Chapter 3

TRV RATING CONCEPTS AND IEC STANDARDS TRV ENVELOPES

3.1 Classification of restriking transients and their circuits

Restriking voltage transients, and consequently their respective circuits can be classified as follows:

(1) Single frequency oscillatory transients

(2) Double frequency oscillatory transients

3.1.1 Single frequency oscillatory transients

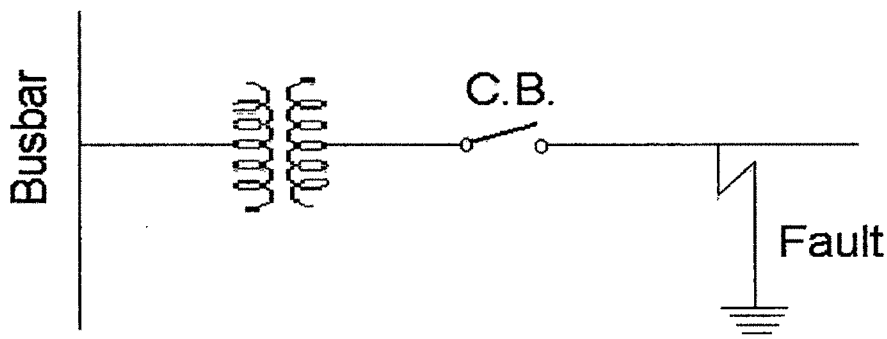


Fig. 3.1 Fault on a feeder near circuit- breaker

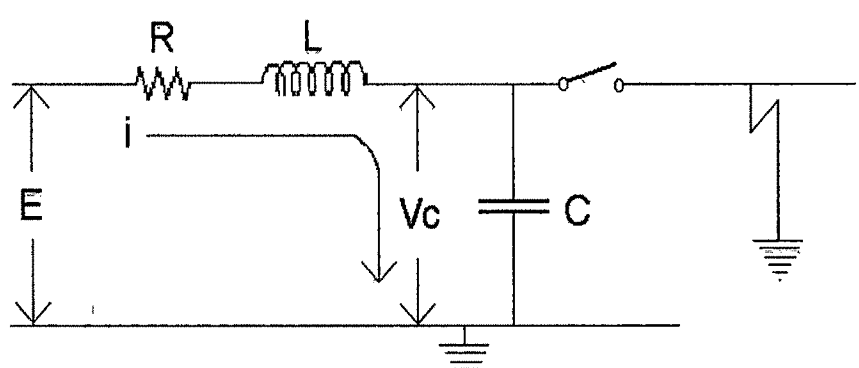


Fig. 3.2 Electrical equivalent circuit for the analysis of restriking voltage

Figure 3.1 shows a short circuit on a feeder beyond the location of the circuit breaker. Fig.3.2 shows an electrical equivalent circuit where L and C are the inductance and capacitance per phase of the system up to the point of circuit-breaker location respectively.

When the circuit-breaker is closed, the short-circuit current flows through R, L and the contacts of the circuit-breaker, the capacitance C being short-circuited by the fault. When the circuit-breaker contacts are opened and the arc is extinguished, the current i is diverted through the capacitance C, resulting in a transient condition. The inductance and the capacitance form a series oscillatory circuit. The voltage across the capacitance which is restriking voltage, rises and oscillates, as shown in figure 2.3.

The natural frequency of oscillation is given by

$$f_n = \frac{1}{2\pi\sqrt{LC}}$$

The voltage across the capacitance which is voltage across the contacts of the circuit-breaker can be calculated in terms of L, C, f_n and system voltage.

The mathematical expression for transient condition is as follows:

$$L\frac{di}{dt} + \frac{1}{C}\int idt = E \qquad \text{------- ------} \qquad (3.1)$$

Where E is the system voltage at the instant of arc interruption.

