Chapter-4

ANALYSIS, DESIGN AND SIMULATION OF 2-PARAMETERS TRV SYNTHETIC TEST CIRCUIT

4.1 Analysis and Mathematical Modeling of 2-Parameters TRV Synthetic Test Circuit

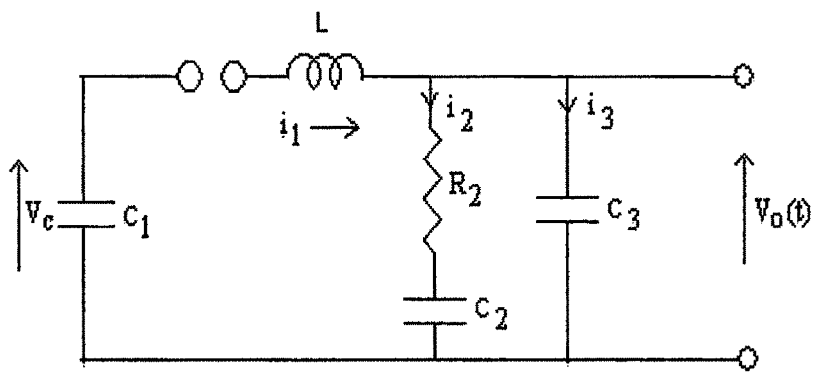

Fig.4.1 2-Parameters TRV synthetic test circuit

The circuit shown in Fig.4.1 permits to produce 2 – Parameters transient recovery voltages (TRV) according to IEC standards. The circuit consists of the following components:

- Main capacitor bank C_1
- TRV capacitor bank C_2
- Stray capacitor bank C_3
- Reactor L
- Resistor R

V_C is the charging voltage. The C_1, C_2, C_3, L and R_2 are the circuit components. The magnitude and the frequency of the transient recovery voltage depend on the voltage to which the main capacitor C_1 is charged and the values of circuit components. $V_O(t)$ is the transient recovery voltage. L, R_2, C_2 and C_3 are to control TRV and RRRV.

For the circuit shown in Fig.4.1, the output voltage across C_3 is given by

$$V_O(t) = \frac{1}{C_3}\int_0^t i_3 dt$$

Taking Lap lace transformation

$$V_O(S) = \frac{1}{C_3 s} I_3(s) \qquad \text{------} \qquad \text{------} \qquad \text{-----} (4.1)$$

Where i_3 is the current through C_3

Now, $$I_1(s) = I_2(s) + I_3(s) \qquad \text{------} \qquad \text{------} \qquad \text{-----} (4.2)$$

$$I_2(s) = \frac{V_O(s)}{(R_2 + \frac{1}{C_2 s})}$$

$$\therefore I_1(s) = \frac{V_O(s)}{(R_2 + \frac{1}{C_2 s})} + I_3(s) \qquad \text{------} \qquad \text{------} \qquad \text{-----} (4.3)$$

Substituting the value of $V_O(s)$ from equation (4.1) into the equation (4.3)

$$\therefore I_1(s) = \frac{I_3(s)}{C_3 s(R_2 + \frac{1}{C_2 s})} + I_3(s)$$

$$= I_3(s)\left[1 + \frac{1}{C_3 s\left(R_2 + \frac{1}{C_2 s}\right)}\right]$$

$$\therefore I_3(s) = I_1(s)\left[\frac{(R_2 + \frac{1}{C_2 s})}{(R_2 + \frac{1}{C_2 s}) + \frac{1}{C_3 s}}\right] \qquad \text{----} \qquad \text{----} \qquad \text{-----} \qquad (4.4)$$

The value of current $I_1(s)$ in terms of voltage V_c of capacitance C_1 is given by

$$I_1(s) = \frac{V_C}{s} \cdot \frac{1}{\frac{1}{C_1 s} + Ls + \frac{(R_2 + \frac{1}{C_2 s}) \times \frac{1}{C_3 s}}{R_2 + \frac{1}{C_2 s} + \frac{1}{C_3 s}}} \qquad \text{----} \qquad \text{-----} \qquad \text{-----} \qquad (4.5)$$

