happens when (a) a generator is switched on accidentally to the network at a phase angle which is out of phase (b) different parts of a transmission network lose their synchronism.

Under the worst possible out-of-phase conditions, the voltage vectors on each side of the circuit breaker may be separated by 180 electrical degrees. The corresponding maximum power frequency recovery voltage will be twice the voltage across each breaker pole in case of effectively earthed neutral and may reach thrice the value in case of effectively earthed neutral.

Both IEC and IEEE standards specify tests at twice the rated voltage for effectively earthed neutral systems and in case of non-effectively earthed neutral systems a value of 2.5 is adopted.

3.4 Capacitive Switching

Interruption of capacitive currents encountered during switching of capacitor / filter banks, no load transmission lines/cables etc is generally an easy duty for a circuit breaker as the currents are generally small. But however due to restrikes that occur, undesirable over voltages may occur in the network.

The peak value of recovery voltage for capacitor switching is generally found to be three times the supply voltage for the first pole to clear. The IEC and IEEE standards specify capacitive voltage factors for different types of capacitive loads. These capacitive voltage factors are used for calculation of the relevant test voltage in a single-phase test circuit for simulating the conditions in the first-pole-to-clear of a three-phase network.

3.5 Inductive Switching

Inductive switching occurs in the case of either switching of shunt reactors or switching of unloaded transformers. The currents to be interrupted are in the range of a few amperes to some hundreds of amperes (low compared to the short-circuit currents).

3.6 Transformer Limited Faults (TLF)

Severe TRV conditions occur, when faults occurs immediately after the transformer without appreciable impedance between transformer and the circuit breaker. Fault and circuit breaker can be on the same side of the transformer or on either side. In such cases, the rate-of-rise of transient recovery voltage (RRRV) exceed the values specified in the standards for terminal fault test duty T10 and hence cannot be covered by T10 duty for terminal fault. Accordingly in IEC 62271-100, a separate TLF test duty has been specified for high voltage CBs [2].

4.0 TEST DUTIES

The important basic short circuit test series consists of test duties such as (a) T10, T30, T60 and T100 for terminal faults (b) L90, L75 and (L60) for short line faults (c) OP1 and OP2 for out of phase faults as defined below.

(a) Test duty T10- It consists of the rated operating sequences at 10% of the rated short circuit breaking current with a dc component at contact separation not exceeding 20% and a transient and power frequency recovery voltage.

(b) Test duty T30- It consists of the rated operating sequences at 30% of the rated short circuit breaking current with a dc component at contact separation not exceeding 20% and a transient and power frequency recovery voltage.

(c) Test duty T60- It consists of the rated operating sequences at 60% of the rated short circuit breaking current with a dc component at contact separation not exceeding 20% and a transient and power frequency recovery voltage.

(d) Test duty T100- It consists of the rated operating sequences at 100% of the rated short circuit breaking current with a transient and power frequency recovery voltage.

(e) Test duty L90 and L75- For short-line fault breaking tests IEC considers primarily the test current for faults at line lengths corresponding to 90 % and 75 % of the rated short circuit breaking current.

(f) OP1 and OP2- The test duties defined in IEC standards for out of phase switching is OP1 and OP2. IEC requires the test to be performed at 7.5 % and 25% of the rated short-circuit breaking current.

5.0 CASE STUDIES FOR ANALYSIS OF TRV

(a) A typical 1100 kV power system model (Figure 6) as considered by CIGRE WG A3.28 for computation of TRV was simulated. All simulations have been done using EMTP software.

The complete data for the system was available for simulation. The sources at substations A, B, C and D (500 kV substations) are represented as equivalent sources with a short circuit current of 50 kA, and having a TRV peak of 784.9 kV with RRRV of 2.04 kV/µs.

