Chapter-6

DESIGN, SIMULATION AND COMPARISON OF 4–PARAMETERS TRV SYNTHETIC TEST CIRCUITS

6.1 Design and simulation of 4 - Parameters TRV parallel current injection synthetic test circuit

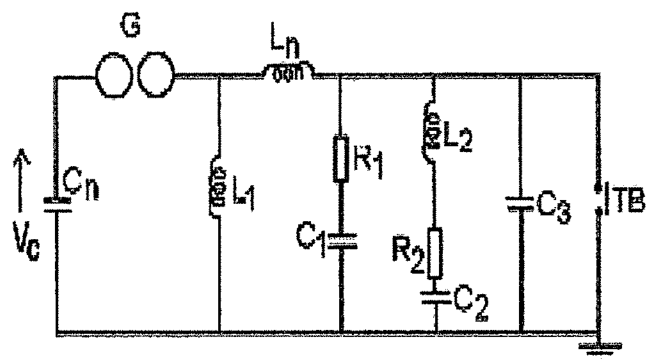

Fig.6.1. 4 -Parameters TRV parallel current injection synthetic testing circuit (control circuit-I, Weil - Dobke type)

To produce four-parameter TRV, several TRV control circuits have been developed but parallel current injection method with a Weil-Dobke TRV control circuit [12],[14] shown in Fig.6.1 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.6.1 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

Cn is the main capacitor bank

C_1 and C_2 are the TRV capacitor banks

C_3 is the stray capacitor bank,

L_n, L_1 and L2 are the reactors and

R_1 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 Cn is charged and the values of circuit components. The circuit components C_1, C_2, L_n, L_1, L_2, R_1 and R_2 are to control TRV and RRRV.

The circuit shown in Fig.6.1 is also used in new synthetic test plant in ABB, Ludvika [14].

The optimized circuit components for the desired frequencies of fn_1 and fn_2 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. This is discussed in the previous chapter 5. 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 high voltage and 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 245kV, 420kV and 800kV 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.6.2.

The main capacitor Cn is charged to provide recovery voltage. It is charged to a voltage equal to the peak power frequency voltage which will appear across the contacts at the moment the circuit-breaker under test interrupts the current. The main capacitor Cn 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).

$$V_C = 0.95 \text{ x } k_{pp} \text{ x } \sqrt{\frac{2}{3}}\ U_r$$

Where U_r = rated voltage of circuit-breaker

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

=1.3 for terminal fault

= 1.0 for short line fault

Therefore, the charging voltage for 420kV rating circuit-breakers is as follows:

$V_C = 423.51 \approx 424$ kV for terminal fault test duty

$= 325.78 \approx 326$ kV for short line fault test duty

Pre-charged capacitor bank supplies the recovery voltage (both transient and power frequency) after current interruption. Stray capacitance and the inductance of the bus bar system contributes their influence on the initial portion of the prospective TRV. This is taken into account by providing the time delay for the TRV. The influence of local capacitance on the source side of the circuit-breaker produces a slower rate-of-rise of the voltage during the first few microseconds of the TRV. This is taken in to account by introducing a time delay. Stray capacitance bank C_3 provides the time delay for the TRV. To meet the time delay requirement a value of 21nF is chosen for the parallel connected capacitor across the test circuit-breaker. A group of air-core coils L_1 is used to obtain the power frequency recovery voltage.

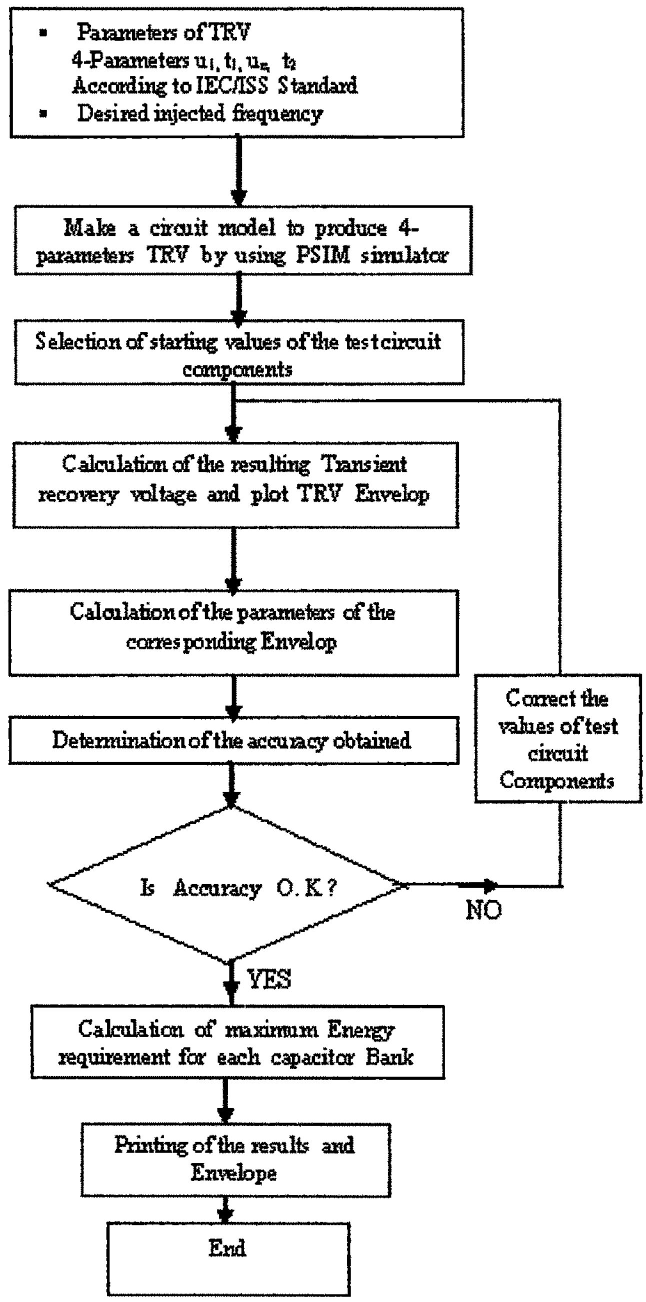

Fig.6.2 Algorithm for the design and simulation of synthetic testing circuits for High Voltage circuit Breakers using PSIM Simulator

6.2 Design and simulation of 4-Parameters TRV synthetic test circuit for 245 kV rating circuit-breakers

The circuit shown in Fig.6.1 is designed and simulated for both terminal fault as well as short line fault test duty conditions for 245 kV rating circuit-breakers by using PSIM simulator as per new TRV requirements given in IEC 62271-100.

The TRV envelopes obtained for terminal as well as short-line fault duty conditions to test 245 kV rating circuit-breakers are shown in Fig.6.3 to Fig.6.7. TRV Parameters obtained/realized from these envelopes are given in Table 6.2. The expected TRV parameters as per IEC for testing 245 kV rating circuit breakers for both terminal and short line fault test duty are given in Table 6.1.

In order to find better and economical TRV control circuit and to optimize the values of circuit components for the same test conditions, 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. Table 6.3 shows the optimal circuit components of TRV control circuit for testing 245 kV rating CBs. Table 6.4 shows the energy required by each capacitor bank and the total energy required for terminal fault test duty condition.

TRV envelopes obtained for terminal as well as short-line fault duty conditions to test 245 kV rating circuit-breakers are as follows:

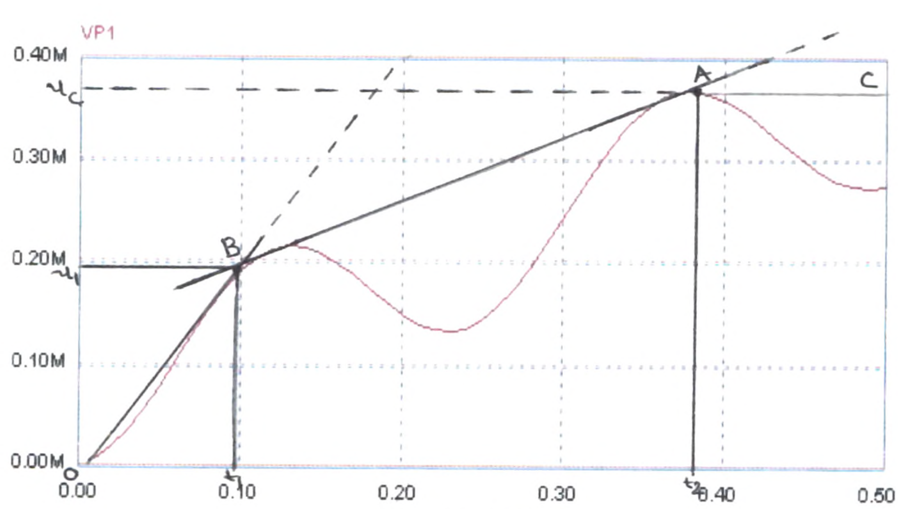

Fig.6.3 Terminal fault TRV for 245 kV circuit breaker as per case-I
(TRV curve represented in Fig.3.9 as per IEC)