Substituting the value of $I_1(s)$ from equation (4.5) into (4.4) and then value of $I_3(s)$ from equation (4.4) into (4.1), we get

$$V_O(s) = \frac{1}{C_3 s} \cdot \frac{V_C}{s} \cdot \frac{1}{\dfrac{1}{C_1 s} + Ls + \dfrac{(R_2 + \frac{1}{C_2 s}) \times \frac{1}{C_3 s}}{(R_2 + \frac{1}{C_2 s}) + \frac{1}{C_3 s}}} \cdot \frac{(R_2 + \frac{1}{C_2 s})}{(R_2 + \frac{1}{C_2 s}) + \frac{1}{C_3 s}}$$

$$\therefore V_O(s) = \frac{1}{C_3 s} \cdot \frac{V_C}{s} \cdot \frac{(R_2 + \frac{1}{C_2 s})}{\frac{1}{C_1 s}\left[(R_2 + \frac{1}{C_2 s}) + \frac{1}{C_3 s}\right] + Ls\left[(R_2 + \frac{1}{C_2 s}) + \frac{1}{C_3 s}\right] + (R_2 + \frac{1}{C_2 s}) \times \frac{1}{C_3 s}}$$

Simplifying the above equation, the transient recovery voltage

$$V_O(s) = -\frac{C_1 V_C}{s} \cdot \frac{(1 + sR_2 C_2)}{s^3 LR_2 C_1 C_2 C_3 + s^2 LC_1 (C_2 + C_3) + sR_2 C_2 (C_1 + C_3) + C_1 + C_2 + C_3}$$

If we ignore the capacitor C_3, this expression is simplified and becomes,

$$V_O(s) = -\frac{C_1 V_C}{s} \cdot \frac{(1 + sR_2 C_2)}{s^2 LC_1 C_2 + sR_2 C_1 C_2 + C_1 + C_2}$$

$$= -\frac{C_1 V_C}{s} \cdot \frac{(1 + sR_2 C_2)}{s^2 + s\frac{R_2}{L} + \frac{C_1 + C_2}{LC_1 C_2}}$$

$$\therefore V_O(s) = -C_1 V_C \left[\frac{1 + sR_2 C_2}{s\left(s^2 + s\frac{R_2}{L} + \frac{C_1 + C_2}{LC_1 C_2}\right)}\right] \quad \text{---- ---- -----} \quad (4.4)$$

Taking Inverse lap lace transformation of the above equation (4.4) we get, The transient recovery voltage

$$\therefore V_O(t) = -\frac{C_1 V_C}{C_1 + C_2}\left[\sin\phi + e^{-\alpha t}\sin(\beta t - \phi)\right] \quad ---- \quad ---- \quad ----- (4.5)$$

OR

$$V_O(t) = -\frac{C_1 V_C}{C_1 + C_2}\sin\phi\left[1 + \frac{e^{-\alpha t}}{\sin\phi}\cdot\sin(\beta t - \phi)\right]$$

$$\text{Where} \quad \alpha = \frac{R_2}{2L}$$

$$\beta = \sqrt{\frac{C_1 + C_2}{LC_1C_2} - \frac{R_2^2}{4L^2}}$$

$$\tan\phi = \frac{C_1}{2C_2}\cdot\frac{\beta}{\alpha}$$

Equation (4.5) gives the relationship between transient recovery voltage and time in terms of charging voltage V_C and the circuit components C_1, C_2, L and R_2.

4.2 Design of 2-Parameters TRV Synthetic Test Circuit by using MATLAB

Short circuit tests require circuit with response specified by IEC standards. According to IEC standards, for circuit-breakers rated less than 100kV, the TRV envelope is defined by two parameters method as discussed in previous chapter 3. The two parameters are:

u_c = reference voltage (TRV peak value) in kV;

t_3 = 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:

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

Where k_{af} = 1.54 for terminal fault and short line fault, in the case of line systems;

= 1.4 for terminal fault in the case of cable systems;

k_{pp} = 1.5 for terminal fault

= 1.0 for short line fault

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 flowchart or algorithm to design 2-Parameters TRV synthetic testing circuit is shown Fig.4.2. The program has been developed for finding TRV parameters and envelopes according to IEC standards for both terminal fault and short line fault test duty conditions by using MATLAB M-file.

