

TRV Rating Concepts and Generation of TRV Envelopes for Synthetic Testing of Extra High Voltage Circuit Breakers

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Abstract— Development in electrical power transmission system requires the use of circuit breakers with increasing breaking capacity. At present circuit breakers are to be installed on 245 kV to 1200 kV power system with short circuit ratings up to 120kA. To test high voltage CBs, direct testing using the power system or short circuit alternators are not feasible. The testing of high voltage CBs of larger capacity requires very large capacity of testing station. To increase testing plant power is neither an economical nor a very practical solution. Synthetic testing is an alternative equivalent method for testing of high voltage circuit breakers and is accepted by the standards. This paper presents a TRV rating concepts, IEC standards TRV envelopes and types of synthetic test circuits and their comparison. Analysis and mathematical modeling of 4-parameters TRV synthetic test circuit is done. A 4-parameters TRV synthetic test circuit based on parallel current injection method is designed and simulated for testing 420kV and 800 kV rating circuit-breakers as per new TRV requirements given in IEC 62271-100(2008).

Index Terms— A.C. high voltage circuit breakers, Direct testing, Synthetic tests, TRV circuits, Terminal and Short-line faults.

I. INTRODUCTION

In Synthetic testing, there are two sources of power supply for the testing

- (i) Current source (ii) Voltage source

The current source is a high current, low voltage source. It supplies short circuit current during the test. The voltage source is a high voltage low current source. It provides transient recovery voltage.

The largest test facility in the world, KEMA high power laboratory, with a maximum short-circuit power of 8400MVA and a 145kV, 31.5kA, 3-phase direct test capability, is limited in its power to perform the direct tests. At the present time a complete pole of SF₆ circuit-breaker can consist of a single interrupting chamber with an interrupting power above the 10GVA level. Even KEMA'S high power laboratory can not verify the short-circuit interrupting capability by direct test methods[11],[13].

The unit testing method is used in laboratory to test

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Extra and ultra high voltage circuit-breakers at present. With this method, interrupting units are tested at a part of rated voltage of the complete breaker. This method is recognized by the IEC standard, but one major problem remains, namely the influence of the post-arc conductivity on the voltage distribution across the units. The trend of increasing the interrupting capability of a single interrupting unit will result in it being impossible to test a single unit in the high power laboratory[13].

II. TYPES OF SYNTHETIC TEST CIRCUITS AND COMPARISON

Several synthetic testing methods have been developed and their performances have been studied in the past forty years[2],[4],[5]. If the source of energy during the interaction interval is used to classify the methods adopted, they can be distinguished by two basic methods:

- (i) Current injection and (ii) Voltage injection method.

Depending on whether voltage circuit or source is switched on before or after current zero, the type of synthetic testing is known as current injection or voltage injection respectively.

Further the current injection method can be classified as parallel current injection and series current injection method. In parallel current injection method, the voltage circuit is inserted in parallel with the test breaker, while in series current injection method, it is inserted in series. The parallel current injection type synthetic testing is popular in Germany and is known as Weil - Dobke circuit. The series current injection type synthetic test circuit was suggested by Koplán Bashatyr (U.S.S.R) and is known as Russian circuit. In voltage injection method, the voltage source is switched on after the current zero. This method was suggested by Siemens, Germany.

More than forty years of synthetic testing experience shows that the current injection method has better equivalence than the voltage injection method. To produce four-parameter TRV, several TRV circuits have been developed but parallel current injection method with a Weil-Dobke TRV control circuit is the most popular used synthetic testing circuit in the high power laboratories as it is capable of providing RRRV and recovery voltage as required by various standards. Weil-Dobke circuit has a low capacity requirement on

the main capacitor bank as compared to other TRV control circuits and is easy to design the various components. However, special attention should be paid on the insulation coordination of TRV branches [10-14].

