3

Fundamentals of Fault Clearing, Switching Phenomena and Circuit-Breaker Ratings

Transient phenomena during fault clearing—Shortcircuit current—Transient, Sub-trasient and Steady-State—Current and voltage variation during arc extinction process—Transient Recovery voltage—Switching phenomena--Circuit-breaker ratings.

3.1. INTRODUCTION

The following phenomena can be observed during the fault clearing process :

1. As the fault occurs, the current increases to a high value during the first half cycle of the wave and thereafter the amplitude of the wave goes on reducing as the waveform passes through the sub-transient, transient and steady state. The waveform of the current is asymmetrical about the normal zero axis.

2. The voltages across the circuit-breaker pole after the final arc extinction (called the transient recovery voltage) has a relatively high amplitude and rate of rise. The voltage has a high frequency transient component superimposed on a power frequency component.

In this chapter the above mentioned phenomena have been studied with reference to the behaviour of circuit-breaker. For the purpose of analysis, simple RLC networks have been considered. The generator has been represented by an e.m.f source. The equations of voltage and current have been solved by simple rules of differential calculus.

The analysis of short-circuit current and transient recovery voltage is followed by *Circuit-Breaker Ratings* (Sec. 3.19)

3. Overvoltages can be generated while closing circuit-breaker on capacitor banks or loaded transmission lines. These are minimised by pre-closing resistors and surge suppressors.

3.2. NETWORK PARAMETERS : R, L, C

An electrical network comprises the following network parameters:

— Inductance — Capacitance — Resistance.

The resistance can be neglected as a first approximation.

(*i*) **Inductance.** Inductance is defined as

$$L = \frac{d\Lambda}{di} \text{ henry} \qquad \text{...(3.1)}$$

where L = Inductance of circuit, henry.

A = Flux linkage due to current i, weber turns

i = current in the circuit, amp.

The e.m.f. induced in an inductor is given by,

$$e = \frac{d\Lambda}{di} = L\frac{di}{dt} \text{ volts} \qquad \text{...(3.2)}$$

Energy in inductance L henry at the instant when the current in it is i amp. is given by,

$$W_m = 1/2Li^2 \text{ joules} \qquad \text{...(3.3)}$$

(1 joule = 1 watt second)

In an inductive circuit current cannot change instantaneously. Hence when the *e.m.f* is applied at $t = 0$. The current is zero at the instant of closing the switch. Also we know that the current lags behind applied voltage by 90° in the inductance.

Considering sinusoidal voltage applied to an inductance, the current lags by 90°, therefore, the voltage of the circuit has maximum instantaneous value at the current zero.

While interrupting the current flowing through an inductive circuit such as a transformer on no load, a transformer loaded by an inductor, etc. the circuit-breaker should interrupt the arc at natural current zero of the altenating current wave. If the arc extinction takes place at the natural current zero, the energy in the inductance ($1/2Li^2$) is zero. However, if the arc is suddenly interrupted before the natural current zero, at the instantaneous value of current, say i amperes, the energy $1/2Li^2$ is suddenly interrupted by the chopping of current to an artificial zero value. Due to such a phenomenon. The interrupting of low magnetising currents of transformers, reactors need a particular attention. The circuit-breaker should be capable of interrupting such currents without getting damaged or without giving rise to over voltage above the permissible limits.

(*ii*) **Capacitance.** The well-known definition of the capacitor is: "Two or more conductors separated by dielectric (insulating) medium." The capacitance C is given by

$$C = \frac{dq}{dv} \text{ farads} \qquad \text{...(3.4)}$$

where C = capacitance farads ; q = charge, coulombs ; v = voltage, volts.

From the above definition, it is understandable that transmission lines, bushing, circuit-breakers etc. have inherent capacitance between phase and ground. In some cases the capacitance may be negligible. In h.v. circuit it becomes important and may not be negligible. In circuit-breaking phenomenon, capacitance plays an important role. The voltage across capacitor is given by

$$dv = \frac{dq}{C} \text{ volts}$$

$$v = \frac{1}{C}\int dq = \frac{1}{C}\int idt$$

Energy in a capacitor is in the form of electric field and is given by

$$W_c = \frac{1}{2}Cv^2 \text{ joules} \qquad \text{...(3.5)}$$

where C is in farads

v is in volts, q is the charge in coulombs.