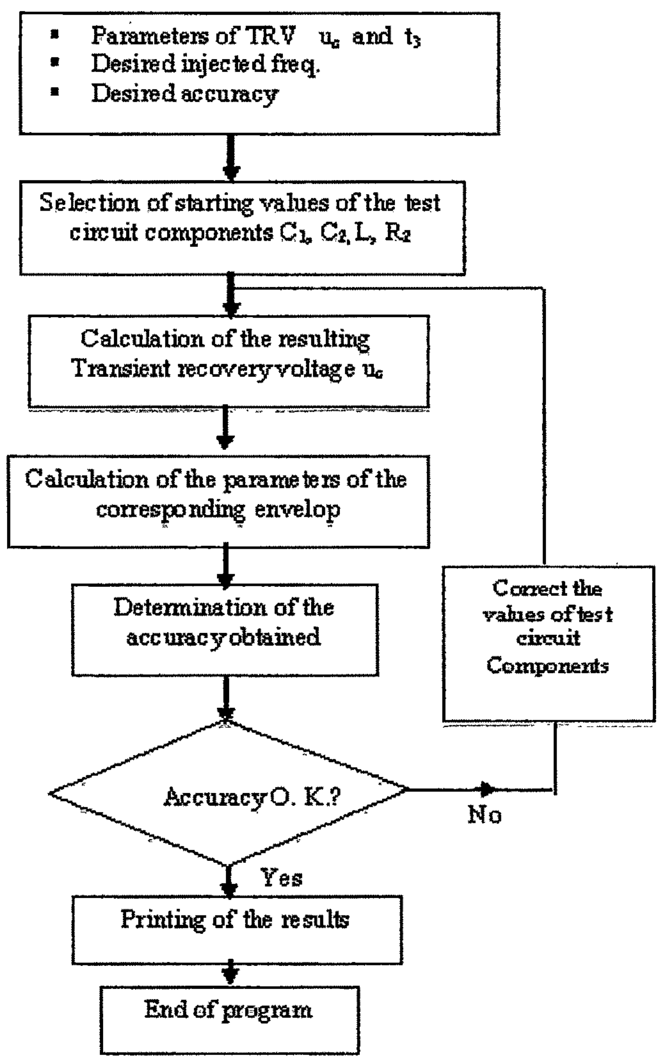

Fig.4.2 Flow chart for design of 2-parameters TRV synthetic test circuit

Algorithm

- Desired TRV parameters u_c and t_3 for a particular rating of circuit-breakers as per IEC standards.
- Selection of starting values of the circuit components

  Input data or enter the values of the following;

  1. Main capacitor bank C_1
  2. TRV capacitor bank C_2
  3. Reactor L
  4. Resistor R
  5. Charging Voltage V_C
  6. Time step dt
- Calculation of resulting transient recovery voltage

$$\therefore V_O(t) = -\frac{C_1 V_C}{C_1 + C_2}\left[\sin\phi + e^{-\alpha t}\sin(\beta t - \phi)\right]$$

- Plot TRV envelope (voltage in kV Vs. Time in μs)
- Determination of the TRV parameters of the corresponding envelope as per IEC (discussed in chapter 3, section 3.6)

The main capacitor C_1 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 C_1 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} = 1.5 for terminal fault

= 1.0 for short line fault

Therefore, the charging voltage for 36kV rating circuit-breakers is as follows:

V_C = 41.886 ≈ 42kV for terminal fault test duty

= 27.924 ≈ 28kV for short line fault test duty

The developed program is tested for finding TRV parameters and envelopes to test 36kV rating circuit-breakers for terminal as well as short line fault test duty condition. The TRV envelopes obtained for terminal and short line fault duty conditions to test 36kV rating circuit-breakers are shown in Fig.4.3 to Fig.4.6.The Table 4.1 shows the optimal components of 2-parameters TRV control circuit for testing 36kV rating circuit-breakers.

The expected TRV parameters according to IEC standards for testing 36kV rating circuit-breakers are given in Table 4.2. The actual TRV parameters obtained from TRV envelopes are given in Table 4.3.