III. TRV RATING CONCEPTS AND IEC STANDARDS TRV ENVELOPES

As per IEC 62271-100, the rated characteristics of a circuit breaker include rated transient recovery voltage for terminal faults as well as short line fault condition.

The terminal fault is defined as a fault occurring very near to the terminal of the circuit breaker and that the reactance between the fault point and breaker is negligible. Under this condition, the fault or short circuit current depends upon the source voltage and source impedance, as the impedance between the breaker and the fault is negligible.

The faults occurring between a distance of a few km to a few tens km from the circuit breaker are called the short line or kilometric faults. Such faults are characterized by high frequency of restriking voltage of the order of 10 to 100kHz depending upon the line length and fault location. The resulting TRV for short line fault appearing across CB pole is the vector sum of the voltage from the source and the line side.

Short circuit tests on High voltage circuit-breakers require circuit with response specified by IEC standards represented by either Fig.1 or Fig.2. IEC standards define two TRV envelopes [1], [3].

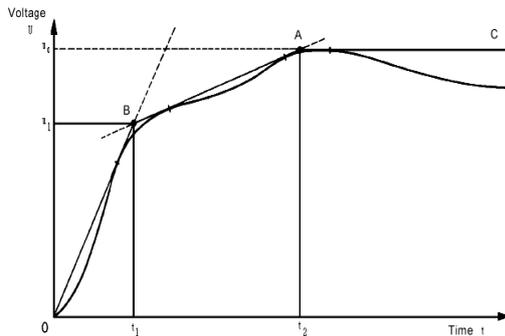


Fig.1. Representation by four parameters (u_1 and t_1 , u_c and t_2) of a prospective transient recovery voltage of a circuit, **case-1**

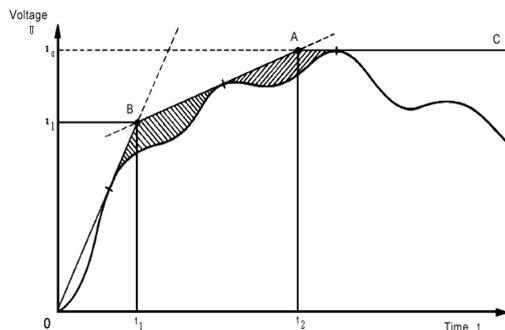


Fig.2. Representation by four parameters (u_1 and t_1 , u_c and t_2) of a prospective transient recovery voltage of a circuit **case-2**

A. Case of two parameters

For circuit breakers rated less than 100 kV, the envelope is defined by the two parameter method.

- u_c = reference voltage (TRV peak value) in kV;
- t_3 = time to reach u_c in microseconds.

B. Case of four parameters

For circuit breakers rated 100kV and above, the TRV envelope is defined by the four-parameter method represented by either Fig.1 or Fig.2.

- u_1 = first reference voltage, in kV,
- t_1 = time to reach u_1 , in microseconds
- u_c = second reference voltage (TRV peak value), in kV
- t_2 = time to reach u_c in microseconds.

TRV parameters are defined as a function of the rated voltage (U_r), the first-pole-to-clear factor (k_{pp}) and the amplitude factor (k_{af}) as follows:

$$u_1 = 0.75 \times (k_{pp}) \times U_r \sqrt{\frac{2}{3}}$$

t_1 is derived from u_1 and the specified value of the rate of rise $u_1/t_1 = RRRV$.