There exists a distributed capacitance between conductors and between conductor and ground in case of transmission lines. The flow of alternating current in the transmission line is associated with alternate charging and discharging of this capacitance. The currents taken by the capacitance for charging are called charging currents. The charging current flow in transmission line, even if the receiving end is open circuited. The voltage across a capacitor cannot change instantaneously.

While closing a circuit-breaker on a predominantly capacitive circuit like a capacitor bank, the current flowing in the capacitance is given by

$$i = C\frac{dv}{dt}$$

where i = Instantaneous value of current amperes

C = Capacitance farads

dv/dt = Rate of change of voltage, volts/sec.

The current inrush during the closing of capacitive circuit can occur during pre-arcing between the circuit-breaker contacts. The following duties can produce severe stresses on the circuit-breaker:

— Paralleling of two capacitor banks
— Closing and opening capacitor banks.
— Closing and opening unloaded transmission lines on no load

3.3. VOLTAGE EQUATION OF AN RLC SERIES CIRCUIT

The voltage equation of an RLC series circuit is given by

$$e = L\frac{di}{dt} + Ri + \frac{1}{C}\int idt \text{ volts} \quad ...(3.6)$$

where e = impressed voltage

$L\frac{di}{dt}$ = voltage across inductor

Ri = voltage across resistor

$\frac{1}{C}\int idt$ = voltage cross capacitor.

For an alternating $e.m.f.$ the induced voltage e is given by

$$e = E_m \sin(\omega t + \theta) \quad ...(3.7)$$

where, $E_m = \sqrt{2}$ Erms and $\omega = 2\pi f$. Angle θ depends on magnitude of e at $t = 0$. If e is Zero at $i = 0$, then $\theta = 0$ if $e = E_m$ at $t = 0$ then $\theta = \pi/2$.

3.4. SUDDEN SHORT CIRCUIT OF R.L. SERIES CIRCUIT

Let us see, what happens, when switch S of circuit shown in Fig. 3.1 is suddenly closed.

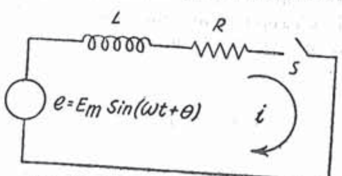


Fig. 3.1. RL series circuit under study.

Writing as equation for current i on the basis described in section 3.3,

$$L\frac{di}{dt} + Ri = e = E_m \sin(\omega t + \theta) \quad ...(3.8)$$

We shall solve this equation to obtain an expression for current i.

Eq. (3.8) is a non-homogeneous differential equation of first order. The complete solution is the sum of complementary solution, $i.e.$ and particular solution ip $i.e.$

$$i = i_c + i_p \quad ...(3.9)$$

Complementary Solution, i_c. The auxiliary equation is obtained by putting the right hand side Eq. (3.8) equal to zero,

i.e. $$L\frac{di}{dt} + Ri = 0$$

Rearranging the terms,

$$\frac{di}{i} + \frac{R}{L}dt = 0$$

Integrating, $\log i + \frac{R}{L}t = k$

i.e., $\log i = -\frac{R}{L}t + k$

where k is a constant of integration given by $k = \log_e A$, where A is some other constant. Further, we know that $\log_e e^x = x$ Hence

$$\log_e i = \log_e e^{(-R/L)t} + \log A$$

Taking anti-log $$i = A\,e^{(-R/L)t} \quad ...(3.10)$$

This is complementary solution of current i. It is an exponentially decaying component called *D.C. Component*. The magnitude of constant A depends on initial conditions. A may be zero, positive or negative depending upon magnitude of e at $t = 0$.

Particular solution of i (i_p) Take a trial solution

$$i = C\cos(\omega t + \theta) + D\sin(\omega t + \theta) \quad ...(3.11)$$

Such a trial solution is taken because the R.H.S. of Eq. (3.8) is of the form $E_m \sin(\omega t + \theta)$.