TABLE 4.1
OPTIMAL CIRCUIT COMPONENTS OF TRV SHAPING CIRCUIT FOR TESTING 36 KV RATING CIRCUIT BREAKERS

Rating of CB	Circuit components	Terminal Fault Test Duty	Short line fault Test Duty
36kV	**Capacitor Banks**		
	Main Capacitor Bank: C_1	15μF	15μF
	TRV Capacitor Bank: C_2	0.6 μF	0.6 μF
	Stray capacitor Bank: C_3	21nF	21nF
	Reactor : L	1mH	1mH
	Resistor : R	11.6 Ω	11.6 Ω
	Charging Voltage : V_C	42 kV	28 kV

4.3 TRV envelopes obtained for testing 36kV rating circuit-breakers by using MATLAB

TRV envelopes obtained for terminal as well as short-line fault duty conditions to test 36 kV rating circuit-breakers are as follows:

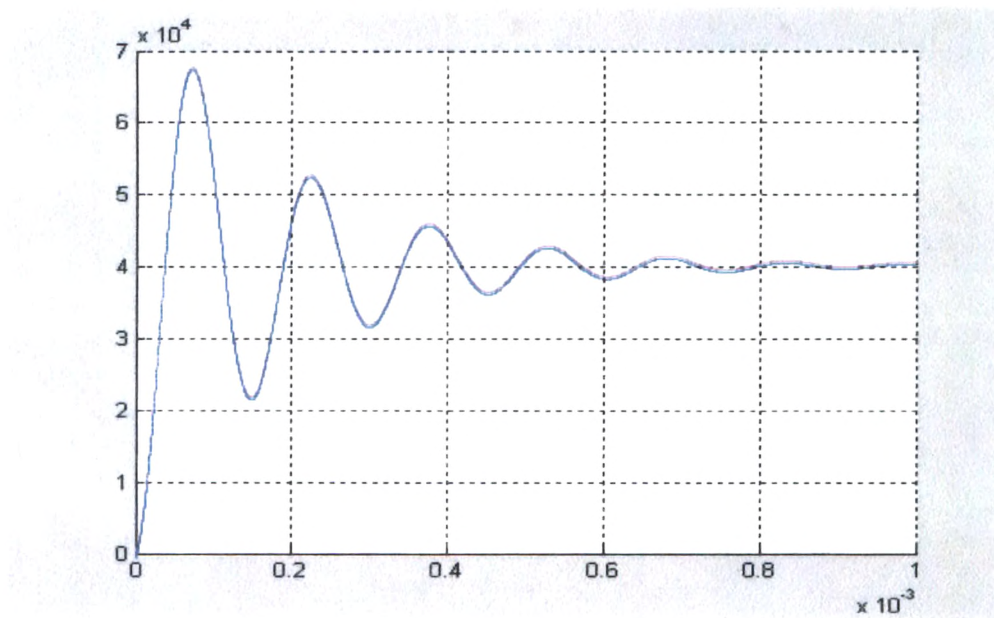

Fig.4.3. Terminal fault TRV envelope for 36kV rating circuit-breaker by using MATLAB (TRV envelope represented in Fig.3.8 as per IEC)