$$i = \frac{dq}{dt} = \frac{d}{dt}(CV_C)$$

Where V_C = voltage across the capacitor

$$\therefore \frac{di}{dt} = \frac{d^2(CV_C)}{dt} = \frac{Cd^2V_C}{dt^2}$$

$$\int \frac{i}{C}dt = \frac{q}{C} = V_C$$

Substituting these values in the equation (3.1), we get

$$LC\frac{d^2V_C}{dt^2} + V_C = E \qquad \text{------- ------} \qquad (3.2)$$

Taking laplace transform of both sides of the equation (3.2), we get

$$LCs^2V_C(s) + V_C(s) = \frac{E}{s}$$

$$V_C(s)\left[LCs^2 + 1\right] = \frac{E}{s}$$

$$\therefore V_C(s) = \frac{E}{s\left[LCs^2+1\right]} = \frac{E}{LCs(s^2+\frac{1}{LC})}$$

$$\omega_n = \frac{1}{\sqrt{LC}},$$

$$\therefore \omega_n{}^2 = \frac{1}{LC}$$

$$\therefore V_C(s) = \frac{\omega_n{}^2 E}{s(s^2+\omega_n{}^2)}$$

$$V_C(s) = \frac{\omega_n E}{s}\left(\frac{\omega_n}{s^2+\omega_n{}^2}\right) \qquad \text{-------} \quad \text{------} \qquad (3.3)$$

Taking the inverse laplace of equation (3.3), we get

$$V_C(t) = \frac{\omega_n E}{s}\sin\omega_n t$$

$$= \omega_n E \int_0^t \sin \omega_n t$$

$$= \omega_n E\left[\frac{-\cos\omega_n t}{\omega_n}\right]_0^t$$

As $V_C(t) = 0$ at t = 0, constant = 0

$$\therefore V_C(t) = E(1-\cos\omega_n t) \qquad \text{-------} \quad \text{------} \qquad (3.4)$$

= Restriking Voltage

The maximum value of restriking voltage occurs when $\omega_n t = \pi$

$$\therefore t = \frac{\pi}{\omega_n} = \frac{\pi}{2\pi f_n} = \frac{1}{2f_n}$$

Hence maximum value of restriking voltage = 2Epeak

= 2 x peak value of the system voltage

Expression for RRRV (Rate of Rise of Restriking Voltage):

$$RRRV = \frac{dV_C}{dt}$$

$$RRRV = E.\omega_n \sin\omega_n t$$

Maximum value of RRRV occurs, when $\omega_n t = \frac{\pi}{2}$

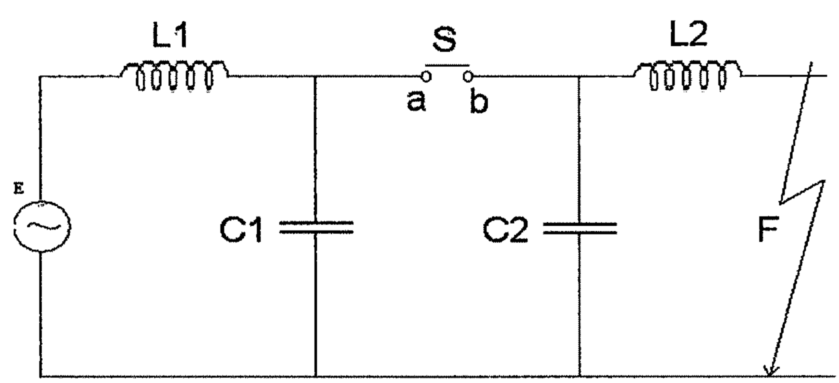
$$\therefore t = \frac{\pi}{2\omega_n} = \frac{\pi}{2 \times 2\pi f_n} = \frac{1}{4 f_n}$$

Hence the maximum value of RRRV = E ω_n

For single frequency oscillatory transients, the natural frequencies are of the order of 1kHz to 10kHz.

3.1.2 Double frequency oscillatory transients

The circuit-breaker S may have L and C parameters on its two sides, as shown in Figure 3.3. Before clearance the points **a** and **b** are at the same potential. After the fault is cleared, i.e. the arc has been extinguished , both the circuits oscillate at their own natural frequencies, a composite double frequency transient appears across the circuit breaker S.