$t_2 = 4t_1$ for terminal fault and short line fault;

For rated voltages equal or higher than 100kV, the time delay $t_d = 2 \mu s$ for terminal fault and short line fault;

$$u_c = k_{af} \times k_{pp} \times U_r \sqrt{\frac{2}{3}}$$

Where $k_{af} = 1.4$ for terminal and short line fault;

$k_{pp} = 1.3$ for terminal fault

= 1.0 for short line fault

IV. ANALYSIS AND MATHEMATICAL MODELING OF 4-PARAMETERS TRV SYNTHETIC TEST CIRCUIT

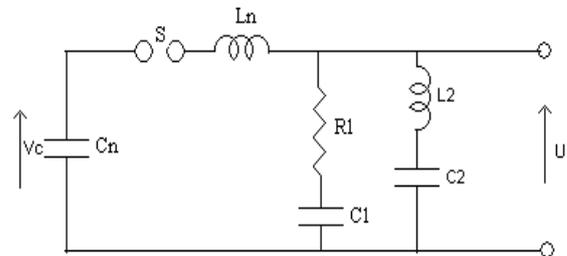


Fig.3. Multi Frequency Circuit

The circuit shown in Fig.3 permits to produce 4- parameters transient recovery voltages (TRV) according to IEC standards. V_c is the charging voltage. C_n , C_1 , C_2 , L_n , L_2 and R_1 are the circuit components. The magnitude and the frequency of the transient recovery voltage depend on the voltage to which the capacitor C_n is charged and the values of circuit components. u is the transient recovery voltage. C_1 , C_2 , L_n , L_2 and R_1 are to control TRV and RRRV.

The expression for the transient recovery voltage is as follows:

$$u(s) = -\frac{C_n V_c}{s} \frac{(1 + sR_1C_1)(1 + s^2L_2C_2)}{s^4 L_n C_n L_2 C_2 C_1 + s^3 R_1 C_n C_1 C_2 (L_n + L_2) + s^2 [L_n C_n (C_1 + C_2) + L_2 C_2 (C_n + C_1)] + sR_1 C_1 (C_n + C_2) + C_n + C_1 + C_2}$$

The time expression of the recovery voltage is complex, but by making some hypotheses, it is possible to obtain some fundamental information concerning the TRV generated by this configuration[9]. Indeed, a simple

analysis of the position of the poles of the above mentioned expression reveals the existence of 2 frequencies:

A. Low Frequency circuit

The low frequency voltage wave corresponds to the natural oscillation of the circuit represented by Fig.4. This low frequency circuit consists of circuit components C_n , C_2 , L_n and L_2 .

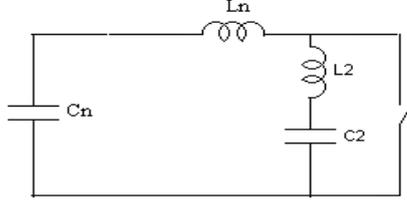


Fig.4. Low frequency circuit

$$\text{Low frequency } f n_2 = \frac{1}{2\pi\sqrt{(L_n + L_2) \cdot \frac{C_n \times C_2}{C_n + C_2}}}$$

$$\therefore t_{m_2} = \frac{10^3}{2 \times f n_2}$$

Where

$f n_2$ = low frequency oscillation of the voltage wave, in kHz

t_{m_2} = time to reach peak of low frequency voltage wave, in μ s

B. High Frequency circuit

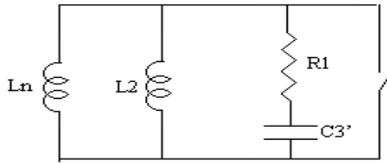


Fig.5. High frequency circuit

The high frequency voltage wave arises from the free oscillation of the circuit shown in Fig.5. The value of high frequency depends upon the circuit components C_3' , L_n and L_2 .

$$C_3' = C_1 \times \frac{C_n + C_2}{C_n + C_1 + C_2}$$

$$L_{eq} = L_n \parallel L_2 = \frac{L_n \times L_2}{L_n + L_2}$$

$$f n_1 = \frac{1}{2\pi\sqrt{L_{eq} \times C_3'}}$$

$$t_{m_1} = \frac{10^3}{2 \times f n_1}$$

Where

$f n_1$ = high frequency oscillation of the voltage wave, kHz

t_{m_1} = time to reach peak of high frequency voltage wave, μ s.

The TRV can then be considered as a result of the oscillations of both low frequency and high frequency circuits.