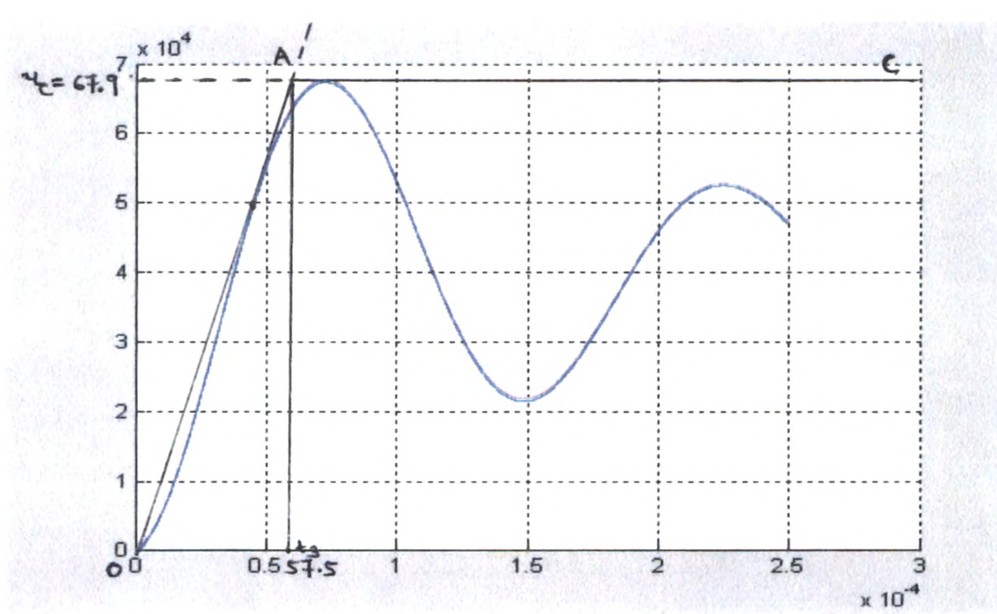

Fig.4.4. Expanded view of Terminal fault TRV envelope for 36kV rating circuit-breaker by using MATLAB (TRV envelope represented in Fig.3.8 as per IEC)

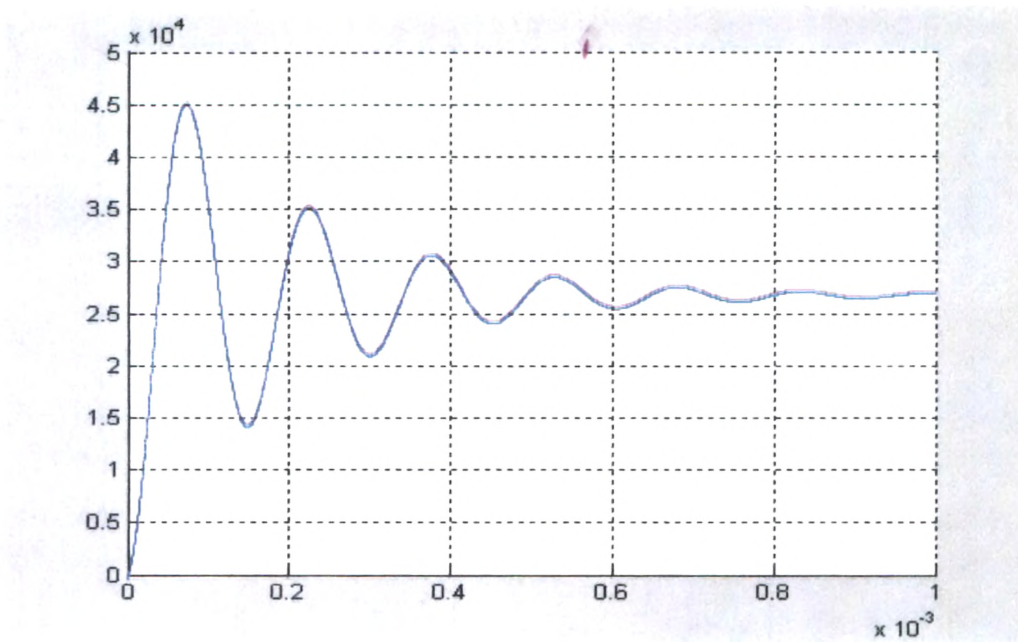

Fig.4.5. Short line fault TRV envelope for 36kV rating circuit-breaker by using MATLAB (TRV envelope represented in Fig.3.8 as per IEC)