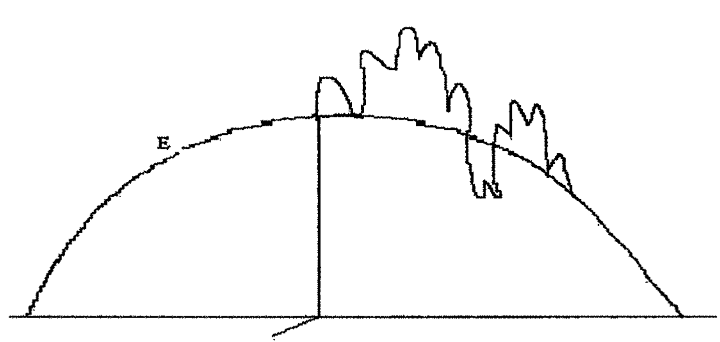


Fig.3.3 Double frequency restriking transient

The frequencies are given by

$$f_{n1} = \frac{1}{2\pi\sqrt{L_1 C_1}} \quad \text{and} \quad f_{n2} = \frac{1}{2\pi\sqrt{L_2 C_2}}$$

The magnitude and the Waveform for the total voltage is proportional to the inductances and is given by :

$$E_{TRV} = E\,[a_1(1-\cos\omega_1 t) + a_2(1-\cos\omega_2 t)]$$

Where $a_1 = L_1/(L_1+L_2)$ and $a_2 = L_2/(L1+L_2)$

$$\omega_1 = \frac{1}{\sqrt{L_1 C_1}} \quad \text{and} \quad \omega_2 = \frac{1}{\sqrt{L_2 C_2}}$$

3.2 Characteristics of Restriking Voltage

The important characteristics of restriking voltage which affect the circuit-breaker performance are:

(a) Amplitude factor

(b) RRRV

The Amplitude factor is defined as the ratio of the peak of transient voltage to the peak system frequency voltage.

The rate of rise of restriking voltage (RRRV) is defined as the slope of the steepest tangent to the restriking voltage curve **or** it is the slope of a line from voltage zero to the first peak of the wave. It is expressed in Volts/μs.

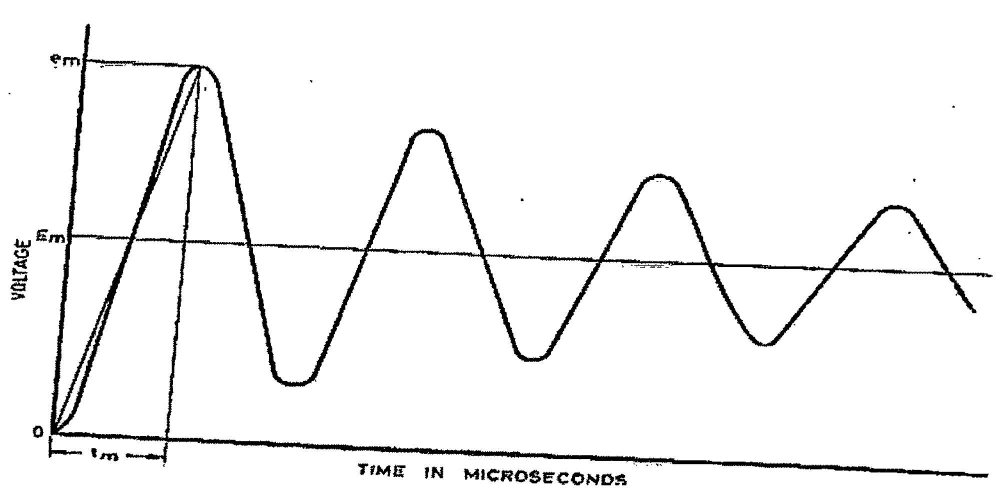


Fig. 3.4 Method of evaluation for single frequency curves

As shown in Fig. 3.4

e_m = peak transient recovery voltage

t_m = time in microseconds between voltage zero and voltage peak,

E_m = peak value of the recovery voltage in volts

Amplitude Factor = $\frac{e_m}{E_m}$

Rate of Rise of Restriking Voltage, $RRRV = \frac{e_m}{t_m}$ Volts/μs

The Natural frequency = $\frac{10^3}{2t_m}$ kHz

3.3 Interruption of Terminal and Short-line Faults

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 circuit-breaker should be capable of performing following switching duties:

(i) Interruption of terminal faults

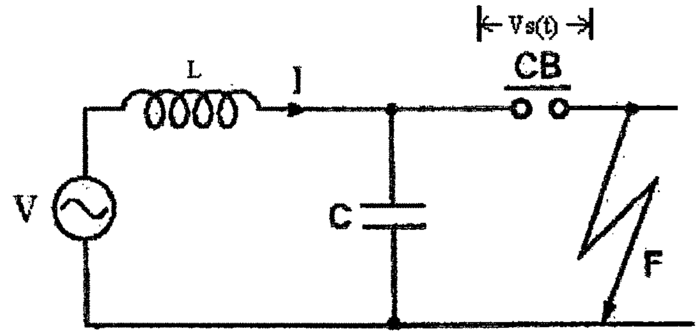
(ii) Interruption of short line faults

(iii) Out of phase switching

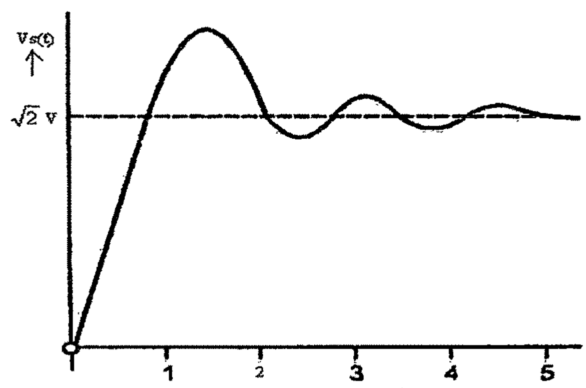
3.3.1 Interruption of Terminal Faults

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.

Figure 3.5 shows a single phase representation of a terminal fault condition. Consider circuit-breaker closed and a short circuit F occurs very near the breaker terminal so that the impedance between the breaker and the fault 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. After the arc extinguishes at natural zero of the power frequency waveform, the circuit recovers and transient recovery voltage (TRV) appears across the breaker pole.



(a) Circuit diagram



(b) Simplified TRV waveform

Fig.3.5 Conditions representing terminal fault

The circuit being predominantly inductive, the power factor of current is low, about 0.1. The simplified waveform of transient recovery voltage is shown in Figure 3.5(b). In practice, quite complex waveforms are possible. The frequencies of TRV vary from several hundred to several thousand cycles under the condition of terminal short circuit.

As per IEC 62271-100, the rated characteristics of a circuit breaker include rated transient recovery voltage for terminal faults. The rated short-circuit breaking current is specified with reference to the rated TRV for terminal faults.

3.3.2 Interruption of short line faults

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.

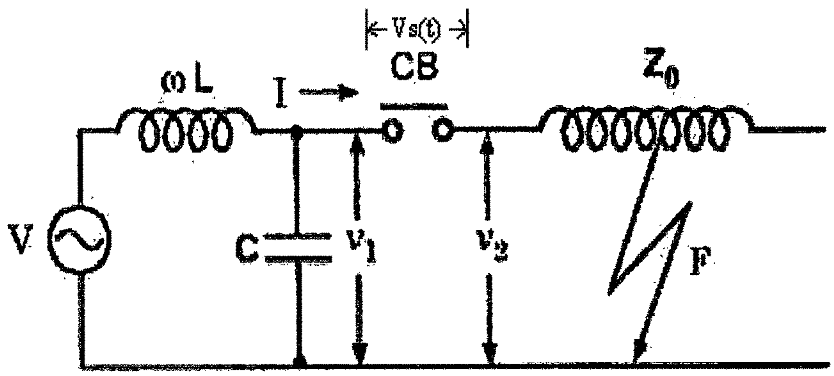
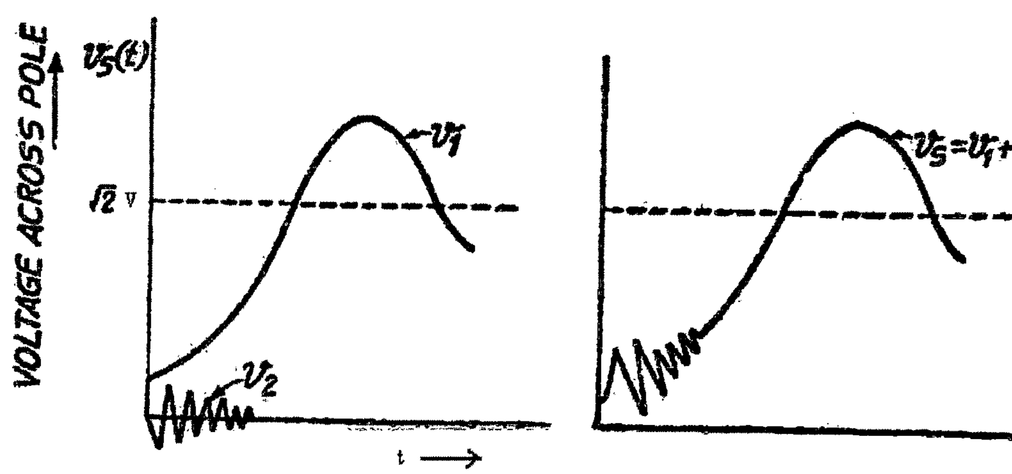