Obtain $\frac{di}{dt}$ and $\frac{di^2}{dt^2}$ of Eq. (3.11)

and subtitute in Eq. (3.8). Equate the coefficients of like terms from both the sides to get

$$C = -E_m \frac{\omega L}{R^2 + \omega^2 L^2} \quad ...(3.12)$$

$$D = E_m \frac{R}{R^2 + \omega^2 L^2} \quad ...(3.13)$$

Substituting these values of C and D in Eq. (3.8) we get

$$i = -\frac{\omega L}{R^2 + \omega^2 L^2} E_m \cos(\omega t + \theta) + \frac{R}{R^2 + \omega^2 L^2} E_m \sin(\omega t + \theta) \quad ...(3.14)$$

Let ϕ be the angle of impedance triangle

$$\phi = \tan^{-1}\frac{\omega L}{R}$$

$$\sin\phi = \frac{\omega L}{\sqrt{R^2 + \omega^2 L^2}}; \quad \cos\phi = \frac{R}{\sqrt{R^2 + \omega^2 L^2}}$$

Substituting $\sin\phi$ and $\cos\phi$ in Eq. (3.14),

$$i = \frac{-E_m}{\sqrt{R^2 + \omega^2 L^2}}\sin\phi\cos(\omega t + \theta) + \frac{E_m}{\sqrt{R^2 + \omega^2 L^2}}\cos\phi\sin(\omega t + \theta).$$

The R.H.S. of the above Eq. is of the form

$$\sin(A - B) = \sin A\cos B - \cos A\sin B$$

$$\therefore \quad i = \frac{E_m}{\sqrt{R^2 + \omega^2 L^2}}\sin(\omega t + \theta - \phi) \quad ...(3.16)$$

Eq. (3.16) is particular solution of Eq. (3.8). It is sinusoid called *A.C.* Component.

Complete solution

$$i = i_p + i_c$$

From Eqs. (3.10) and (3.16), we get

$$\boxed{i = Ae^{(-R/L)t} + \frac{E_m}{\sqrt{R^2 + \omega^2 L^2}}\sin(\omega t + \theta - \phi)} \quad ...(3.17)$$

This is a complete solution of Eq. (3.8). Let us put the initial condition to evaluate A.

At $t = 0$; $i = 0$. Because the current in inductive circuit does not change instantaneously.

Assuming R to be too small as compared with ωL;

$$\sqrt{R^2 + \omega^2 L^2} = \omega L$$

and $$\omega = \tan^{-1}\frac{\omega L}{L} = 90°$$

Case 1. Switch closed at $e = 0$

Hence $\quad e = 0$ at $t = 0$

$\therefore \quad \theta = 0.$

Also $\quad i = 0$ at $t = 0.$

From Eq. (3.17) $$0 = A + \frac{E_m}{\sqrt{R^2 + \omega^2 L^2}} \sin(-90°)$$

$$\therefore \quad A = +\frac{E}{\omega L}$$

This is maximum value of A, hence the d.c. component is maximum when switch is closed at voltage zero. This case is called *Doubling Effect.* Because peak value is $2E_m/\omega L$, at the peak of first current loop. There is as slight drop in the instantaneous value of the current from $t = 0$ to the $t = \frac{\pi}{2}$. Therefore, the peak value can be considered to be approximately $1.8E_m/\omega L$ instead of $2E_m/\omega L$.

Case II. Switch closed at $e = E_{max}$

$$e = E_{max} \text{ at } t = 0.$$

$$\theta = \pi/2$$

$i = 0$ at $t = 0$ we get

$$0 = A + E_m/\omega L \sin(\pi/2 - \pi/2).$$

$$A = 0$$

Hence A is zero, if switch is closed when $e = E_{max}$. Thereby the d.c. component is also zero.

From cases I and II we observe that the magnitude of initial value of d.c. component $Ae^{-(R/L)t}$ depends upon the moment of closure of switch, or voltage at the instant of occurrence of short circuit.

Let us interpret result of the solution.

When an R-L series circuit is closed with an alternating voltage source, the resulting current consists of two components, the d.c. component and a.c. component. The a.c. component is superimposed on the d.c. component. The magnitude of d.c. component depends upon the voltage at the instant of closing the switch. When the switch is closed at voltage zero, the d.c. component is maximum (Fig. 3.2). If the switch is closed at voltage maximum, d.c. component is zero and the waveform is symmetrical about the normal zero axis as shown in Fig. 3.3.