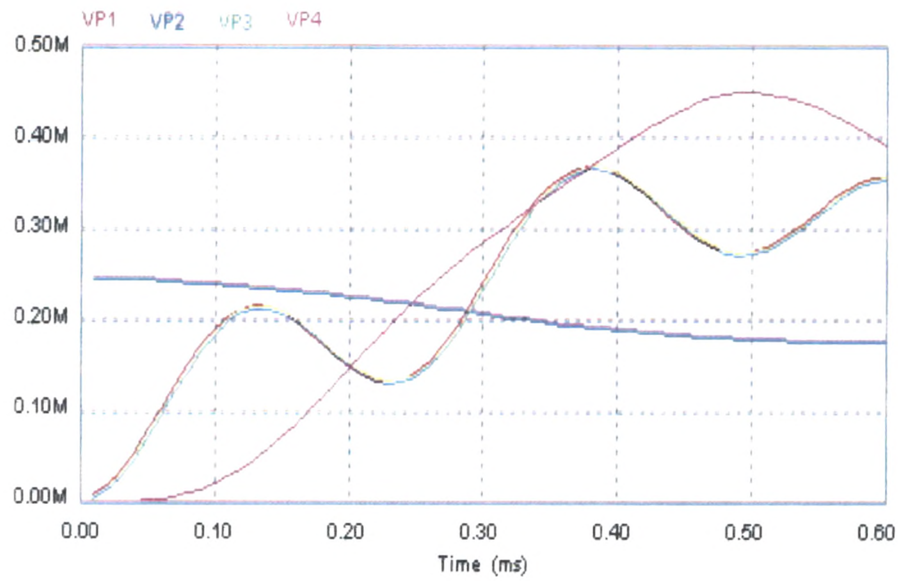

Fig.6.4 Terminal fault TRV curve and Voltage across each capacitor bank for 245 kV CB as per case-I (Fig.3.9)

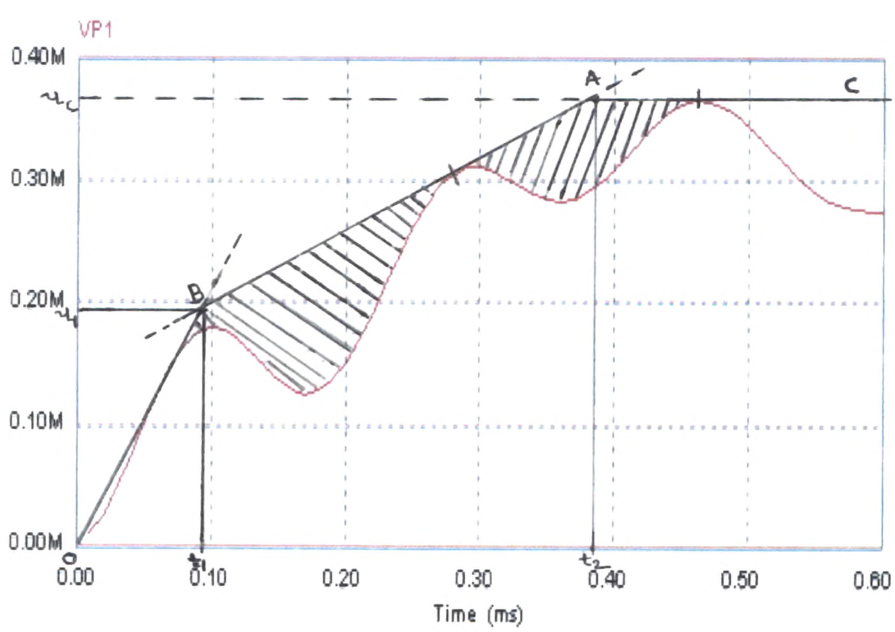

Fig.6.5 Terminal fault TRV for 245 kV circuit breaker as per case-II (TRV curve represented in Fig.3.10 as per IEC)

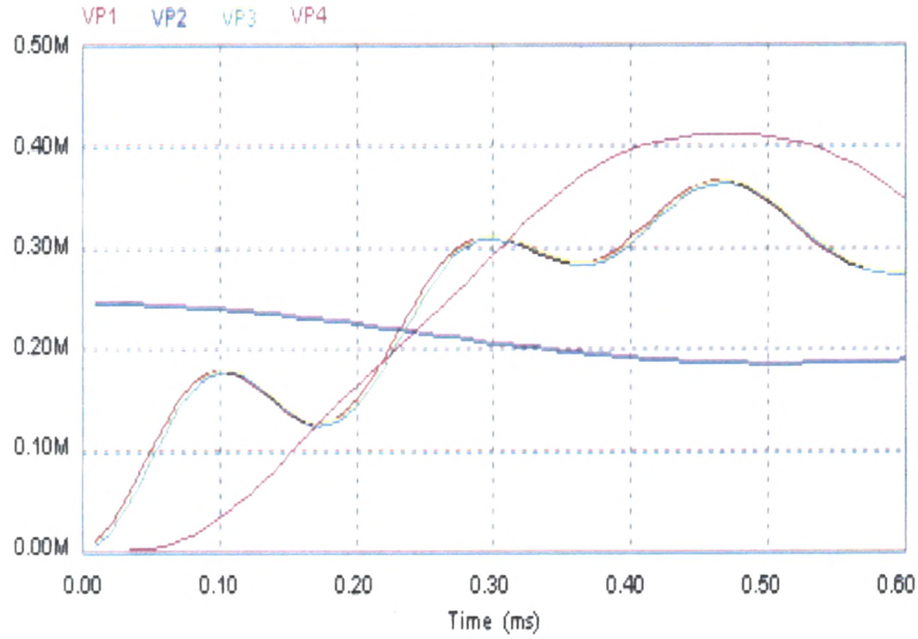

Fig.6.6 Terminal fault TRV curve and Voltage across each capacitor bank for 245 kV CB as per case-II (Fig.3.10)

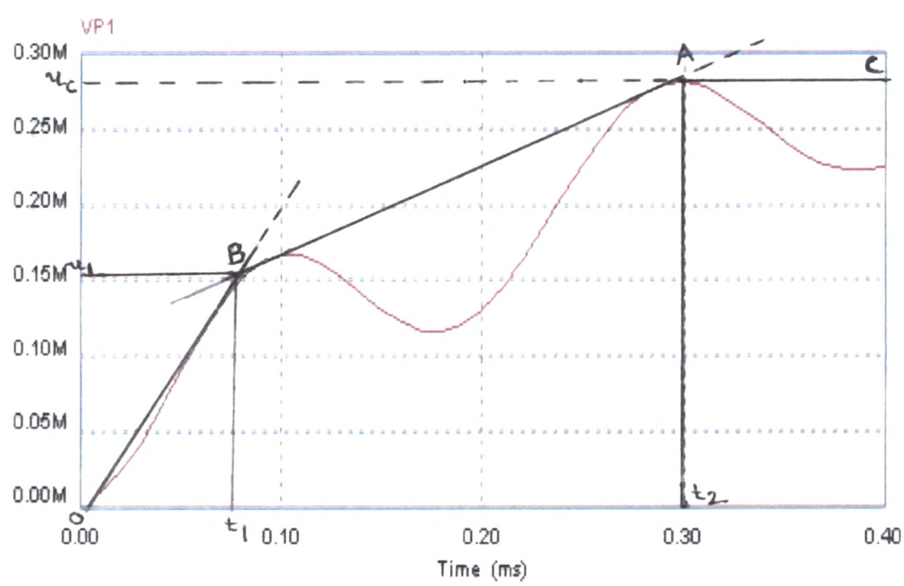

Fig.6.7 Short-line fault TRV for 245 kV circuit breaker as per case-I (TRV curve represented in Fig. 3.9 as per IEC)

TABLE 6.1

EXPECTED TRV PARAMETERS ACCORDING TO IEC 62271-100 (2008) FOR 245 KV RATING CBS

TRV Parameters	**Test duty: Terminal fault**	**Test duty: Short line fault**
First reference voltage u_1, kV	195	150
Time to reach u_1, t_1 μs	98	75
TRV peak value , u_c kV	364	280
Time to reach u_c, t_2 μs	392	300
Rate of rise, u_1/t_1, kV/μs	2	2

TABLE 6.2

TRV PARAMETERS OBTAINED OR REALISED FOR 245 KV RATING CBS

TRV Parameters	**Test duty: Terminal fault**	**Test duty: Short line fault**
First reference voltage u_1, kV	195	152
Time to reach u_1, t_1 μs	98	75
TRV peak value , u_c kV	364.5	279.5
Time to reach u_c, t_2 μs	390	300
Rate of rise, u_1/t_1, kV/μs	1.99	2.02

TABLE 6.3

OPTIMAL CIRCUIT COMPONENTS OF TRV SHAPING CIRCUIT FOR TESTING 245 KV RATING CIRCUIT BREAKERS (WITH THE TRV CONTROL CIRCUIT SHOWN IN FIG. 6.1)

Rating of CB	**Circuit components**		Terminal Fault		Short line fault
			As per case-I	As per case-II	As per case-I
	Capacitor Banks				
	Main Capacitor Bank:	C_n	16 μF	16 μF	16 μF
	TRV Capacitor Bank:	C_1	0.35 μF	0.35 μF	0.35 μF
245kV		C_2	1.5 μF	2.5 μF	1.4 μF
	Stray capacitor Bank:	C_3	21 nF	21 nF	21 nF
	Reactors :	L_n	10 mH	6 mH	6 mH
		L_1	100 mH	100 mH	100 mH
		L_2	8 mH	3.5 mH	5 mH
	Resistors :	R_1	8 Ω	8 Ω	10 Ω
		R_2	2 Ω	6 Ω	4 Ω
	Charging Voltage , V_C		247 kV		190 kV

TABLE 6.4
MAXIMUM VOLTAGE ACROSS EACH CAPACITOR BANK AND ENERGY REQUIREMENT FOR EACH CAPACITOR BANK FOR TESTING 245 KV RATING CIRCUIT BREAKERS

Type of Test Duty	Capacitor Banks	Value	Max. Voltage across each capacitor Bank, Vmax, kV	Energy required by each capacitor Bank, kJ	Total Energy required
Terminal fault As per case-I	Main Capacitor Bank: C_n TRV Capacitor Bank: C_1 C_2 Stray capacitor Bank: C_3	16 µF 0.35 µF 1.5 µF 21 nF	247 363 449 364	488.00 23.06 151.20 1.39	664 kJ
Terminal fault As per case-II	Main Capacitor Bank: C_n TRV Capacitor Bank: C_1 C_2 Stray capacitor Bank: C_3	16 µF 0.35 µF 2.5 µF 21 nF	247 364.5 412 364	488.00 23.18 212.20 1.39	725 kJ

6.3 Design and simulation of 4-Parameters TRV synthetic test circuit for 420 kV rating circuit-breakers

The circuit shown in Fig.6.1 is designed and simulated for both terminal fault as well as short line fault test duty conditions for 420 kV rating circuit-breakers by using PSIM simulator as per new TRV requirements given in IEC 62271-100.