Fig. 3.6 (a) Circuit diagrams



(b) Simplified TRV Waveform

Fig.3.6 Conditions representing short-line fault

Figure 3.6 represents a condition of a short-line fault and simplified TRV waveform. Referring to Fig.3.6, source voltage cause short-circuit current I flowing through the circuit comprising the following impedances :

ωL = impedance of source

λ = impedance per km length of the line

l = length of line between breaker and the fault, km

The voltage appearing across breaker pole after final current interruption has two components v_1 and v_2.

Where v_1 = voltage at the terminals from supply side

v_2 = voltage at the terminals from line side

The voltage v_1 has power frequency component and high frequency component and reaches a peak value $\sqrt{2}$ V shown in figure 3.6 (b). Whereas v_2 has a saw-tooth waveform and drops to zero after a few microseconds. The transient recovery voltage V_S across the breaker pole is the sum of v_1 and v_2.

The superimposed high frequency component due to line frequency F_L has a value of $v_p / 4\lambda$, where v_p is propagation velocity on the line and λ is the impedance per unit length of line. F_L may reach a value between 10 to 100kHz depending upon length of line location of fault. The peak value of high frequency component is reached in a few microseconds. Hence the rate of rise of TRV is very high.

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.

The interruption of fault current due to short line faults on overhead lines imposes a serious duty on the CB. This is because the transient recovery voltage (TRV) across the breaker terminals is accompanied by a high frequency line side component, whereas the reduction of fault current due to the inductance of the short-circuited line is only slightly less than that of a terminal fault. The transient voltage of a short-circuited line is proportional to the magnitude of the fault current, and the frequency is inversely proportional to the length of the short-circuited line.

The rate of rise of oscillations is quite high due to the effective surge impedance of the short-circuited line. The RRRV is given as