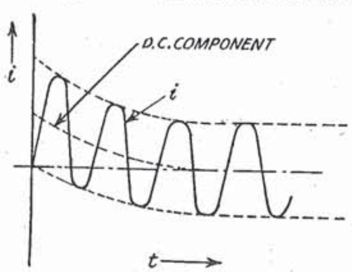


Fig. 3.2 Switch closed at voltage zero, d.c. component maximum.

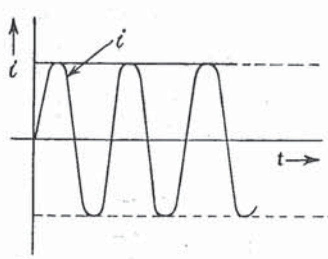


Fig. 3.3 Switch closed at voltage maximum, no d.c. component.

Example 3.1. A.C. transient R-L circuit. *A 50 Hz sinusoidal voltage of amplitude 400 volts is applied to a series circuit of resistance 10 ohm and inductance of 0.1 H. Find an expression for the value of the current at any instant after the voltage is applied, assuming the voltage is zero at the instant of application. Calculate the value of the transient current 0.02 sec after switching on (P. Sm.)*

Solution. Refer to the derivation in section 3.2

Given : $\quad R = 10$ ohm

$L = 0.1$ henry

$f = 50$ Hz

$2\pi f = 314$

$$\sqrt{R^2 + \omega^2 L^2} = \sqrt{10^2 + (31.4)^2} = 33 \text{ ohm}$$

$$\text{Angle } \phi = \tan^{-1}\omega L/R = \tan^{-1} 31.4/10$$

From the mathematical table, we get

$$\phi = 73.35° = 1.26 \text{ radians}$$

$$e = E_m \sin(\omega t + \theta)$$

at $\quad t = 0, e = 0$

since the switch is closed at voltage zero.

Hence $\quad \theta = 0$

The equation for R-L circuit current is

$$L\frac{di}{dt} + Ri = e = E_m \sin(\omega t + \theta).$$

The solution (Eq. 3.17) is $i = Ae^{-(R/L)t} + \frac{E_m}{\sqrt{R^2 + \omega^2 L^2}} \sin(\omega t + \theta + \phi)$

Putting the value of i at $t = 0$ and other given quantities

$$0 = A(e^0) + \frac{E_m}{\sqrt{R^2 + \omega^2 L^2}} \sin(0 + 0 - 72.35°)$$

i.e. $$A = \frac{E_m}{\sqrt{R^2 + \omega^2 L^2}} \sin 72.35 = \frac{400}{34}(0.953) = 12.1\ (0.953)$$

Hence $$i = 12.1(0.953e^{-100t} + \sin(314t - 1.26)].$$

Angle in the bracket is given radians. This is the required expression for current. **Ans.**

The magnitude of (d.c. component)

at $t = 0.02$ second is given by

$$i_{dc} = A^{e-(R/L)t} = 12.1 \times 0.953e^{-100 \times 0.2} = 1.56A. \quad \textbf{Ans.}$$

Example 3.2. *A 50-cycle alternating voltage is applied to an R-L series circuit by closing a switch. The resistance is 10 ohm. Inductance is 0.1 Henry. The r.m.s. value of applied voltage is 100 volts.*

(a) Find the value of d.c. component of current upon closing the switch if instantaneous value of voltage is 50 at that time

(b) What value of instantaneous voltage will produce a maximum d.c. component of current upon closing the switch ?

(c) What is the instantaneous value of voltage which will result in the absence of any d.c. component upon closing the switch ?

(d) If the switch is closed when instantaneous voltage is zero, find the instantaneous current 0.5, 1.5, 5.5 cycles later.