The 1100 kV transmission lines have been simulated by the JMarti's model in EMTP at a frequency of 5.0 kHz. Appropriate values of capacitances (phase-to-ground) have been considered for the busbars. Lightning arresters have been simulated at each of the line ends on all transmission lines. The transformers at all the substations are modeled as three-winding transformers with their appropriate winding resistance, leakage reactance and capacitance – phase to ground on each side of the winding.

Table 1 shows the steady state voltage distribution under normal conditions at various buses. Table 2 shows the TRV and RRRV for Circuit Breaker's (B and D) located at either end of the transmission line from substation B to substation D for a three-phase fault at F1 (shown in Figure 6).

The values of TRV and the wave shape obtained for the system studied were closely matching with the values obtained by Cigre WG. This validates the modeling adopted for computation of Transient Recovery Voltages.

(b) A typical 1200 kV Indian Transmission Network (close to practical system - identified

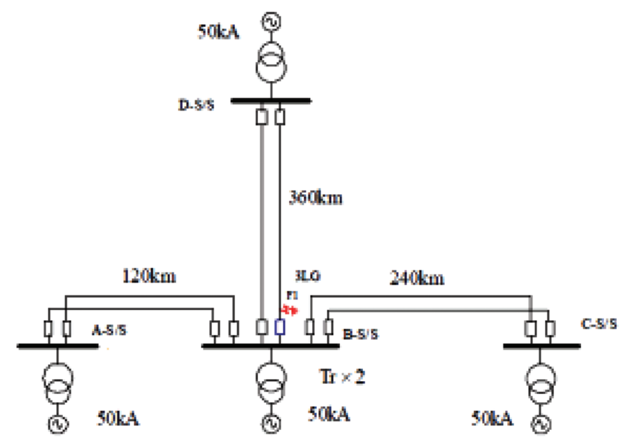

FIG. 6 TYPICAL 1100 KV SYSTEM – CIGRE MODEL

by M/s Power Grid) shown in Figure 9 was next considered for determining the TRV. Faults were created at various locations on the transmission line to assess the TRV associated B*, D *: Breaker at Substation B and D respectively on line BD with different kinds of test duties, viz. T10, T30, T60, T100, Transformer Limited Fault (TLF), Short Line Fault (SLF), Out-of-Phase, Capacitive Current Switching, Reactor Terminal Fault cases etc. In all cases studied and reported, three-phase to ground fault having the lowest probability of occurrence but generally producing the highest TRV has been considered. Appendix I gives the data used in this case study.

TABLE 1

STEADY STATE VOLTAGE DISTRIBUTION

kV Peak, Ph-Grd			
A S/s	**B S/s**	**C S/s**	**D S/s**
898.7	908.8	895.03	897.3
kV RMS, Ph-Ph			
1100.7	1113.04	1096.18	1098.98

TABLE 2

MAXIMUM TRV AND RRRV

CB	**Inter-ruption Order (Ph)**	**Highest Voltage Peak kV**	**Inter-rupting cur-rent kA peak**	**RRRV kV/µs**	**Osc No.**
B*	3 (B ph)	1360	29.8	0.81	Fig 7
	2 (Y ph)	1305		0.84	
	1 (R ph)	1144		0.88	
D*	3 (B ph)	1504	4.03	0.67	Fig 8
	2 (Y ph)	1614		0.96	
	1 (R ph)	1523		0.82	

For standardization purposes upto 800 kV, two-parameter method has been used for short circuit currents equal to/less than 30% of the rated breaking current. For all other short circuit current values, four parameter method has been used [2].