V. PROGRAM/SOFTWARE DEVELOPMENT FOR FINDING CIRCUIT COMPONENTS

The parameters of TRV defined by IEC standards are quite impossible to analytically link with the values of the components of the test circuit. So computer aided design and simulation of synthetic testing circuits (TRV shaping circuits) is first necessary in order to determine the parameters of the TRV corresponding to a given test circuit. In order to find the possible combinations of circuit components and to optimize the values of capacitance of capacitor banks for the desired frequencies t_{m_1} and t_{m_2} of a particular rating of circuit-breaker, program has been developed by using MATLAB M-file. Design optimization is done to reduce the values of capacitance of capacitor banks and hence reduce the energy required, size and cost of the capacitor banks.

Program/software is also developed with the help of VISUAL BASIC 6 software to find all possible combinations of the circuit components and also to optimize the circuit components for the desired frequencies t_{m_1} and t_{m_2} for a particular rating of circuit-breaker. This software is user friendly and speed is very fast, just by one click it will show all the possible combinations of circuit components for the desired frequencies. The algorithm to find optimized circuit components is given below:

Algorithm

Objective Function: Minimize (optimize) the value of capacitance of Capacitor Banks C_n , C_1 and C_2 for a desired frequencies (for the same test conditions) as per IEC for a particular rating of circuit-breaker.

- Enter the desired frequencies (t_{m_1} and t_{m_2}) for a particular rating of circuit-breaker
- Specify the maximum and minimum values of the following independent variables or circuit components:

Main Capacitor Bank: C_n

TRV Capacitor Banks: C_1 and C_2

Reactors: L_n and L_2

- calculate all possible combinations of circuit components for the desired frequencies
- The values of TRV Capacitor Banks can be determined by using the following equations:

$$C_1 = \frac{(C_n + C_2)}{4\pi^2 f n_1^2 L_{eq} (C_n + C_2) - 1}$$

$$C_2 = \frac{C_n}{4\pi^2 f n_2^2 (L_n + L_2) C_n - 1}$$

- Find the optimal values of capacitor banks C_n , C_1 and C_2 .

The developed program/software is tested for finding all possible and optimized circuit components to test 420kV rating circuit-breakers for terminal as well as short line fault test duty condition according to IEC standards. The suitable and optimized circuit components obtained is shown in Table I.

TABLE I
OPTIMAL CIRCUIT COMPONENTS OF TRV SHAPING CIRCUIT FOR TESTING 420 kV RATING CIRCUIT BREAKERS
(WITH THE TRV CONTROL CIRCUIT SHOWN IN FIG. 6)

Rating of CB	Circuit components	Terminal Fault Test Duty		Short line fault Test Duty
		As per case-I	As per case-II	As per case-I
420kV	Capacitor Banks			
	Main Capacitor Bank: C _n	32 μF	32 μF	32 μF
	TRV Capacitor Bank: C ₁	0.6 μF	0.5 μF	0.5 μF
	C ₂	1.4 μF	2.5 μF	1.5 μF
	Stray capacitor Bank: C ₃	21 nF	21 nF	21 nF
	Reactors :			
	L _n	19 mH	18 mH	13 mH
	L ₁	100 mH	100 mH	100 mH
	L ₂	17 mH	9 mH	11 mH
	Resistors :			
R ₁	32 Ω	16 Ω	25 Ω	
R ₂	20 Ω	10 Ω	15 Ω	
Charging Voltage, V_c		424 kV	320 kV	