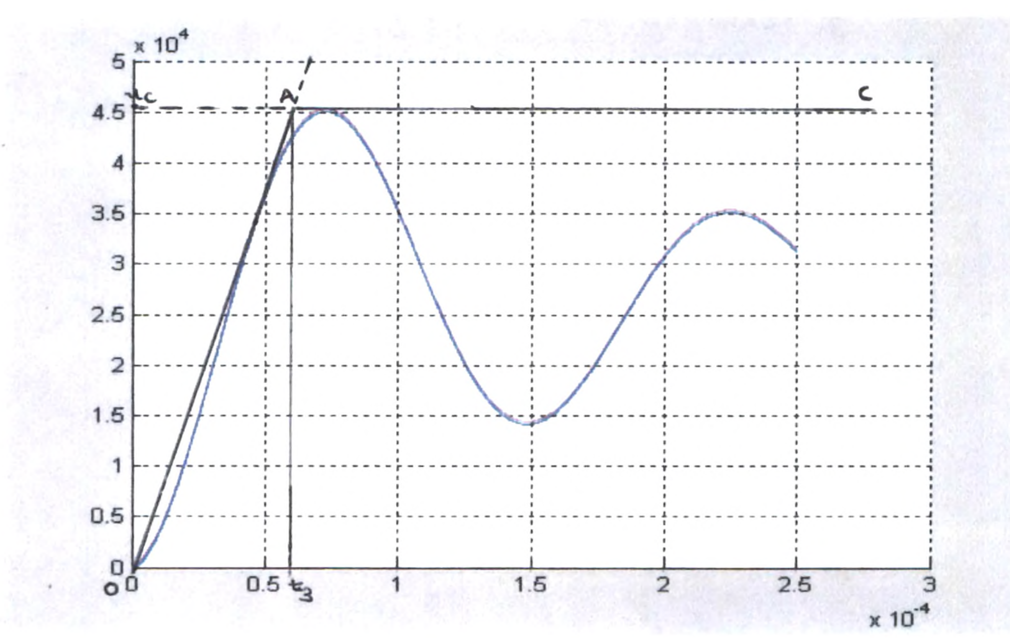

Fig.4.6. Expanded view of short line fault TRV envelope for 36kV rating circuit-breaker by using MATLAB (TRV envelope represented in Fig.3.8 as per IEC)

TABLE 4.2
EXPECTED TRV PARAMETERS ACCORDING TO IEC FOR 36KV RATING CBS

TRV Parameters	Test duty: Terminal fault	Test duty: Short line fault
Reference voltage (TRV peak value) u_c, kV	67.9	45.3
Time to reach u_c, t_3 μs	57	57
Rate of rise(RRRV) u_C/t_3, kV/μs	1.19	0.79

TABLE 4.3
TRV PARAMETERS OBTAINED 0R REALISED FOR 36 KV RATING CIRCUIT-BREAKERS
(BY MATLAB)

TRV Parameters	Test duty: Terminal fault	Test duty: Short line fault
Reference voltage (TRV peak value) u_c, kV	67.9	45.3
Time to reach u_c, t_3 μs	57.5	57.3
Rate of rise(RRRV) u_C/t_3, kV/μs	1.18	0.79

4.4 Simulation of 2-Parameters TRV Synthetic Test Circuit by using PSIM Simulator

The simulations are also carried out with the PSIM simulator for the same circuit components to verify the validity and effectiveness of the circuit. The 2-parameters TRV synthetic test circuit shown in Fig.4.1 is designed and simulated for terminal and short-line fault test duties to test 36kV rating circuit-breakers. Fig.4.7 and Fig.4.8 shows terminal fault TRV envelopes obtained for 36kV rating circuit-breakers and short-line fault TRV envelopes are shown in Fig.4.9 and Fig.4.10. The actual TRV parameters obtained from TRV envelopes are given in Table 4.4.

TRV envelopes obtained for testing 36kV rating circuit-breakers by using PSIM Simulator

TRV envelopes obtained for terminal as well as short-line fault duty conditions to test 36 kV rating circuit-breakers are as follows:

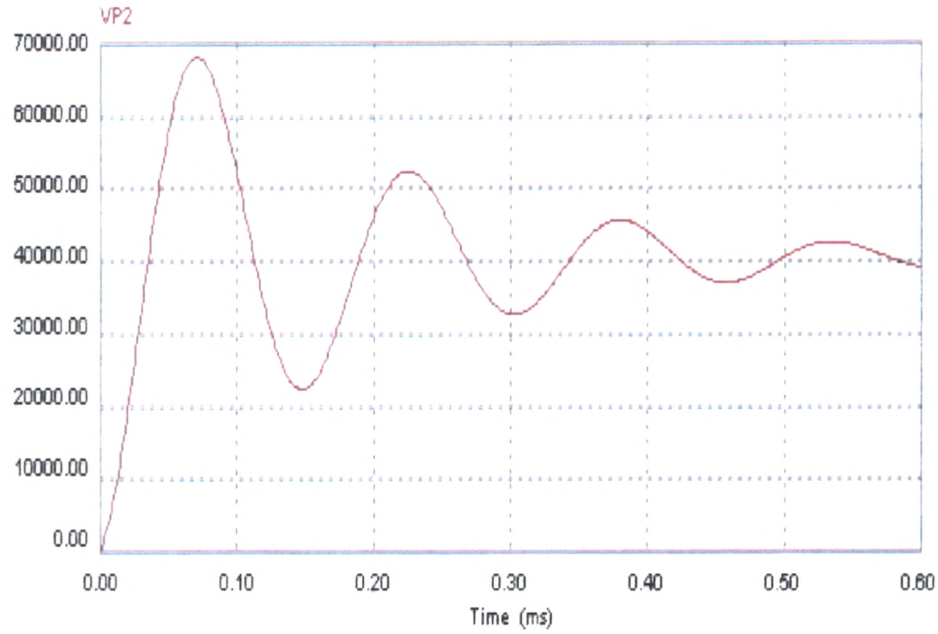

Fig.4.7. Terminal fault TRV envelope for 36kV rating circuit-breaker by using PSIM simulator (TRV envelope represented in Fig.3.8 as per IEC)

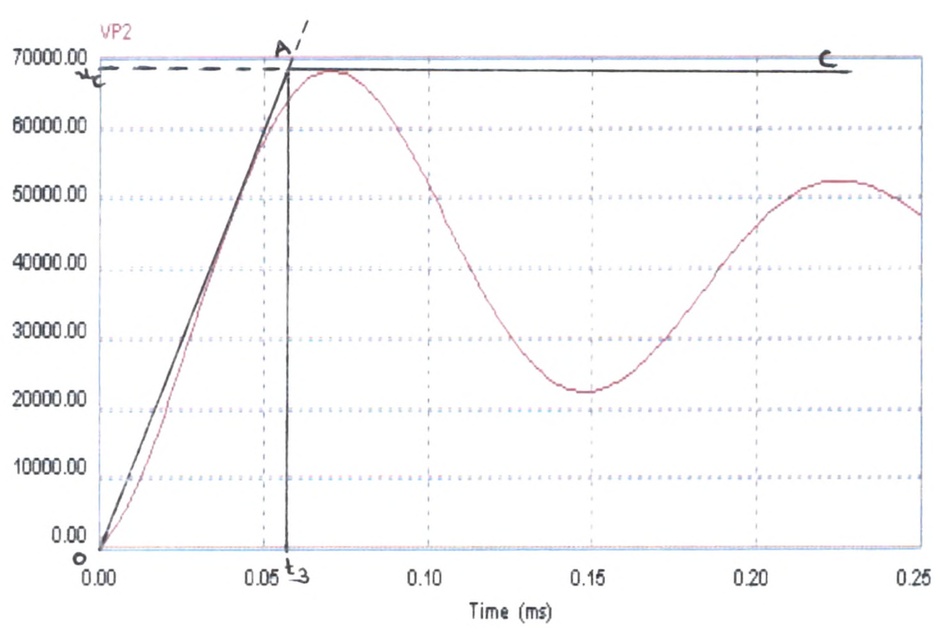

Fig.4.8. Expanded view of Terminal fault TRV envelope for 36kV rating circuit-breaker by using PSIM simulator (TRV envelope represented in Fig.3.8 as per IEC)