Solution. Let us calculate the quantities for Eq. (3.17) *i.e.*

$$i = Ae^{-(R/L)t} + \frac{E_m}{\sqrt{R^2 + \omega^2 L^2}} \sin(\omega t + \theta + \phi)$$

$$R = 10\Omega$$

$$L = 0.1 \text{ H}$$

$$e^{-(R/L)t} = e^{-100t}$$

$$\sqrt{R^2 + \omega^2 L^2} = \sqrt{10^2 + (0.4)^2} = 33 \text{ ohm}$$

$$\phi = \tan^{-1}\frac{\omega L}{R} = \tan^{-1}\frac{31.4}{10} = 72.35°$$

$$2\pi \text{ radians} = 360°$$

$$72.35° = 1.26 \text{ radians}$$

$$E_{rms} = 100 \text{ V}$$

$$E_{\max} = \sqrt{2}E_{rms} = \sqrt{2} \times 100 = 141.3$$

$$i. = e^{-100t} + \frac{141.3}{33}\sin(314t + \theta - 1.26)$$

$$i = Ae^{-100t} + 4.3 \sin(314t + \theta - 1.26) \qquad ...(i)$$

This is the equation of current in the circuit.

(*a*) Switch closed at $t = 0$, when $e = 0$ and in an inductive circuit, current does not change instantaneously. Therefore,

$$i = 0 \text{ at } t = 0$$

$\therefore$ From Eq. (1), we get

$$0 = A + 4.3 \sin(-1.26)$$

$$A = 4.3 \sin 1.26 \text{ (Note 1.26 is angle in radians)}$$

$$= 4.3 \times 0.953 = 4.1$$

$\therefore$ D.C. component at $t = 0$ is given by

$$Ae^{-(R/L)t} = 4.1e^{-100t} = 4.1e^0 = 4.1 \text{ amp}$$

(*b*) The maximum d.c. component will be produced if instantaneous value of applied voltage is zero at the instant of closing the switch.

(*c*) The d.c. component will vanish if $e = E_{max}$, *i.e.* $\sqrt{2} \times 100 = 131.3$ V (instantaneous) at the instant of closing the switch.

(*d*) Like Problem 3.1,

$$0.5 \text{ cycles} = 0.5 \times 0.02 \text{ second}$$

$$1.5 \text{ cycles} = 0.03 \text{ second}$$

$$5.5 \text{ cycles} = 0.11 \text{ second}$$

Substitute in Eq. (1) taking A = 4.1 from part (*a*).

3.5. SUB-TRANSIENT, TRANSIENT AND STEADY STATE

The analysis of sudden short-circuit of an R-L series circuit (section 3.4) will now be applied to three-phase short-circuit of an alternator. An alternator has stator windings having certain resistance and reactance. If we neglect the armature reaction and variation in field current, the current flowing in an altenator phase during the short-circuit has waveform similar to that of an *R-L* circuit short-circuit current wavaform given in Figs. 3.2 and 3.3. However, in the alternator, the waveform is modified by armature reaction. An oscillogram of three-phase currents is shown in Fig. 3.4.

When the alternator is short-circuited, the currents in all the three phases rise rapidly to a high value (10 to 25 times full load current), during the first quarter cycle. The flux crossing the airgap is large during a first couple of cycles. The reactance during these first two or three (there

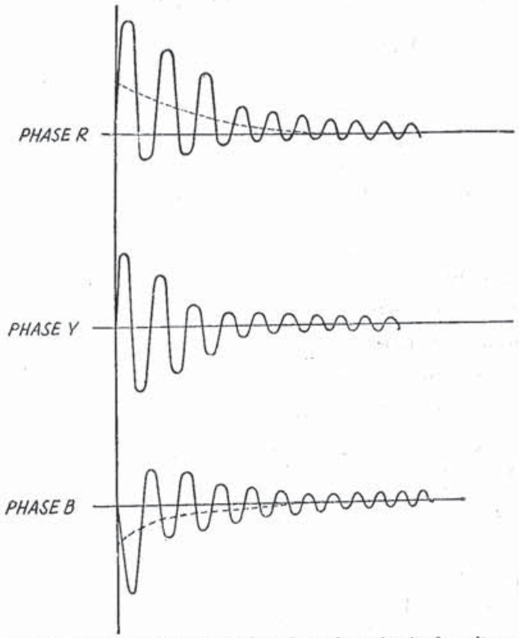


Fig. 3.4 Waveforms of currents in 3-phase short circuit of an alternator.

is no definite number, it depends on the machine) cycles is least and the short circuit current is high. This reactance is called *sub-transient reactance* and is denoted by X''. The first few cycles come under *sub-transient state.*

After a first few cycles the decrement in the r.m.s. value of short circuit current is less rapid than the decrement during the first few cycles. This state is called the *Transient* State the reactance in this state is called transient reactance X'. The circuit-breaker contacts separate in the transient state.