$$RRRV = \sqrt{2}\,\omega\, I\, Z_o$$

Where ω = supply or source angular frequency

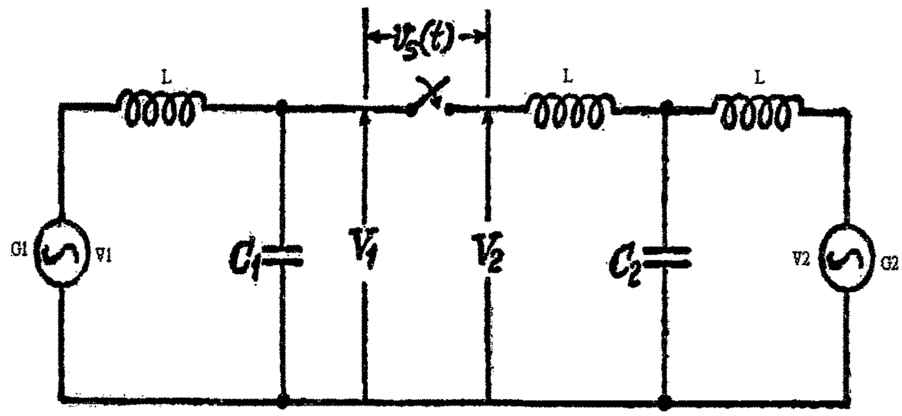
I = short-circuit current

Z_o = effective surge impedance of the short-circuited line

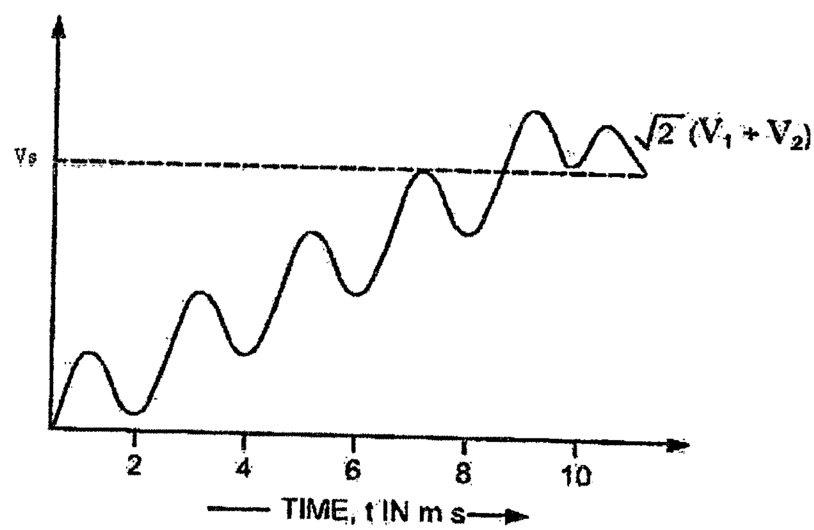
The RRRV after interruption of a short-line fault(short-circuit about 1km away from a line CB) current may be of the order of 6 to 8 kV/μs, depending upon the surge impedance of the line while in case of a terminal fault, RRRV is of the order of 1.5kV/μs.

3.3.3 Out of phase switching (Phase opposition switching)

When two systems are to be synchronized, it may happen that the breaker opens on non-synchronous condition.



(a) Circuit diagram



(b) Waveform of voltage across the breaker pole during out-of-phase opening

Fig.3.7 Out-of-phase switching

In Figure 3.7, if V_1 and V_2 are not in synchronous during opening of breaker the likely waveform of transient recovery voltage is shown in fig.3.7(b). Under certain conditions, the voltage across pole may reach three times phase voltage or in extreme cases it may reach twice line-to-line voltage.

The circuit-breakers used for synchronizing, should be capable of opening satisfactory under non-synchronous condition. In such case the recovery voltage may be much higher than that for other short-circuit duties. The magnitude of recovery voltage depends upon the phase angle between the voltages on two sides of the circuit-breaker.

The recovery voltage has a maximum value when the two voltages are 180^0 out-of-phase, given by

$$Vs = \sqrt{2}V_1 + \sqrt{2}V_2$$

$$= \sqrt{2}\,(V_1+V_2)$$

Where Vs = maximum value of power frequency recovery voltage

V_1 = component from source side

V_2 = component from line side

3.4 Representation of TRV Waves [25], [30]

The waveform of transient recovery voltages varies according to the arrangement of actual circuits.

In some cases, particularly in systems with a voltage 100kV and above, and where the short-circuit currents are relatively large in relation to the maximum short-circuit current at the point under consideration, the transient recovery voltage contains first a period of high rate of rise, followed by a later period of lower rate of rise. This waveform is generally adequately represented by an envelope consisting of three line segments defined by means of four parameters. Methods of drawing TRV envelopes are given in section 3.6.

In other cases, particularly in systems with a voltage less than 100kV, or in systems with a voltage greater than 100kV in conditions where the short-circuit currents are relatively small in relation to the maximum short-circuit currents and fed through transformers, the transient recovery voltage approximates to a damped single frequency oscillation. This waveform is adequately represented by an envelope consisting of two line segments defined by means of two parameters. Methods of drawing TRV envelopes are given in section 3.6.

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 into account by introducing a time delay.

3.5 IEC Standards TRV Envelopes [25], [30]

Short circuit tests require circuit with response specified by IEC standards shown in Fig. 3.8, 3.9 and Fig. 3.10.

IEC standards define two TRV envelopes.

A. Case of two parameters

For circuit breakers rated less than 100 kV, the envelope is defined by the two parameters method shown in Fig. 3.8.

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

Time delay:

t_d = 0.15 t_3 for terminal fault in case of cable systems;

= 0.05 t_3 for terminal fault and short line fault, in case of line systems;

B. Case of four parameters

For circuit breakers rated 100 kV and above, the TRV envelope is defined by the four-parameter method shown in Fig. 3.9 and Fig.3.10.

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:

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

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

$t_2 = 4\ t_1$ 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;

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

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

k_{pp} = 1.3 for terminal fault

= 1.0 for short line fault

It is seen that, 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.