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.6.8 to Fig.6.13. TRV Parameters obtained/realized from these envelopes are given in Table 6.6. 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 6.5.

In order to find better and economical TRV control circuit and to optimize the values of circuit components for the same test conditions, 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. Table 6.7 shows the optimal circuit components of TRV control circuit for testing 420 kV rating CBs. Table 6.8 shows the energy required by each capacitor bank and the total energy required for terminal fault test duty condition.

TRV envelopes obtained for terminal as well as short-line fault duty conditions to test 420 kV rating circuit-breakers are as follows:

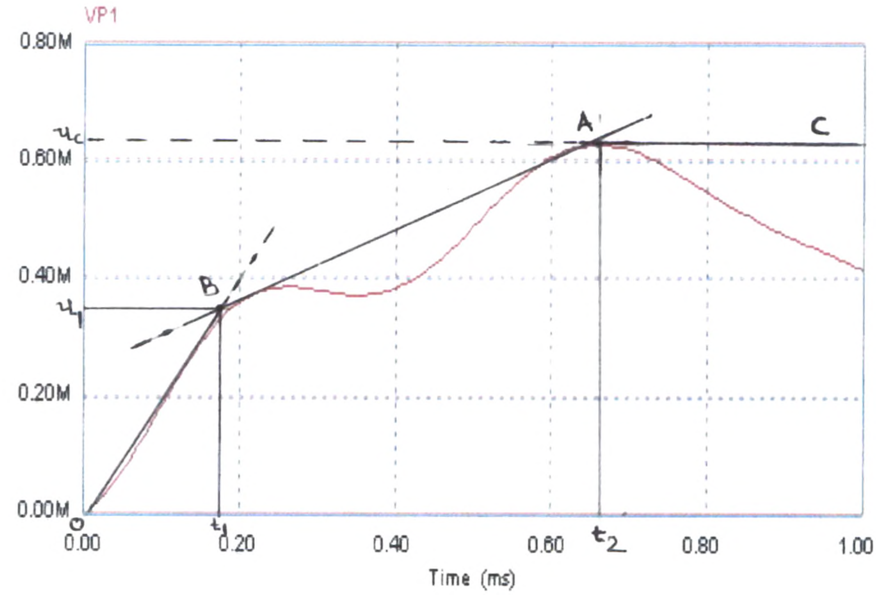

Fig.6.8 Terminal fault TRV for 420 kV circuit breaker as per case-I (TRV curve represented in Fig.3.9 as per IEC)

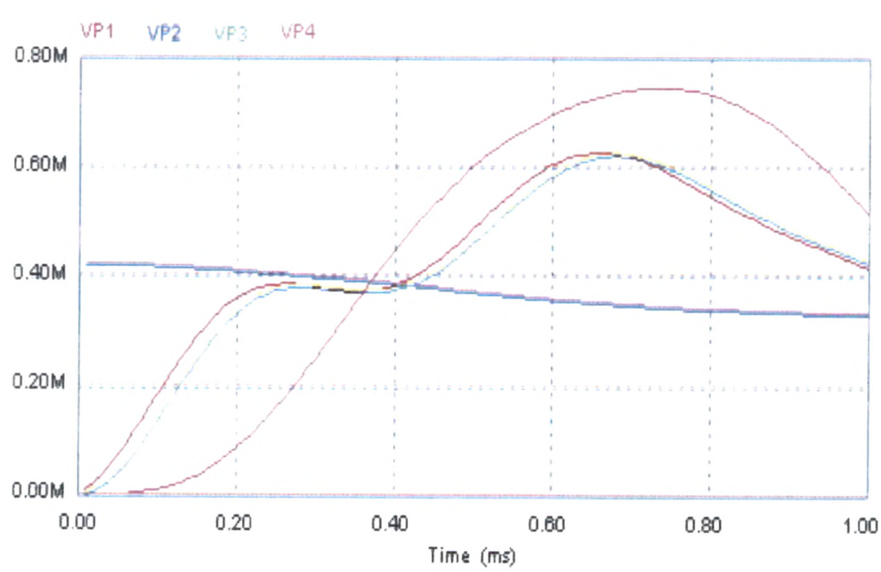

Fig.6.9 Terminal fault TRV curve and Voltage across each capacitor bank for 420 kV CB as per case-I (Fig.3.9)

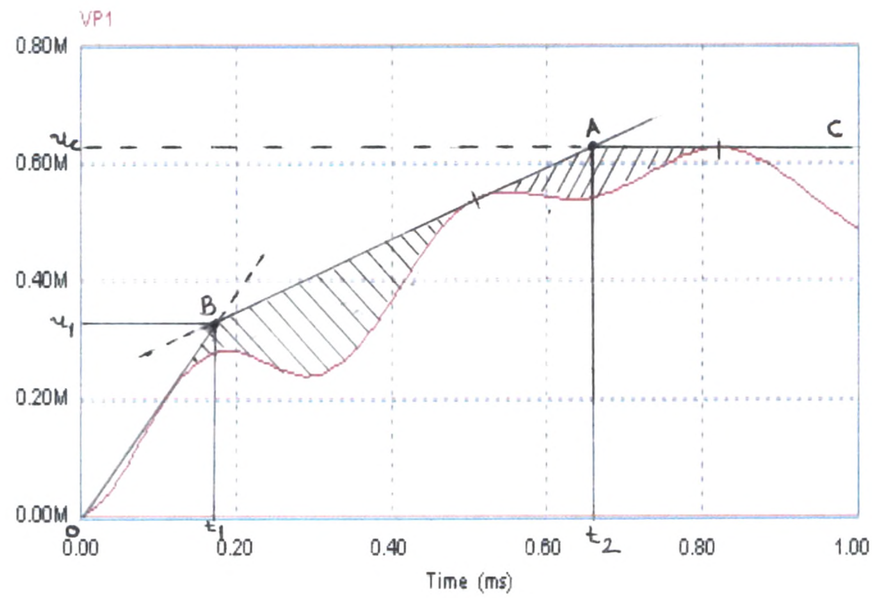

Fig. 6.10 Terminal fault TRV for 420 kV circuit breaker as per case-II
(TRV curve represented in Fig.3.10 as per IEC)

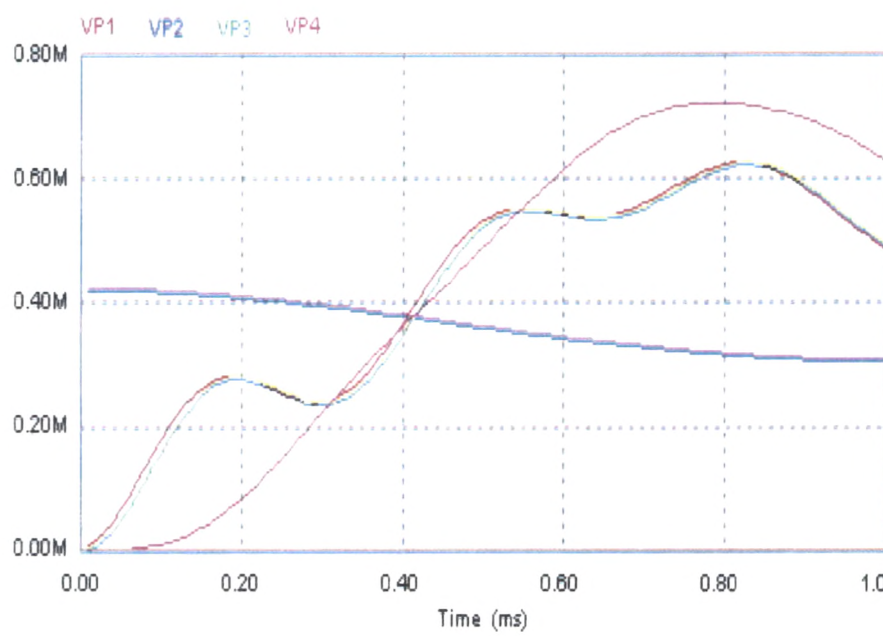

Fig.6.11 Terminal fault TRV curve and Voltage across each capacitor bank for 420 kV CB as per case-II (Fig.3.10)