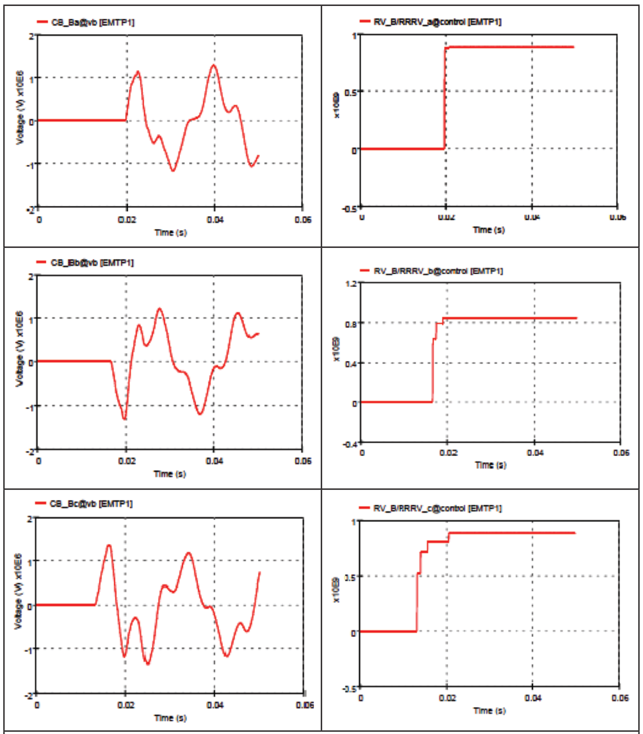

FIG. 7 TRV AND RRRV FOR CB ‘B’

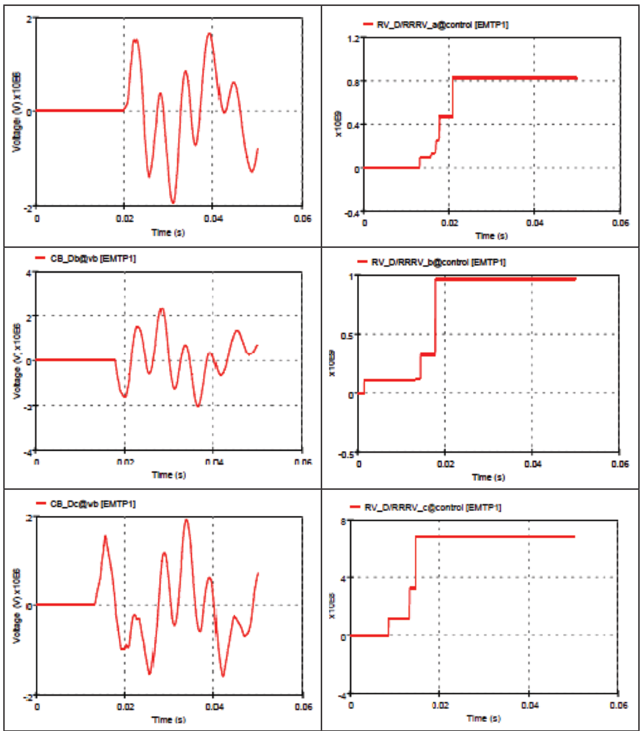

FIG. 8 TRV AND RRRV FOR CB ‘D’

The same is also observed for 1200 kV, that two parameter method is sufficient to analyze the test duties i.e. T10, T30. However, four parameter method is required to analyze other test duties. The system modeling adopted for various power system components is similar to that adopted for the typical 1200 kV system explained in (a). The results of simulation studies for computation of TRV Peaks and RRRV as seen by different circuit breakers are given in Table 3. The fault locations indicated in the table are shown in the single line diagram of Figure 9.