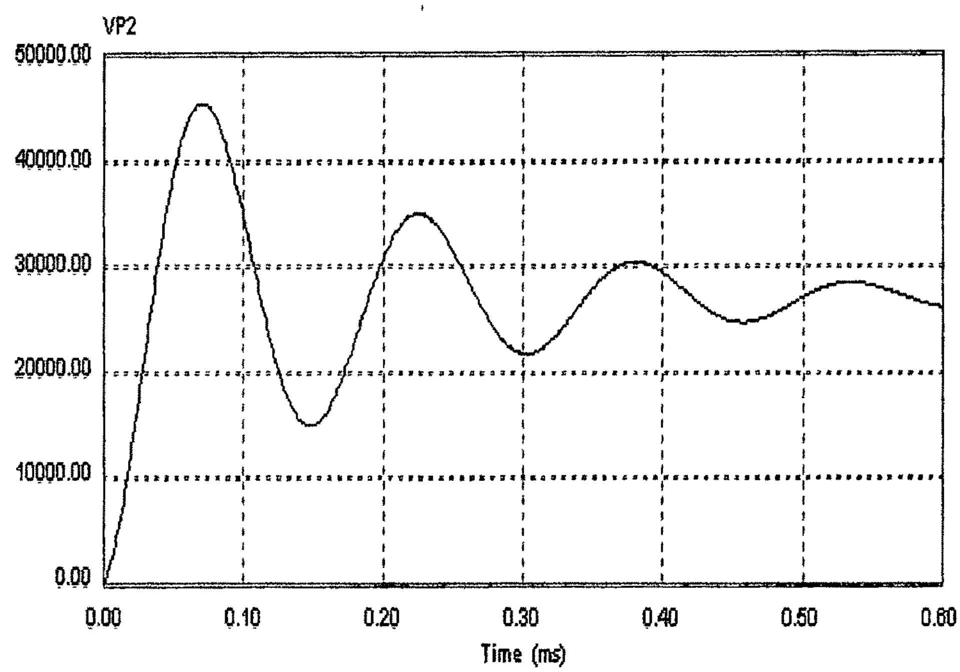

Fig.4.9. Short line fault TRV envelope for 36kV rating circuit-breaker by using PSIM simulator (TRV envelope represented in Fig.3.8 as per IEC)

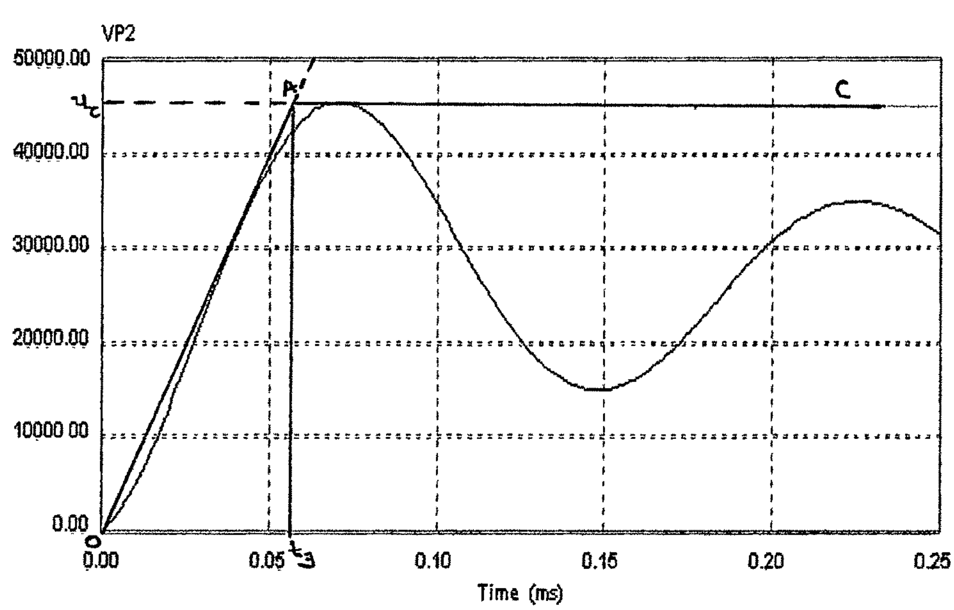

Fig.4.10. Expanded view of short line fault TRV envelope for 36kV rating circuit-breaker by using PSIM simulator (TRV envelope represented in Fig.3.8 as per IEC)

TABLE 4.4
TRV PARAMETERS OBTAINED OR REALISED FOR 36 KV RATING CIRCUIT-BREAKERS
(BY PSIM SIMULATOR)

TRV Parameters	Test duty: Terminal fault	Test duty: Short line fault
Reference voltage (TRV peak value) u_c, kV	67.9	45.3
Time to reach u_c, t_3 μs	56.5	57.3
Rate of rise(RRRV) u_C/t_3, kV/μs	1.20	0.79

4.5 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 analysis and mathematical modeling of 2-parameters TRV synthetic testing circuit is done. Design of 2-parameters TRV synthetic testing circuit is done by using MATLAB. The program has been developed for finding TRV parameters and envelopes according to IEC standards for both terminal fault and short line fault test duty conditions by using MATLAB M-file.

The simulations are also carried out with the PSIM simulator for the same circuit components to verify the validity and effectiveness of the circuit. The 2-parameters TRV synthetic test circuit is designed and simulated for terminal and short-line fault test duties to test 36kV rating circuit-breakers. The results i.e. the TRV envelopes and parameters obtained are the same according to IEC standards.