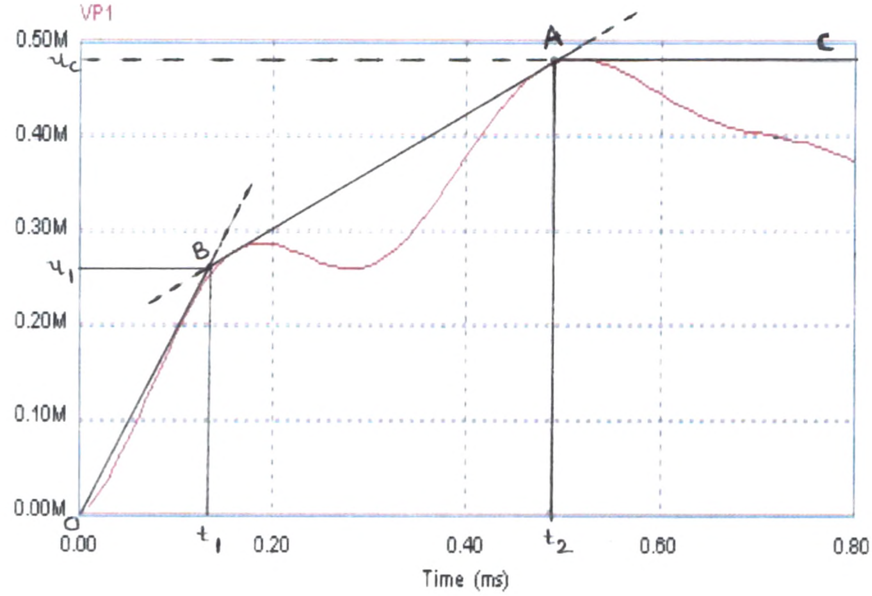

Fig.6.12 Short-line fault TRV for 420 kV circuit breaker as per case-I (TRV curve represented in Fig. 3.9)

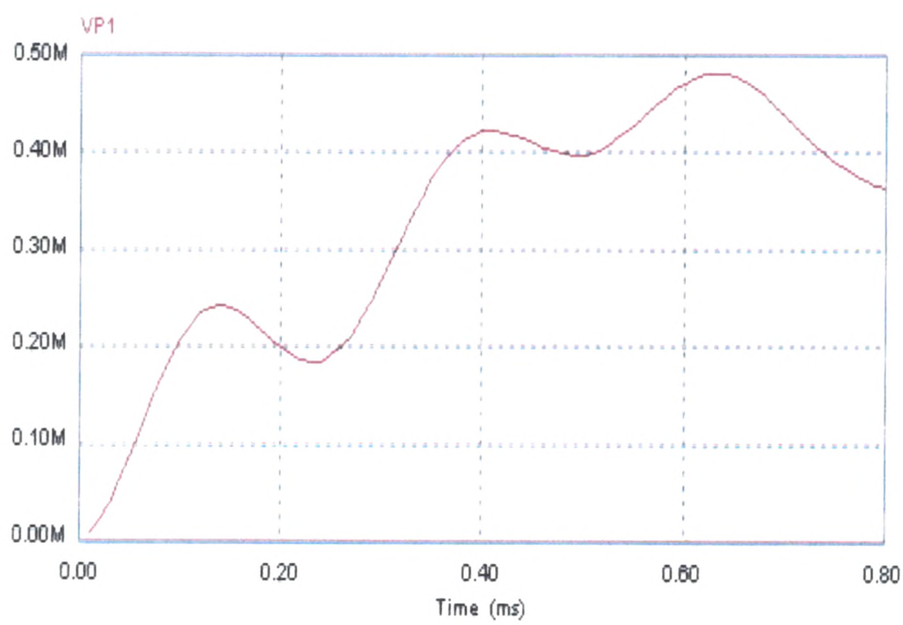

Fig.6.13 Short-line fault TRV for 420 kV circuit breaker as per case-II (TRV curve represented in Fig.3.10)

TABLE 6.5

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 μs	167	129
TRV peak value, u_c kV	624	480
Time to reach u_c, t_2 μs	668	516
Rate of rise, u_1/t_1, kV/μs	2	2

TABLE 6.6

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 μs	168	130
TRV peak value, u_c kV	623.6	482
Time to reach u_c, t_2 μs	668	516
Rate of rise, u_1/t_1, kV/μs	2	2

TABLE 6.7

OPTIMAL CIRCUIT COMPONENTS OF TRV SHAPING CIRCUIT FOR TESTING 420 KV RATING CIRCUIT BREAKERS (WITH THE TRV CONTROL CIRCUIT SHOWN IN FIG. 6.1)

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	As per case-II
	Capacitor Banks					
	Main Capacitor Bank:	C_n	32 μF	32 μF	32 μF	32 μF
	TRV Capacitor Bank:	C_1	0.6 μF	0.5 μF	0.5 μF	0.45 μF
420kV		C_2	1.4 μF	2.5 μF	1.5 μF	2.6 μF
	Stray capacitor Bank:	C_3	21 nF	21 nF	21 nF	21 nF
	Reactors :	L_n	19 mH	18 mH	13 mH	10 mH
		L_1	100 mH	100 mH	100 mH	100 mH
		L_2	17 mH	9 mH	11 mH	6 mH
	Resistors :	R_1	32 Ω	16 Ω	25 Ω	11 Ω
		R_2	20 Ω	10 Ω	15 Ω	9 Ω
	Charging Voltage , V_C		424 kV		326kV	

TABLE 6.8

MAXIMUM VOLTAGE ACROSS EACH CAPACITOR BANK AND ENERGY REQUIREMENT FOR EACH CAPACITOR BANK FOR TESTING 420 KV RATING CIRCUIT BREAKERS

Type of Duty	Capacitor Banks	Value	Max. Voltage across each capacitor Bank, Vmax, kV	Energy required by each capacitor Bank, kJ	Total Energy required
Terminal fault As per case-I	Main Capacitor Bank: C_n	32 μF	424	2876.41	3385 kJ
	TRV Capacitor Bank: C_1	0.6 μF	623	116.43	
	C_2	1.4 μF	744	387.47	
	Stray capacitor Bank: C_3	21 nF	624	4.10	
Terminal fault As per case-II	Main Capacitor Bank: C_n	32 μF	424	2876.41	3624 kJ
	TRV Capacitor Bank: C_1	0.5 μF	623.5	97.20	
	C_2	2.5 μF	719	646.20	
	Stray capacitor Bank: C_3	21 nF	624	4.10	

6.4 Design and simulation of 4-Parameters TRV synthetic test circuit for 800kV rating circuit-breakers

The circuit shown in Fig.6.1 is also designed and simulated for both terminal faults as well as short line faults test duty conditions for 800kV rating circuit-breakers by using PSIM simulator as per new TRV requirements given in IEC 62271-100. The algorithm for the design and simulation of synthetic testing circuit for High Voltage circuit-breakers is shown in Fig.6.2.

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. 6.14 to Fig. 6.18. TRV Parameters obtained/realized from these envelopes are given in Table 6.10. 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 6.9.

In order to find better and economical TRV control circuit and to optimize the values of circuit components for the same test conditions, 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. Table 6.11 shows the optimal circuit components of TRV control circuit for testing 800kV rating CBs. Table 6.12 shows the energy required by each capacitor bank and the total energy required for terminal fault test duty condition.

The TRV envelopes obtained for terminal as well as short-line fault duty conditions to test 800 kV rating circuit-breakers:

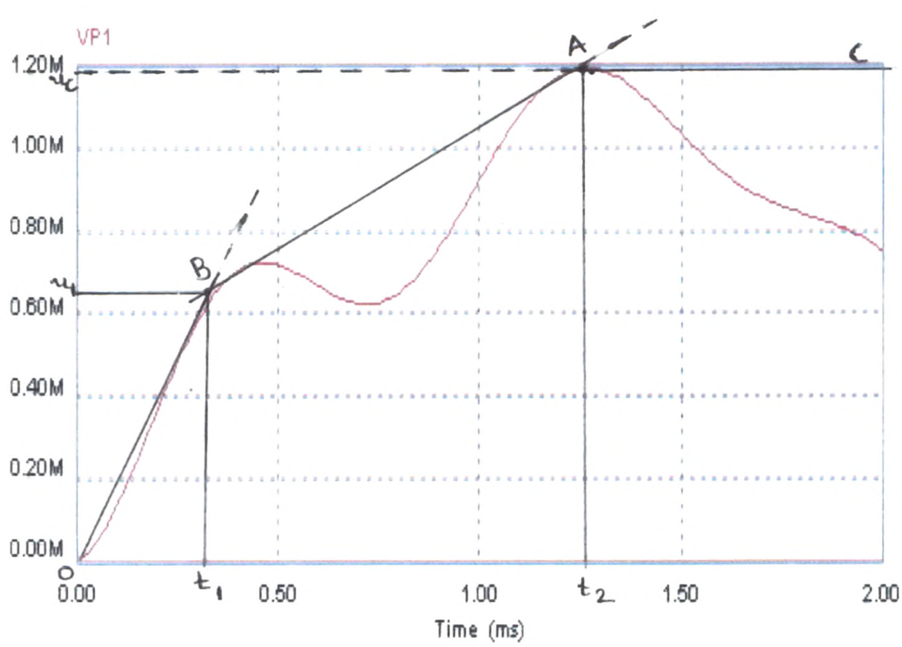

Fig.6.14 Terminal fault TRV for 800 kV circuit breaker as per case-I (TRV curve represented in Fig.3.9 as per IEC)