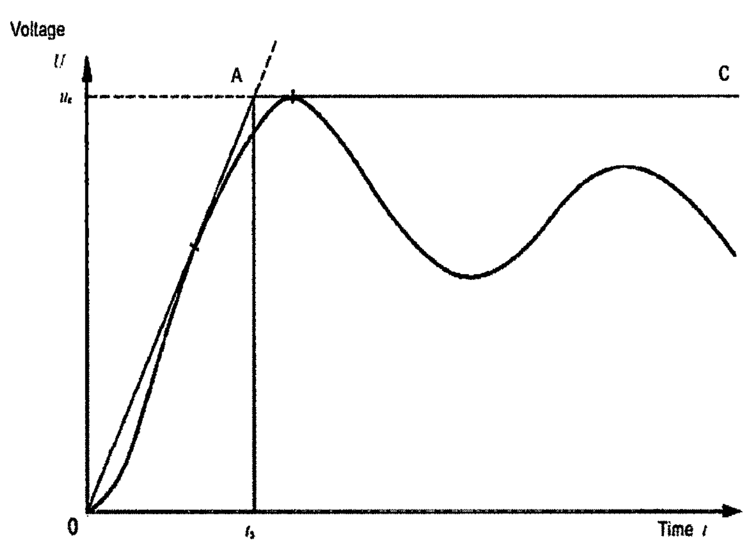


Fig.3.8 Representation by two parameters (u_c and t_3) of a prospective transient recovery voltage of a circuit

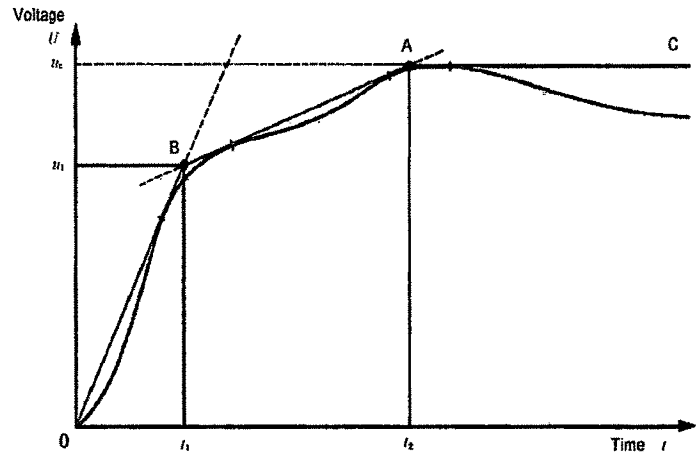


Fig.3.9 Representation by four parameters (u_1 and t_1, u_c and t_2) of a prospective transient recovery voltage of a circuit: Case I

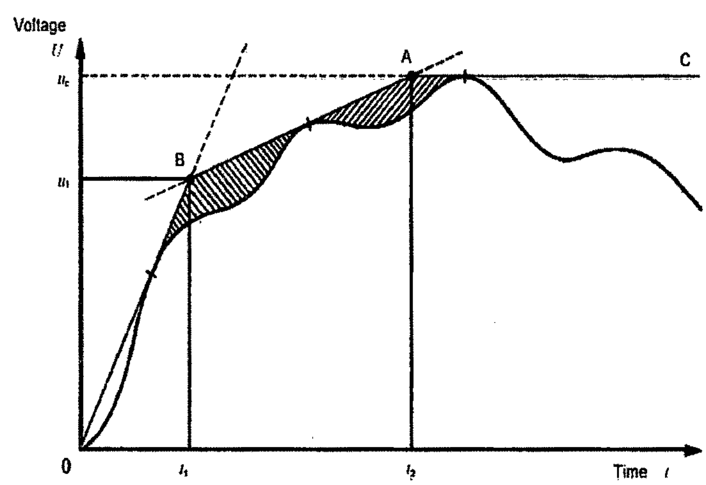


Fig.3.10 Representation by four parameters (u_1 and t_1, u_c and t_2) of a prospective transient recovery voltage of a circuit: Case II

3.6 Method of drawing the envelope of the prospective TRV of a circuit and determination of parameters [25],[30]

A transient recovery voltage wave may assume different forms, both oscillatory and non-oscillatory. The wave may be defined by means of an envelope made up of three consecutive line segments.

Drawing the envelope:

The following method is used for constructing the line segments forming the envelope of the prospective TRV curve.

(a) the first line segment passes through the origin O is tangential to the curve and does not cut the curve
(See Figures 3.9 and 3.10, segment OB and Figure 3.8 segment OA)

(b) the second line segment is a horizontal line tangential to the curve at its highest peak
(See Figures 3.8 to 3.10, segment AC)

(c) The third line segment is tangential to the curve at one or more points situated between the first two points of contact and does not cut the curve.