VI. DESIGN AND SIMULATION OF 4 – PARAMETERS TRV PARALLEL CURRENT INJECTION SYNTHETIC TEST CIRCUIT

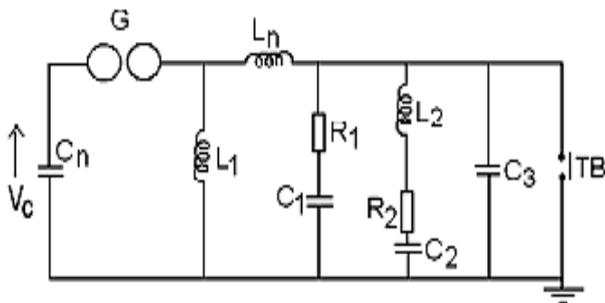


Fig.6. 4 -Parameters TRV parallel current injection synthetic testing circuit (Control circuit-I, Weil - Dobke type)

To produce four-parameter TRV, several TRV control circuits have been developed but parallel current injection method with a Weil-Dobke TRV control circuit [9],[10] shown in Fig.6 is the most popular used synthetic testing circuit in the high power laboratories as it is capable of providing RRRV and recovery voltage as required by various standards. Weil-Dobke circuit has a low capacity requirement on the main capacitor bank as compared to other TRV control circuits and is easy to design the various circuit components. The circuit shown in Fig.6 permits to produce 4 – parameters transient recovery voltages (TRV) according to IEC standards. The circuit consists of the following components: V_c is the charging Voltage, C_n is the main capacitor bank, C₁ and C₂ are the TRV capacitor banks, C₃ is the stray capacitor bank; L_n, L₁ and L₂ are the reactors; R₁ and R₂ are the resistors. The magnitude and the frequency of the transient recovery voltage depend up on the voltage to which the main capacitor C_n is charged and the values of circuit components. The circuit shown in Fig.6 is also used in new synthetic test plant in ABB, Ludvika and it is proposed by A. K. Bystruev[10].

The optimized circuit components for the desired frequencies of f_{n1} and f_{n2} according to IEC standards for a particular rating of circuit-breaker can be determined by the proposed Program/Software developed by using MATLAB/Visual Basic 6. After finding optimal circuit components for a particular rating of circuit-breaker, design and simulation of 4-parameters TRV parallel current injection method synthetic testing circuit (Weil

Dobke type) is done by using PSIM simulator for testing Extra high voltage circuit breakers according to new TRV requirements given in IEC62271-100(2008). The circuit is designed and simulated for both terminal fault as well as short line fault test duty for testing 420kV and 800 kV rating circuit-breakers. Design optimization is done to reduce the energy required by the capacitor banks and hence reduce the size and cost of capacitor banks also to save the space required.. The algorithm for the design and simulation of synthetic testing circuit for High Voltage circuit Breakers is shown in Fig.7.