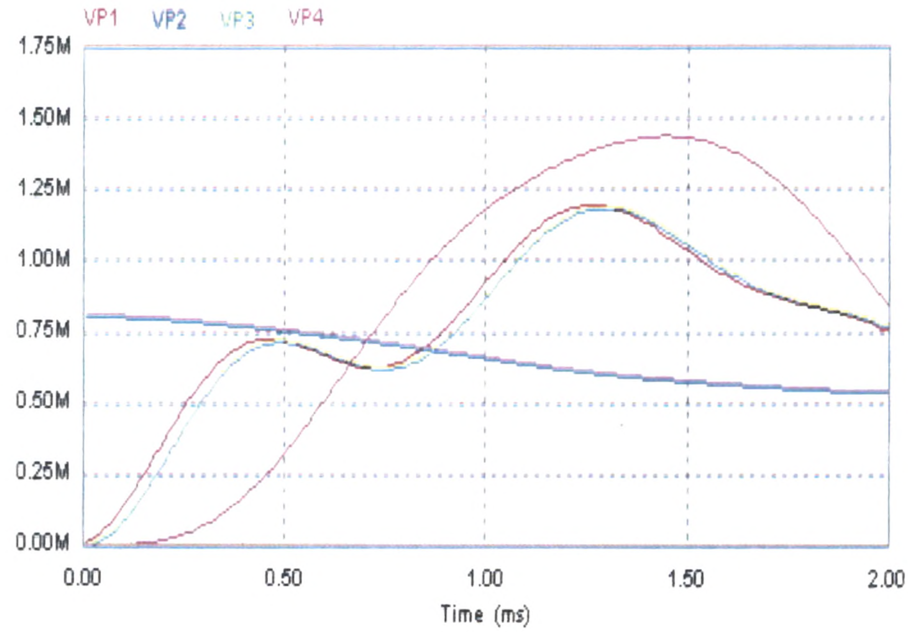

Fig.6.15 Terminal fault TRV curve and Voltage across each capacitor bank for 800 kV CB as per case-I(Fig.3.9)

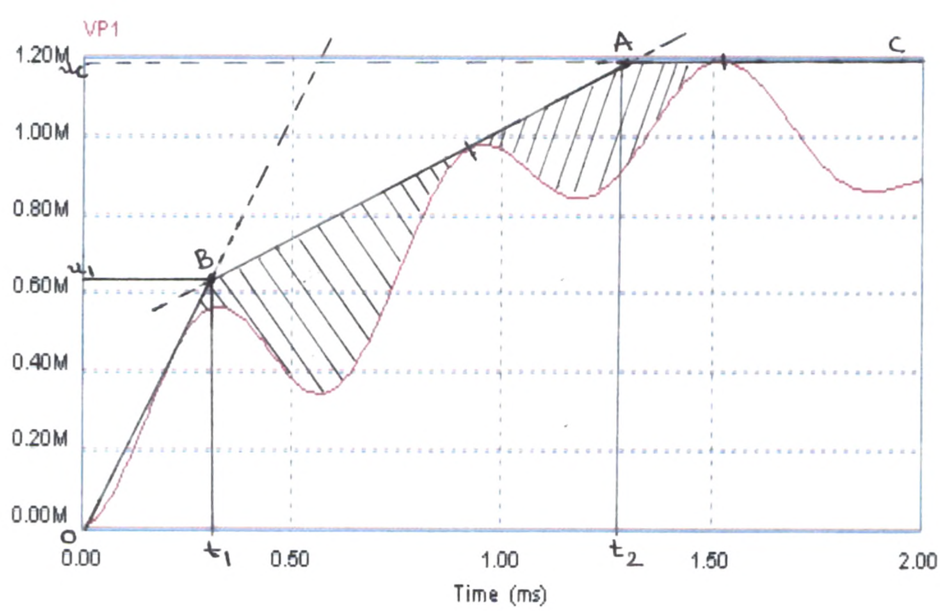

Fig.6.16 Terminal fault TRV for 800 kV circuit breaker as per case-II (TRV curve represented in Fig.3.10 as per IEC)

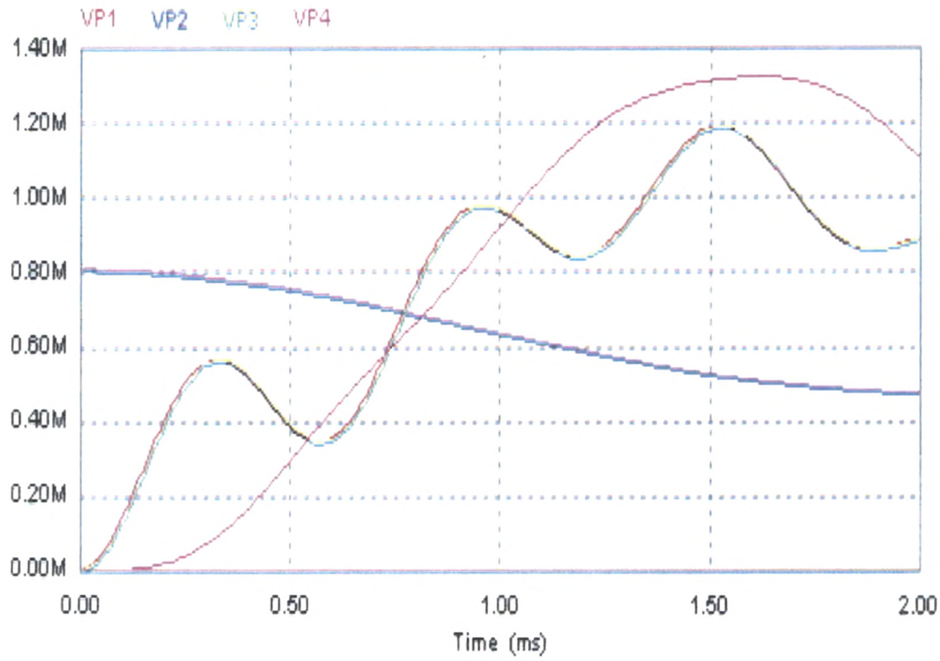

Fig.6.17 Terminal fault TRV curve and Voltage across each capacitor bank for 800 kV CB as per case-II(Fig.3.10)

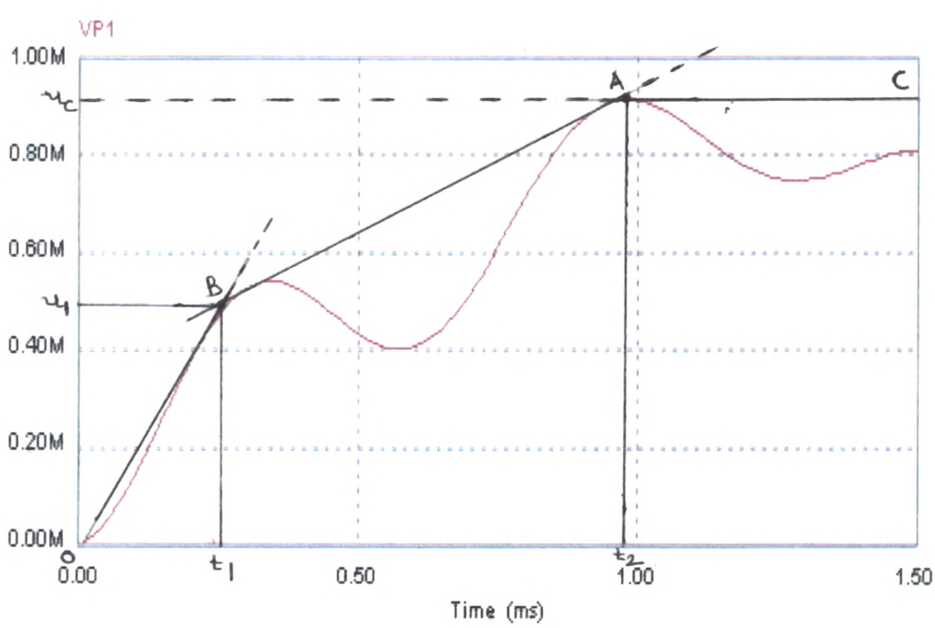

Fig.6.18 Short-line fault TRV for 800 kV circuit breaker as per case-I (TRV curve represented in Fig.3.9 as per IEC)

TABLE 6.9

EXPECTED TRV PARAMETERS ACCORDING TO IEC 62271-100 (2008) FOR 800 KV RATING CBS

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 µs	318	245
TRV peak value, u_c kV	1189	914
Time to reach u_c, t_2 µs	1272	980
Rate of rise, u_1/t_1, kV/µs	2	2

TABLE 6.10

TRV PARAMETERS OBTAINED OR REALISED FOR 800 KV RATING CBS

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 µs	320	244
TRV peak value, u_c kV	1189	913
Time to reach u_c, t_2 µs	1270	980
Rate of rise, u_1/t_1, kV/µs	2	1. 99

TABLE 6.11

OPTIMAL CIRCUIT COMPONENTS OF TRV SHAPING CIRCUIT FOR TESTING 800 KV RATING CIRCUIT BREAKERS (WITH THE TRV CONTROL CIRCUIT SHOWN IN FIG. 6.1)