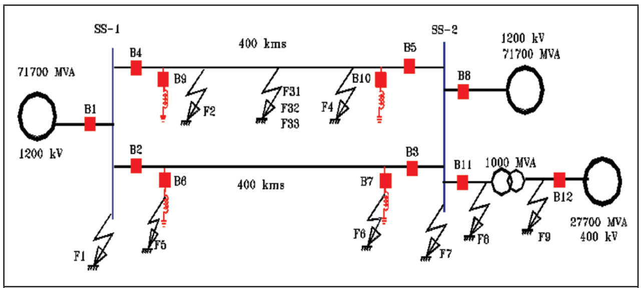

FIG. 9 SLD OF TYPICAL INDIAN SYSTEM

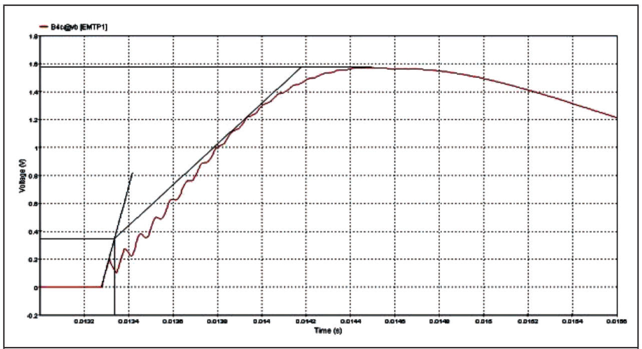

FIG. 10 TRV FOR L90

The TRV characteristic for short line fault (L90) for the typical Indian system is shown in Figure 10 above. The TRV peak (Uc) in this case was found to be 1592.1 kV peak and the RRRV was 3.99 kV/μs. For the case of transformer limited fault, the TRV peak and RRRV was found to be 1664.5 kV peak and 12.46 kV/μs respectively (Figure 11). These values are well within those specified by standards [2-3] i.e. 1799 kV peak for TRV and 16.1 to 18.0 kV/μs for RRRV.

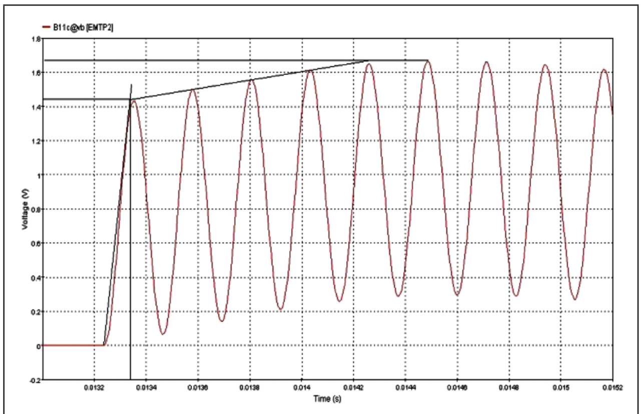

FIG. 11 TRV FOR TRANSFORMER LIMITED FAULT

6.0 CONCLUSIONS

Transient Recovery Voltage (TRV) of Circuit Breaker is a decisive parameter that limits the interrupting capability of the circuit breaker. As the TRV parameters for 1200 kV circuit breaker cannot be extrapolated from the lower voltage system, transient studies are to be carried out. Thus, studies have been carried out to determine the Transient Recovery Voltage (TRV) and RRRV for a typical 1200 kV Indian system using EMTP software.

In this paper, results of the TRV parameters associated with Terminal Fault test Duties, Transformer Limited Fault (TLF), Short Line Fault (SLF), Out-of-Phase, Capacitive Current Switching, Reactor Terminal Fault cases etc. has been presented.

The highest computed RRRV value of 12.46 kV/µsec is met during Transformer limited fault (TLF). Study shows that special attention is to be given while designing/optimizing the 1200 kV circuit breakers parameters for actual commercial 1200 kV transmission network for few cases such as transformer limited fault, short line fault & capacitor switching current interruption cases where UHV circuit breaker duties are more stringent. Such studies are helpful in fine tuning the technical parameters for upcoming commercial projects.

ACKNOWLEDGEMENT

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[2] IEC 271-100:2008, High-voltage switchgear and controlgear - Part 100: Alternating-Current Circuit-Breakers.

[3] CIGRE Technical Brochure 456, April 2011, "Background of Technical Specifications for Substation Equipment exceeding 800 kV AC".

[4] CIGRE Technical Brochure 362, December 2008, "Technical Requirements for Substation Equipment exceeding 800 kV AC".