There are three possible cases for drawing this latter line segment:

(i) One single line segment can be drawn touching the curve at two points.
In this case, it forms part of the envelope (see Figure 3.9, segment BA)
The four parameters envelope O,B,A,C is then obtained.

(ii) Several segments can be drawn which touch the curve at two points (or possibly at more than two points) without cutting it.
In this case, the segment to be used for the envelope is that which touches the curve at one point only, situated so that the areas on either side of this point between the curve and the envelope are approximately equal. (See Figure 3.10, segment BA).
The four parameters envelope O,B,A,C is then obtained.

(iii) No segment can be drawn touching the curve at more than one point without cutting it.
In this case the following distinction should be made.
The point of contact of the first line segment and the highest peak are comparatively close to each other.
This is the case for a curve representing a damped oscillation of single frequency or a curve of similar shape.

In this case, a third line segment is not drawn and representation by two parameters, corresponding to the first two line segments, is adopted (see Figure 3.8).

The two parameter envelope O, A, C is then obtained.

Determination of parameters:

The representative parameters are, by definition, the coordinates of the points of intersection of the line segments constituting the envelope.

When the envelope is composed of three line segments, the four parameters u_1, t_1, u_c and t_2 shown in Figures 3.9 and 3.10 can be obtained as coordinates of the points of intersection B and A.

When the envelope is composed of two line segments only, the two parameters u_c and t_3 shown in Figure 3.8 can be obtained as coordinates of the point of intersection A.

3.7 Standard Values of TRV [25],[30]

Standard values of TRV for three-pole circuit breakers of rated voltages less than 100kV make use of two parameters. Values are given in Table 3.1 for line systems.

For rated voltages of 100kV and above, four parameters are used. Table 3.2 gives values for rated voltages of 245kV and above.

The tables also indicate values of rate of rise, taken as u_c/t_3 and u_1/t_1, in the two-parameter and four-parameter cases, respectively, which together with TRV peak values u_c may be used for purposes of specification of TRV. The values given in the tables are prospective values. They apply to circuit-breakers for general transmission and distribution in three-phase systems having service frequencies of 50Hz or 60Hz and consisting of transformers, overhead line and cables.

TABLE 3.1 STANDARD VALUES OF TRANSIENT RECOVERY VOLTAGE FOR CIRCUIT BREAKERS - RATED VOLTAGES EQUAL TO OR HIGHER THAN 12KV AND LESS THAN 100KV – REPRESENTATION BY TWO PARAMETERS

Rated Voltage U_r kV	Type of Test duty	First-pole-to-clear factor k_{pp} p.u.	Amplitude factor k_{af} p.u.	TRV peak value u_c kV	Time to reach u_c, t_3 µs	RRRV u_c / t_3 kV/ µs
12	Terminal fault	1.5	1.54	22.6	26.5	0.85
	Short-line fault	1	1.54	15	26.5	0.57
36	Terminal fault	1.5	1.54	67.9	57	1.19
	Short-line fault	1	1.54	45.3	57	0.79
72.5	Terminal fault	1.5	1.54	137	93	1.47
	Short-line fault	1	1.54	91.2	93	0.98

TABLE 3.2 STANDARD VALUES OF TRANSIENT RECOVERY VOLTAGE FOR CIRCUIT BREAKERS - RATED VOLTAGES 245KV AND ABOVE FOR EFFECTIVELY EARTHED SYSTEMS- REPRESENTATION BY FOUR PARAMETERS

Rated Voltage U_r kV	Test duty	First-pole-to-clear factor k_{pp} p.u.	Amplitude factor k_{af} p.u.	First reference voltage u_1 kV	Time to reach u_1, t_1, µs	TRV peak value u_c kV	Time to reach u_c, t_2, µs	RRRV u_1/t_1 kV/ µs
245	Terminal fault	1.3	1.4	195	98	364	392	2
	Short-line fault	1	1.4	150	75	280	300	2
420	Terminal fault	1.3	1.4	334	167	624	668	2
	Short-line fault	1	1.4	257	129	480	516	2
800	Terminal fault	1.3	1.4	637	318	1189	1272	2
	Short-line fault	1	1.4	490	245	914	980	2