Rating of CB	**Circuit components**		Terminal Fault		Short line fault
			As per case-I	As per case-II	As per case-I
	Capacitor Banks				
	Main Capacitor Bank:	C_n	36 µF	36 µF	36 µF
	TRV Capacitor Bank:	C_1	0.85 µF	0.6 µF	0.6 µF
800kV		C_2	2.2 µF	4.0 µF	2.2 µF
	Stray capacitor Bank:	C_3	21 nF	21 nF	21 nF
	Reactors :	L_n	48 mH	46 mH	40 mH
		L_1	200 mH	200 mH	200 mH
		L_2	44 mH	25 mH	33 mH
	Resistors :	R_1	34 Ω	12 Ω	24 Ω
		R_2	10 Ω	8 Ω	10 Ω
	Charging Voltage , V_C		807 kV		620kV

TABLE 6.12

MAXIMUM VOLTAGE ACROSS EACH CAPACITOR BANK AND ENERGY REQUIREMENT FOR EACH CAPACITOR BANK FOR TESTING 800 KV RATING CIRCUIT BREAKERS

Type of Duty	Capacitor Banks	Value	Max. Voltage across each capacitor Bank, Vmax, kV	Energy required by each capacitor Bank, kJ	Total Energy required
Terminal fault As per case-I	Main Capacitor Bank: C_n TRV Capacitor Bank: C_1 C_2 Stray capacitor Bank: C_3	36 μF 0.85 μF 2.2 μF 21 nF	807 1185 1435 1189	11722.48 596.80 2265.14 14.85	14.60 MJ
Terminal fault As per case-II	Main Capacitor Bank: C_n TRV Capacitor Bank: C_1 C_2 Stray capacitor Bank: C_3	36 μF 0.6 μF 4.0 μF 21 nF	807 1188 1320 1189	11722.48 423.40 3484.80 14.85	15.65 MJ

6.5 Design and simulation of other 4 -Parameters TRV synthetic test circuits based on parallel current injection method for 245kV and 420kV rating CBs

To produce four-parameters 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.

Again several synthetic test circuits based on Parallel current injection method with a Weil-Dobke type have been studied and developed by many researchers according to various standards. In order to find better and economical TRV control circuit and to optimize the values of circuit components for the same test conditions, design and simulation of different 4-parameters TRV control circuits based on parallel current injection method is done by using PSIM simulator according to new TRV requirements given in IEC 62271-100 for comparison purpose.

One of the most commonly used circuit based on Parallel current injection method with a Weil-Dobke type shown in Fig.6.1 (TRV control circuit-I) is already designed and simulated. The circuit is designed and simulated for both terminal faults as well as short line faults test duty for 245kV, 420kV and 800kV 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. The circuit shown in Fig.6.1 is also used in new synthetic test plant in ABB, Ludvika and it is proposed by A. K. Bystruev.

Two more commonly used circuits based on Parallel current injection method with a Weil-Dobke type are given in Fig.6.19[14] and Fig.6.20 [17],[18] and permits to produce 4 – parameters transient recovery voltages (TRV) according to IEC standards.

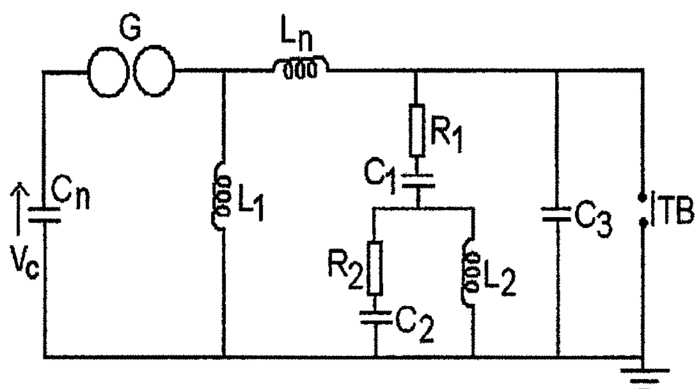

Fig.6.19 4 -Parameters TRV parallel current injection synthetic testing circuit
(TRV control circuit-II)

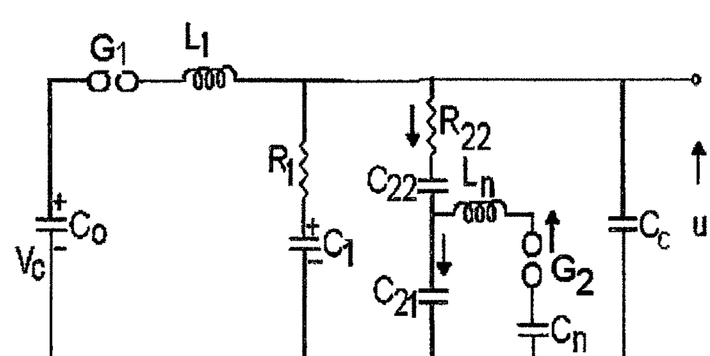

Fig.6.20. 4 -Parameters TRV parallel current injection synthetic testing circuit
(TRV control circuit-III)

The TRV control circuit-II shown in Fig. 6.19 was proposed by V. N. Narancic and the TRV control circuit-III shown in Fig. 6.20 was proposed by B. L. Sheng and L. Van der Sluis (High power Laboratory, KEMA).The design and simulation of these circuits were carried out by using PSIM Simulator and simulated for 245kV and 420 kV rating circuit breakers as per new TRV requirements given in IEC 62271-100. The circuits are designed and simulated for terminal fault test duty condition for comparison purpose.

The algorithm for the design and simulation of synthetic testing circuits for High Voltage circuit Breakers is shown in Fig.6.2. In order to find better and economical TRV control circuit and to optimize the values of circuit components for the same test conditions, design optimization is also done for the various 4-parameters TRV control circuits for the same test conditions 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 comparison of these circuits is made on aspects of equivalence, operation, required capacitive energy and applicability.

Simulation Results of 4-parameters TRV parallel current injection synthetic test circuits (with control circuit-II and III) for 245kV rating CBs, as per IEC 62271-100 (2008)

The TRV envelopes obtained for terminal fault test duty condition to test 245 kV rating circuit-breakers with control circuit-II and III are shown in Fig.6.21 to Fig.6.23. Table 6.13 and Table 6.14 shows the optimal circuit components of TRV control Circuit-II and III for testing 245 kV rating Circuit breakers.

TRV Parameters obtained/realized from TRV envelopes are given in Table 6.15. Table 6.16 shows the calculated total maximum energy requirement of capacitor banks with various control circuits to test 245kV rating circuit-breakers for a terminal fault test duty condition.

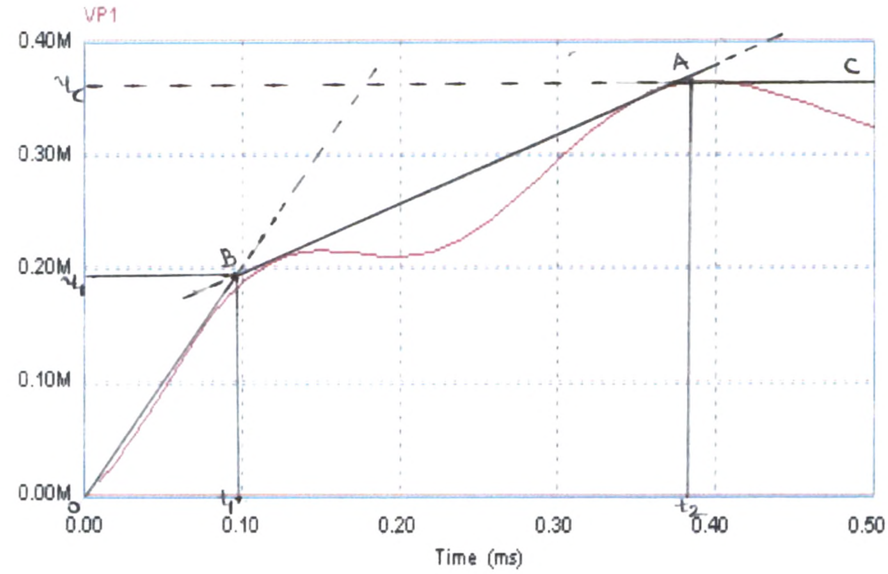

Fig.6.21 Terminal fault TRV for 245kV circuit-breaker as per case-I (TRV curve represented in Fig.3.9 as per IEC) with control circuit-II

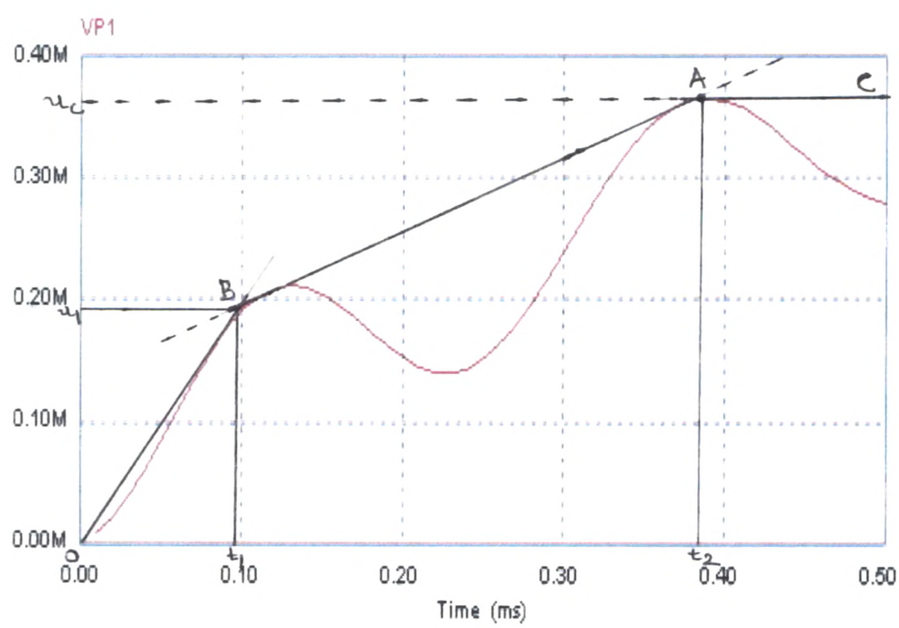

Fig.6.22 Terminal fault TRV for 245kV circuit-breaker as per case-I (TRV curve represented in Fig.3.9 as per IEC) with control circuit-III