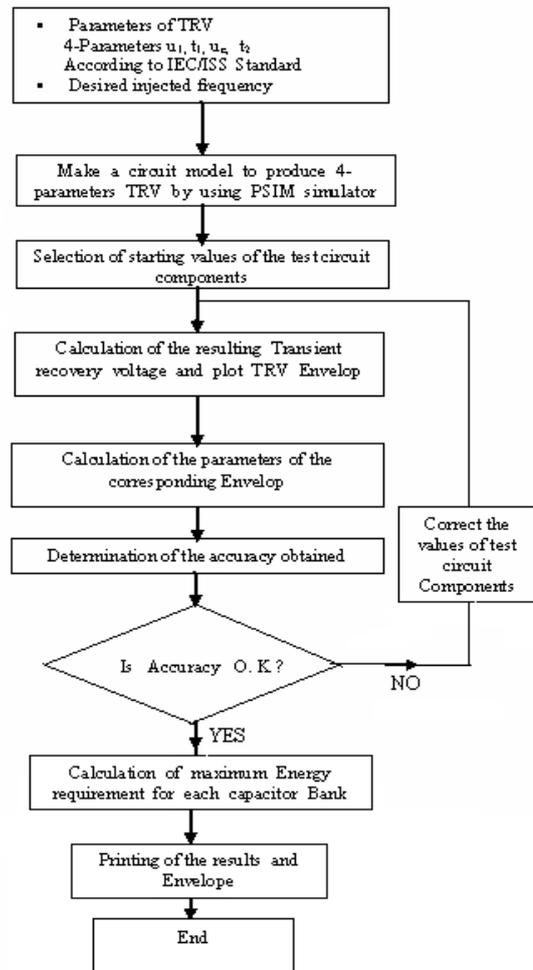


Fig.7. Algorithm for the design and simulation of synthetic testing circuits

The main capacitor C_n is charged to provide recovery voltage. The main capacitor C_n is charged to a peak value of recovery voltage as per the following equation (according to IEEE guide for synthetic testing of high voltage circuit-breakers).

$$V_c = 0.95 \times k_{pp} \times \sqrt{\frac{2}{3}} U_r$$

Where U_r = rated voltage of circuit-breaker

k_{pp} = first-pole-to-clear factor

The TRV envelopes obtained for terminal as well as short-line fault duty conditions to test 420 kV rating circuit-breakers are shown in Fig.8 to Fig.10. TRV Parameters obtained/realized from these envelopes are given in Table III. The expected TRV parameters as per IEC for testing 420 kV rating circuit breakers for both terminal

and short line fault test duty are given in Table II. Table I shows the optimal circuit components of TRV control circuit for testing 420 kV rating CBs. Table IV shows the energy required by each capacitor bank and the total energy required for terminal fault test duty condition.

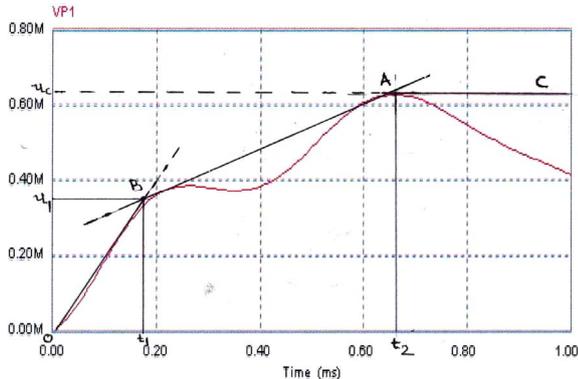


Fig.8. Terminal fault TRV for 420 kV circuit breaker as per case-I (TRV curve represented in Fig.1 as per IEC)

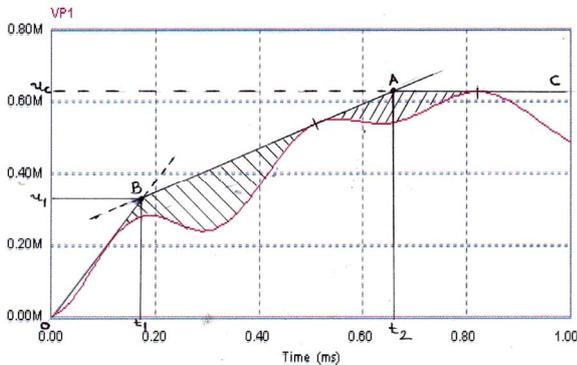


Fig.9. Terminal fault TRV for 420 kV circuit breaker as per case-II (TRV curve represented in Fig.2 as per IEC)

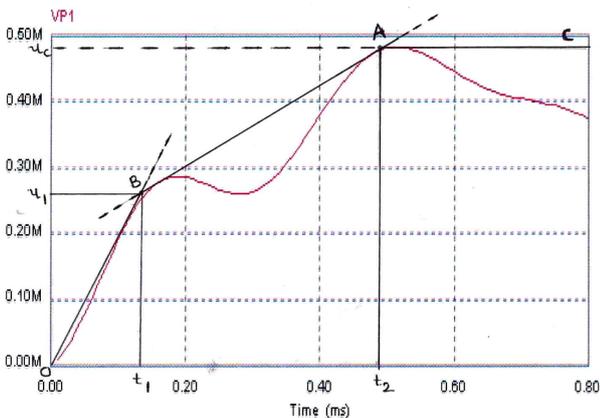


Fig.10. Short-line fault TRV for 420 kV circuit breaker as per case-I (TRV curve represented in Fig.1)