Finally the transient dies out and the current reaches a steady sinusoidal state called the *Steady State.* The reactance in this state is called steady state reactance Xd. The Xd is called direct axis synchronous reactance.

Since the short circuit current of the alternator lags behind the voltage by 90°, the reactances involved are direct axis reactance.

Consider Fig. 3.4; the d.c. components in the three phases are different; hence the wave-forms of the three phases are not identical. If voltage of phase, say, Y, is maximum at the instant of short circuit, d.c. component of short circuit current is zero. Hence the waveform is symmetrical as shown in Fig. 3.5.

Referring to Fig. 3.5 draw an envelope enclosing the waveform.

Extend the portions of the envelopes as shown in the figure. NM is extrended to meet the zero time ordinate at point, A. ML is extended to meet the ordinate at B and LC meets the ordinate of zero time at C. Measure OC, OB and OA.

NM is a portion of envelope in steady state *LM* is a portion of envelope in trasient state *LC* is a portion of the envelope is sub-trasient state and *LC* is the portion of the envelope in sub-transient state.

The currents and reactance are given by the following expressions :

$$I = \frac{OA}{\sqrt{2}} = \frac{E_a}{X_d} \quad ...(3.20)$$

$$I' = \frac{OB}{\sqrt{2}} = \frac{E_a}{X_{d'}} \quad ...(3.21)$$

$$I'' = \frac{OC}{\sqrt{2}} = \frac{E_a}{X_{d''}} \quad ...(3.22)$$

where I = Steady state current, r.m.s. value

I' = Transient current r.m.s. value

I'' = Sub-transient current, r.m.s. value

E_a = Induced e.m.f. per phase

X_d = Direct axis synchronous reactance

$X_{d'}$ = Direct axis transient reactance

$X_{d''}$ = Direct axis sub-transient reactance

OA, OB and OC are intercepts shown in Fig. 3.5.

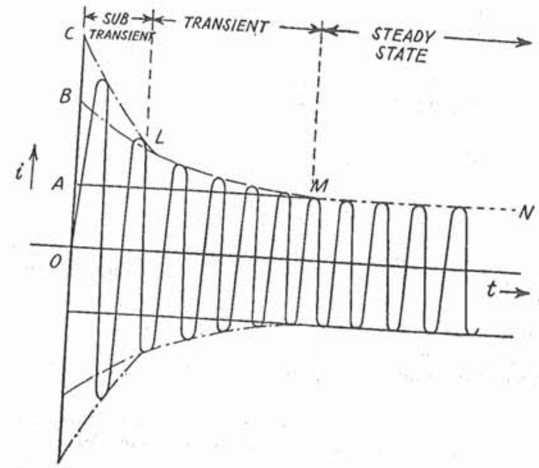


Fig. 3.5 Oscillogram of current is the phase having zero d.c. component.

As the short circuit occurs, the short-circuit current attains high value. The circuit-breaker contacts start separating after the operation of the protective relay. The contacts of the circuit-breaker separate during 'trasient state.' The r.m.s. value of the current at the instant of the contact separation is called the *breaking current* of the circuit breaker and is expressed in kA.

If a circuit-breaker closes on existing fault, the current would increase to a high value during the first, half cycle as shown is Figs. 3.2 and 3.3. The highest peak value of the current is reached during the peak of the first current loop. "This peak value is called *making current* of the cirrcuit-breaker and is expressed in kA." The terms 'breaking current' and 'making current' have been discussed in details in section 3.19.

Though the short-circuit current varies continuously during the sub-transient and trasient states, the representative values can be calculated from the equations 3.20, 3.21, and 3.22. The

subtransient, transient and steady-state reactances can be determined experimentally by conducting short circuit test.

It is clear from Eqs. (3.20) to (3.22) that while calculating subtransient, transient and steady state currents; the respective reactances should be considered. The examples of short-circuit current are given in Section II of the book.

3.6. CURRENT INTERRUPTION IN A.C. CIRCUIT-BREAKERS

The waveform of the current and the voltage during the arc interruption process will be studied in this section. This description applies to the circuit-breakers employing the principle of zero-point interruption. Every a.c. circuit-breaker generally adopts the zero-point interruption technique.