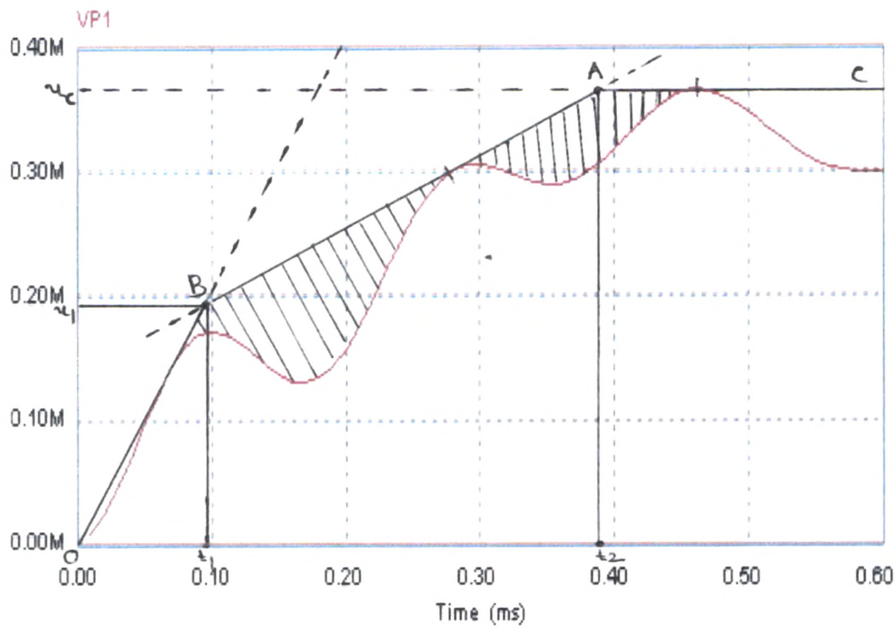

Fig.6.23 Terminal fault TRV for 245kV circuit-breaker as per case-II (TRV curve represented in Fig.3.10 as per IEC) with control circuit-III

TABLE 6.13
COMPONENTS OF TRV SHAPING CIRCUIT FOR TESTING 245 KV RATING CIRCUIT BREAKERS
(WITH TRV CONTROL CIRCUIT-II)

Rating of CB	Circuit components		Terminal Fault
			2-Freq.
	Capacitor Banks		
	Main Capacitor Bank:	C_n	36 μF
	TRV Capacitor Bank:	C_1	1.6 μF
		C_2	0.6 μF
245kV (V_C = 247kV)	Stray capacitor Bank:	C_3	21 nF
	Reactors :	L_n	9 mH
		L_1	100 mH
		L_2	4mH
	Resistors :	R_1	14 Ω
		R_2	23 Ω

TABLE 6.14

COMPONENTS OF TRV SHAPING CIRCUIT FOR TESTING 245 KV RATING CIRCUIT BREAKERS (WITH TRV CONTROL CIRCUIT-III)

Rating of CB	Circuit components		Terminal Fault	
			As per case-I	As per case-II
	Capacitor Banks			
	Main Capacitor Bank:	C_o	12 µF	12 µF
	TRV Capacitor Bank:	C_1	1.0 µF	1.0 µF
245kV		C_{22}	1.5 µF	2.2 µF
(V_C=		C_{21}	1.0 µF	0.8 µF
247kV)		C_h	1.0 µF	1.0 µF
	Stray capacitor Bank:	C_c	21 nF	21 nF
	Reactors :	L_n	3.2 mH	1.6 mH
		L_1	18 mH	14 mH
	Resistors :	R_1	100 Ω	24 Ω
		R_{22}	26 Ω	28 Ω

TABLE 6.15

TRV PARAMETERS OBTAINED OR REALISED FOR 245 KV RATING CBS (TERMINAL FAULT TEST DUTY, WITH VARIOUS CONTROL CIRCUITS)

TRV Parameters/ Control circuit	**I**	**II**	**III**
First reference voltage u_1, kV	195	195	193
Time to reach u_1, t_1 µs	98	98	98
TRV peak value , u_c kV	364.5	364.2	364
Time to reach u_c, t_2 µs	390	392	392
Rate of rise, u_1/t_1, kV/µs	1.99	1.99	1.97

TABLE 6.16

MAXIMUM VOLTAGE ACROSS EACH CAPACITOR BANK AND ENERGY REQUIREMENT FOR EACH CAPACITOR BANK FOR TESTING 245 KV RATING CIRCUIT BREAKERS (TERMINAL FAULT TEST DUTY)

Control Circuit	Capacitor Banks	Value	Max. Voltage across each capacitor Bank, Vmax, kV	Energy required by each capacitor Bank, kJ	Total Energy required
I	Main Capacitor Bank: C_n	16 µF	247	488.00	$E_1 = 664$ kJ
	TRV Capacitor Bank: C_1	0.35 µF	363	23.06	
	C_2	1.5 µF	449	151.20	
	Stray capacitor Bank: C_3	21 nF	364	1.39	
II	Main Capacitor Bank: C_n	36 µF	247	1098.16	$E_2 = 1237$ kJ
	TRV Capacitor Bank: C_1	1.6 µF	410	134.48	
	C_2	0.6 µF	96	2.76	
	Stray capacitor Bank: C_3	21 nF	364	1.39	
III	Main Capacitor Bank: C_o	12 µF	247	366.05	$E_3 = 495$ kJ
	TRV Capacitor Bank: C_1	1.0 µF	299	44.70	
	C_{22}	1.5 µF	115	9.92	
	C_{21}	1.0 µF	270	36.45	
	C_h	1.0 µF	271	36.72	
	Stray capacitor Bank: C_c	21 nF	364	1.39	

$$\frac{E_1}{E_2} = \frac{664}{1237} = 0.5368 = 53.68\%$$

$$\frac{E_3}{E_2} = \frac{495}{1237} = 0.4 = 40\ \%$$

Simulation Results of 4-parameters TRV parallel current injection synthetic test circuits (with control circuit-II and III) for 420kV rating CBs, as per IEC 62271-100 (2008)

The TRV envelopes obtained for terminal fault test duty condition to test 420 kV rating circuit-breakers with control circuit-II and III are shown in Fig.6.24 to Fig.6.26. Table 6.17 and Table 6.18 shows the optimal circuit components of TRV control Circuit-II and III for testing 420kV rating Circuit breakers.

TRV Parameters obtained/realized from these envelopes are given in Table 6.19. Table 6.20 shows the calculated total maximum energy requirement of capacitor banks with various control circuits to test 420kV rating circuit-breakers for a terminal fault test duty condition.

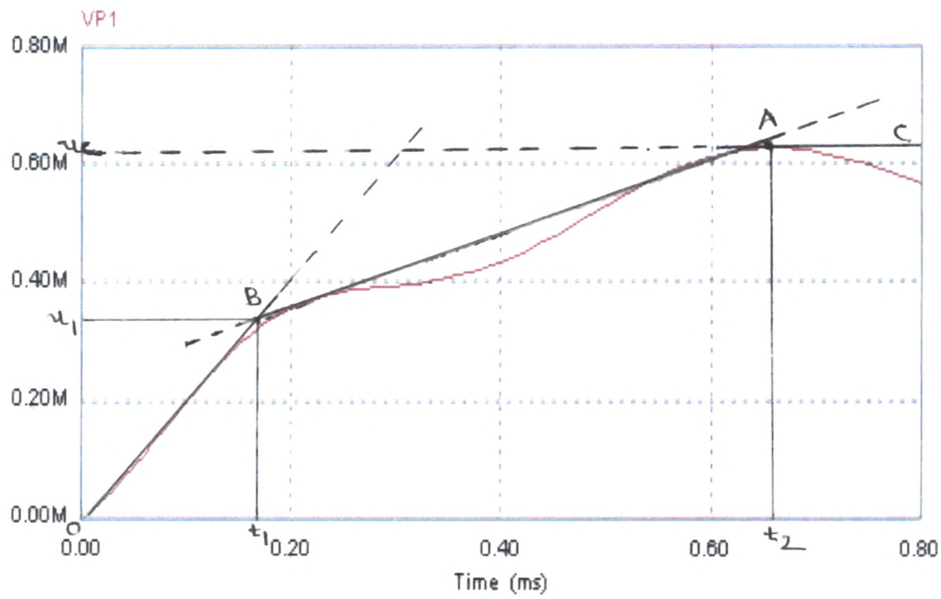

Fig.6.24 Terminal fault TRV for 420 kV circuit-breaker as per case-I (TRV curve represented in Fig.3.9 as per IEC) with control circuit-II