TABLE II
EXPECTED TRV PARAMETERS ACCORDING TO IEC 62271-100(2008)
FOR 420KV RATING CBS

TRV Parameters	Test duty: Terminal fault	Test duty: Short line fault
First reference voltage u_1 , kV	334	257
Time to reach u_1 , t_1 , μ s	167	129
TRV peak value, u_c , kV	624	480
Time to reach u_c , t_2 , μ s	668	516
Rate of rise, u_1/t_1 , kV/ μ s	2	2

TABLE III
TRV PARAMETERS OBTAINED OR REALISED FOR 420KV RATING CBS

TRV Parameters	Test duty: Terminal fault	Test duty: Short line fault
First reference voltage u_1 , kV	336	260
Time to reach u_1 , t_1 , μ s	168	130
TRV peak value, u_c , kV	623.6	482
Time to reach u_c , t_2 , μ s	668	516
Rate of rise, u_1/t_1 , kV/ μ s	2	2

TABLE IV
MAXIMUM VOLTAGE ACROSS EACH CAPACITOR BANK AND ENERGY REQUIREMENT FOR EACH CAPACITOR BANK FOR TESTING 420 KV CBS.

Capacitor Banks	Value	Max. Voltage across cap. Bank, kV	Energy required kJ	Total Energy reqd. MJ
Main Capacitor Bank: C_n	32 μ F	424	2876.41	3.38
TRV Capacitor Bank: C_1	0.6 μ F	623	116.43	
C_2	1.4 μ F	744	387.47	
Stray capacitor Bank: C_3	21 nF	624	4.10	

VII. GENERATION OF TRV ENVELOPES FOR TESTING 800 KV RATING CIRCUIT-BREAKERS

The TRV envelopes obtained for terminal as well as short-line fault duty conditions to test 800 kV rating circuit-breakers are shown in Fig.11 to Fig.13. TRV Parameters obtained/realized from these envelopes are given in Table VI. The expected TRV parameters as per IEC for testing 800 kV rating circuit breakers for both terminal and short line fault test duty are given in Table V. Table VII shows the energy required by each capacitor bank and the total energy required for terminal fault test duty condition for testing 800 kV rating CBs.

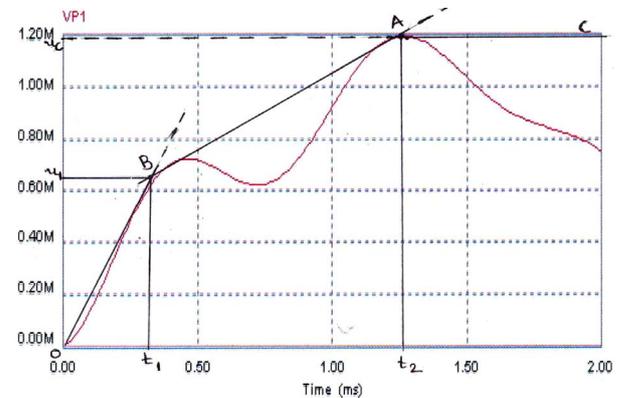


Fig.11. Terminal fault TRV for 800 kV circuit breaker as per case-I (TRV curve represented in Fig.1 as per IEC)

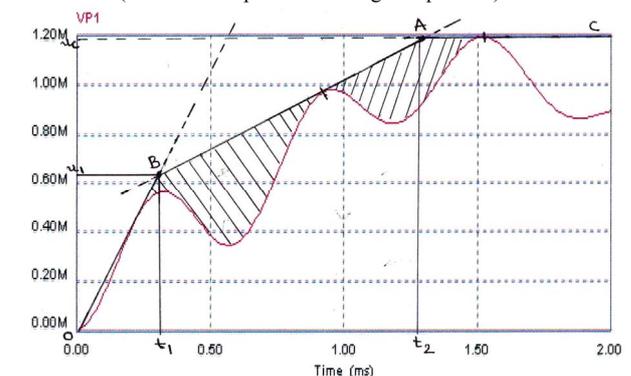


Fig.12. Terminal fault TRV for 800 kV circuit breaker as per case-II (TRV curve represented in Fig.2 as per IEC)