APPENDIX I

(a) 400 kV and 1200 kV equivalent Sources

For 1200 kV:

Positive sequence impedance:

R1 = 0.5018 Ω, L1 = 0.06389 H

Re = 80 Ω, Ce = 1.7 µF Cp = 0.02µF

For 400 kV:

Positive sequence impedance:

R_1 = 0.574 Ω, L_1 = 0.01828 H

R_e = 80 Ω, C_e = 0.66 µF C_p = 0.02µF

(b) Shunt Reactors:

MVAR rating: 660 MVAR

X/R : 346

(c) Bus Bar:

Capacitance (Ph-Grd): 0.01µF

(d) Transformer Parameters

Rated MVA Capacity	Primary :1000 MVA	
	Secondary 1000 MVA	
	Tertiary 333 MVA	
Voltage Rating (kV)	Primary :1150/√3 kV, Y	
	Secondary: 400/√3 kV, Y	
	Tertiary :33 Δ	
Impedance	HV winding resistance (Ω) 0.997	% Xps : 18
	IV winding resistance (Ω) 0.182	% Xpt :40
	LV winding resistance (Ω) 0.005383	% Xst:20
Capacitance (pF)	Cpri-grd	6000
	Csec-grd	3000
	Cter-grd	12000

(e) Transmission lines

- Line Length: 400 km, Two single circuit lines, fully Transposed

Parameters	Phase Conductor	Ground Conductor
Diameter (cm)	3.84	1.9
T/D ratio	0.375	0.39
DC resistance (Ω/km)	0.05595	0.221
No. of sub-conductors	8	-
Bundle Spacing - cm	45	-
Conductor Sag -m	12.7	10.1
Earth Resistivity Ω m	100	

(f) Surge Arrester Characteristics

I (kA_{pk})	0.5	1	2	10	20
V (kV_{pk})	1380	1440	1500	1600	1700

Voltage Rating: 850 kV Ph-Grd, RMS

No. of columns: Four

Energy discharge capability: 55 MJ

TABLE 3

CALCULATED TRV AND RRRV FOR 1200 KV INDIAN TYPICAL SYSTEM

Fault Case		Test Duty	CB	First Ref Voltage U_1 (kV)	Time t_1 (μs)	TRV Peak U_c (kV)	RRRV (U_1/ t_1 kV/ μs)
Terminal Faults(TF)	F1	T30 (TF)	B2	1039.9	1680	1662.9	0.62
		T30 (TF)	B4	1057.3	1655	1659.2	0.64
	F2	T100 (TF)	B4	1343.2	752	1626.01	1.79
		T10 (LLF)	B5	673.3	845	2146.4	0.80
	F4	T10 (LLF)	B4	747.4	900	2250.03	0.83
		T100 (TF)	B5	1247.2	690	1512.7	1.81
	F7	T30 (TF)	B3	1010.3	1630	1683.1	0.62
		T30 (TF)	B5	1018.9	1637	1680.2	0.62
Short Line Fault (SLF)		L90	B4	219.2	55	1592.1	3.99
		L75	B4	677.8	155	1633.9	4.37
Line Faults	F31	T30	B4	1411.2	835	2087.9	1.69
		T30	B5	1251.1	760	1934.6	1.65
	F32	T60	B4	1772.1	670	1772.1	2.64
		T30	B5	1233.01	1125	1923.6	1.10
	F33	T60	B4	1274.1	355	1726.6	3.59
		T30	B5	836.8	850	2098.6	0.98
Reactor Terminal Faults	F5	T100	B6	1201.2	815	1545.2	1.47
	F6	T100	B7	1150.6	780	1437.2	1.48
Transformer Limited Fault	F9	T10 (TLF)	B11	1433.1	115	1664.5	12.46
Out of Phase Switching	OP1	T30	B5	314.3	860	514.4	0.37
	OP2	T100	B5	1096.2	1005	2082.8	1.09
Capacitor Switching Current		Without Shunt Reactor	B4	251.2	940	2271.9	0.27
		With Shunt Reactor	B4	122.8	915	617.6	0.13