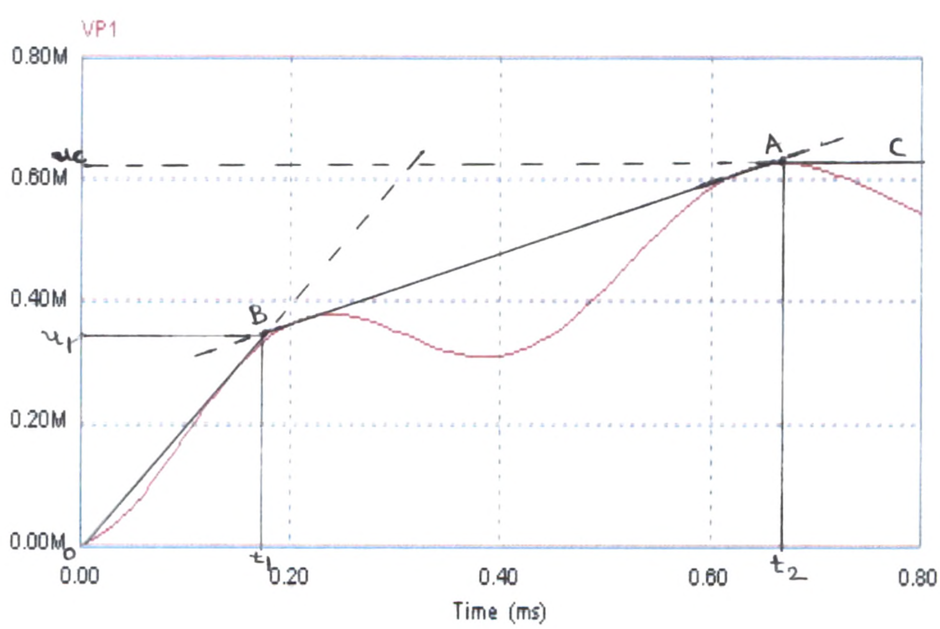

Fig.6.25 Terminal fault TRV for 420 kV circuit-breaker as per case-I (TRV curve represented in Fig.3.9 as per IEC) with control circuit-III

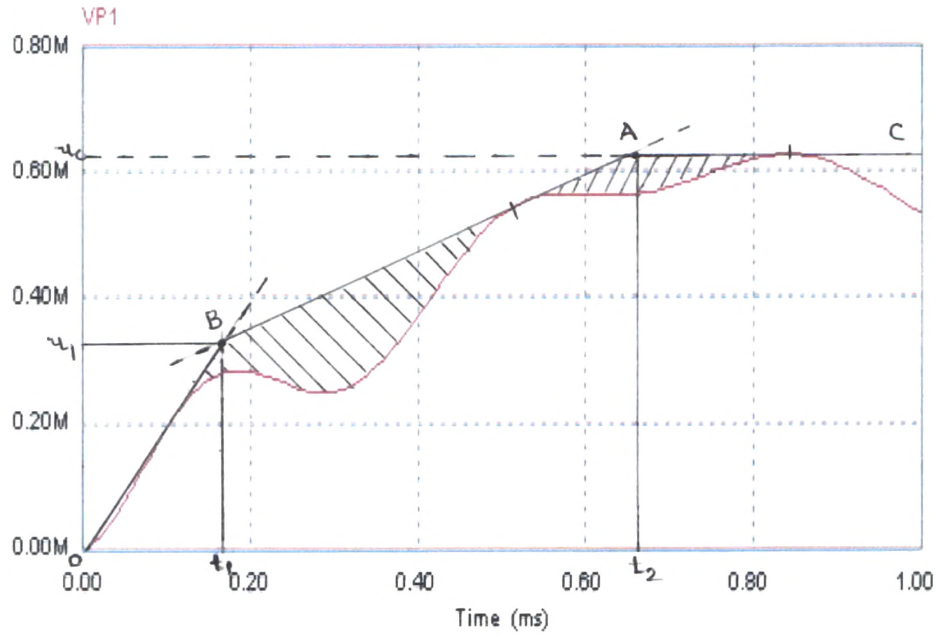

Fig.6.26 Terminal fault TRV for 420kV circuit-breaker as per case-II (TRV curve represented in Fig.3.10 as per IEC) with control circuit-III

TABLE 6.17
COMPONENTS OF TRV SHAPING CIRCUIT FOR TESTING 420 KV RATING CIRCUIT BREAKERS
(WITH TRV CONTROL CIRCUIT-II)

Rating of CB	Circuit components		Terminal Fault
			As per case-I
	Capacitor Banks		
	Main Capacitor Bank:	C_n	60 μF
	TRV Capacitor Bank:	C_1	2.0 μF
		C_2	1.0 μF
420kV (V_C = 424kV)	Stray capacitor Bank:	C_3	21 nF
	Reactors :	L_n	18 mH
		L_1	100 mH
		L_2	7.2mH
	Resistors :	R_1	20 Ω
		R_2	30 Ω

TABLE 6.18

COMPONENTS OF TRV SHAPING CIRCUIT FOR TESTING 420 KV RATING CIRCUIT BREAKERS (WITH TRV CONTROL CIRCUIT-III)

Rating of CB	Circuit components		Terminal Fault	
			As per case-I	As per case-II
420kV (V_C= 424kV)	**Capacitor Banks**			
	Main Capacitor Bank:	C_o	18 μF	18 μF
	TRV Capacitor Bank:	C_1	1.0 μF	1.5 μF
		C_{22}	2.8 μF	2.0 μF
		C_{21}	0.8 μF	0.5 μF
		C_h	1.0 μF	1.0 μF
	Stray capacitor Bank:	C_c	21 nF	21 nF
	Reactors :	L_n	9.4 mH	6 mH
		L_1	38 mH	32 mH
	Resistors :	R_1	78 Ω	30 Ω
		R_{22}	57 Ω	36 Ω

TABLE 6.19

TRV PARAMETERS OBTAINED OR REALISED FOR 420 KV RATING CBS (TERMINAL FAULT TEST DUTY, WITH VARIOUS CONTROL CIRCUITS)

TRV Parameters/ Control circuit	**I**	**II**	**III**
First reference voltage u_1, kV	336	336	338
Time to reach u_1, t_1 μs	168	168	170
TRV peak value , u_c kV	623.6	623.6	625
Time to reach u_c, t_2 μs	668	668	668
Rate of rise, u_1/t_1, kV/μs	2	2	2. 01

TABLE 6.20
MAXIMUM VOLTAGE ACROSS EACH CAPACITOR BANK AND ENERGY REQUIREMENT FOR EACH CAPACITOR BANK FOR TESTING 420 KV RATING CIRCUIT BREAKERS (TERMINAL FAULT TEST DUTY)

Control Circuit	Capacitor Banks	Value	Max. Voltage across each capacitor Bank, Vmax, kV	Energy required by each capacitor Bank, kJ	Total Energy required
I	Main Capacitor Bank: C_n	32 μF	424	2876.41	$E_1 = 3385$ kJ
	TRV Capacitor Bank: C_1	0.6 μF	623	116.43	
	C_2	1.4 μF	744	387.47	
	Stray capacitor Bank: C_3	21 nF	624	4.10	
II	Main Capacitor Bank: C_n	60 μF	424	5393.28	$E_2 = 5899$ kJ
	TRV Capacitor Bank: C_1	2.0 μF	702	492.80	
	C_2	1.0 μF	139	9.66	
	Stray capacitor Bank: C_3	21Nf	624	4.10	
III	**Capacitor Banks**				$E_3 = 2037$ kJ
	Main Capacitor Bank: C_o	18 μF	424	1618.00	
	TRV Capacitor Bank: C_1	1.0 μF	589	173.46	
	C_{22}	2.8 μF	125	21.87	
	C_{21}	0.8 μF	514	105.68	
	C_h	1.0 μF	478	114.24	
	Stray capacitor Bank: C_c	21 nF	624	4.10	

$$\frac{E_1}{E_2} = \frac{3385}{5899} = 0.5738 = 57.38\%$$

$$\frac{E_3}{E_2} = \frac{2037}{5899} = 0.3453 = 35\ \%$$

6.6 CONCLUSION

The TRV control circuit-I shown in Figure 6.1 is designed and simulated for both terminal fault as well as short line fault test duty for testing 245kV, 420kV and 800kV rating circuit-breakers as per new TRV requirements given in IEC 62271-100.

The comparison of TRV control circuits shown in Figures 6.1, 6.19 and 6.20 is made on aspects of equivalence, operation, required capacitive energy and applicability. The energy requirement for each capacitor bank used in different control circuits is given in the Table 6.16 and Table 6.20 for comparison purpose.

It is seen that in control circuit –II, the transformation from a 2 - Parameters to 4 - Parameters TRV circuit is simpler. But this circuit needs the highest capacitive energy and permits the testing of circuit-breakers at lower voltage compared to other two circuits.

TRV waveform of control circuit – I is good and needs only 53 to 57% capacitive energy of circuit – II for the same test conditions. The voltage rating of circuit breaker which can be tested is higher than with circuit – II. The voltage on C_2, however is higher and special attention should be paid to the insulating level of this bank.

Circuit – III is the most economical test circuit in terms of capacitive energy necessary and needs only 35 to 40 % capacitive energy of circuit – II for the same test conditions. Voltage rating which can be tested is highest with circuit – III. But circuit – III is the most complex to operate due the use of two spark gaps and more number of circuit components.

The results obtained by using different circuits have been discussed and compared with the required results according to IEC standards. The results shown are almost the same according to IEC standards. The results shows that although each circuit has its own merits and limitations, the control circuit-I appears to be very effective and is better than other circuits.