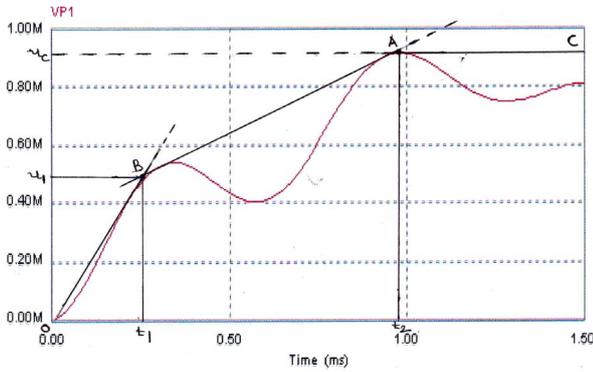


Fig.13. Short-line fault TRV for 800 kV circuit breaker as per case-I (TRV curve represented in Fig. 1)

TABLE V
EXPECTED TRV PARAMETERS ACCORDING OF IEC FOR 800 KV RATING CIRCUIT-BREAKERS

TRV Parameters	Test duty: Terminal fault	Test duty: Short line fault
First reference voltage u_1 , kV	637	490
Time to reach u_1 , t_1 μ s	318	245
TRV peak value, u_c kV	1189	914
Time to reach u_c , t_2 μ s	1272	980
Rate of rise, u_1/t_1 , kV/ μ s	2	2

TABLE VI
TRV PARAMETERS OBTAINED FOR 800 KV RATING CIRCUIT-BREAKERS

TRV Parameters	Test duty: Terminal fault	Test duty: Short line fault
First reference voltage u_1 , kV	640	486
Time to reach u_1 , t_1 μ s	318	244
TRV peak value, u_c kV	1189	913
Time to reach u_c , t_2 μ s	1270	980
Rate of rise, u_1/t_1 , kV/ μ s	2.01	1.99

TABLE VII
MAXIMUM VOLTAGE ACROSS EACH CAPACITOR BANK AND ENERGY REQUIREMENT FOR EACH CAPACITOR BANK FOR TESTING 800KV CBS.

Capacitor Banks	Value	Max. Voltage across capacitor Bank, kV	Energy required kJ	Total Energy reqd. MJ
Main Capacitor Bank: C_n	36 μ F	807	11722.4	14.60
TRV Capacitor Bank: C_1	0.85 μ F	1185	596.80	
C_2	2.2 μ F	1435	2265.14	
Stray capacitor Bank: C_3	21 nF	1189	14.85	

VIII. CONCLUSION

The parameters of TRV defined by IEC standards are quite impossible to analytically link with the values of the components of the test circuit. So computer aided design and simulation of synthetic testing circuits (TRV shaping circuits) is first necessary in order to determine the parameters of the TRV corresponding to a given test circuit.

The objective was to design and simulate 4-Parameters TRV synthetic testing circuit used to generate TRV envelopes for testing Extra high voltage circuit breakers according to new TRV requirements given in IEC 62271-100 (2008). A 4-parameter TRV synthetic test circuit based on parallel current injection method is designed and simulated for both Terminal as well as Short line faults test duty for testing 420kV and 800kV rating circuit-breakers. Design optimization is also done to reduce the energy required by the capacitor banks

and hence reduce the size and cost of capacitor banks also to save the space required.

The results obtained by using synthetic test circuit has been discussed and compared with the required results according to IEC standards. The results shown are almost the same according to IEC standards.

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