Consider a circuit-breaker connected to a generator on no load at rated terminal voltage. The circuit-breaker is in open position and the other side of circuit-breaker is short circuited (Fig. 3.6).

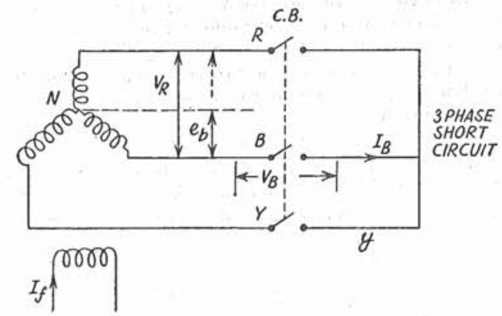


Fig. 3.6 Sudden-3 phase-short circuit of an alternator.

Let the circuit-breaker be closed at the instant when voltage of terminal B w.r.t neutral is zero. In such a case the short circuit current in phase B will have maximum d.c. component and the waveform of current I_b will be unsymmetrical about normal zero axis as shown in Fig. 3.7. The figure shows the typical waveform of short circuit current in a phase having maximum d.c. component. The generator is on no load before $t = 0$. Hence the current is zero before $t = 0$. At $t = 0$, the short circuit is applied and the current increases to a high value during the first quarter cycle. The peak of the first major current loop (shown hatched) is OM and this is the maximum instantaneous value of current during the short-circuit the instantaneous peak value of the first major current loop is called the *Making current.*. In the figure the making current is OM. It is expressed in kA peak.

Let us come to this making current after covering the remaining process (Sec. 3.19.6).

The circuit-breaker contacts separate after a few cycles since the relay and the operating mechanism takes atleast a couple of cycles. Let us assume that the circuit-breaker contacts separate at $t = T_1$ The r.m.s. value of short circuit at the instant of contact separation is termed as *Breaking current.*

After the separation of contacts of the circuit-breaker, an arc is drawn between the contacts. The arc current varies sinusoidally for a few cycles. At $t = T_2$ a particular current zero, the dielectric strength of arc space builds up sufficiently so as to prevent the continuation of arc. At the current zero, this arc is extinguished and is interrupted.

Meanwhile what is happening to the voltage between contacts ? This voltage is recorded in Fig. 3.7. Before $t = 0$, the contacts are closed and the voltage between them is zero. After the separation of the contact ($t = T_1$), the voltage across contact increases. In fact this voltage in the voltage drop across the arc during the arcing period. The voltage across arc is in phase with current since the arc is resistive. The peculiar waveform shape is a result of voltampere characteristic of arc-discharge to be studied later. During subsequent half cycles, the voltages across contact increases due to increased arc resistance. Finally at $t = T_2$ when arc gets extinguished a high frequency voltage transient appears across the contacts which is superimposed on power frequency system voltage. This high frequency transient voltage tries to restrike the arc. Hence it is called Restriking Valtages or Transient Recovery voltage (TRV). The restriking voltage is transient voltage appearing across breaker pole after final current zero. The power frequency system voltage appearing between the poles after arc extinction is called *Recovery voltage.* The transient recovery voltage or restriking voltage has a profound effect on circuit-breaker behaviour. The current that would flow in the circuit if the circuit-breakers were replaced by solid conductor is called prospective current.

The transient recovery voltage (TRV) appearing across the circuit-breaker pole immediately after the final arc interruption causes a high dielectric stress between the circuit-breaker contacts. If the dielectric strength of the medium between the contacts does not build up faster than the rate of rise of the trasient recovery voltage, the breakdown takes place causing re-establishment of the arc. If the dielectric strength of the contact-space builds up very rapidly so that it is more than the rate of rise of transient recovery voltage the circuit-breaker interrupts the current successfully. The rate of rise of TRV, generally depends on the circuit parameters and the type of the switching duty involved. The rate of building up of the dielectric strength depends upon the effective design of the interrupter and the circuit-breaker.

While switching capacitive currents, the high voltage appearing across the contact gap can cause reignition of the arc after initial arc extinction. If the contact space breaks down within a period of one-fourth of a cycle (0.02×0.25) second from initial arc extinction, the phenomenon is called *Reignition.* If the breakdown occurs after one-fourth of a cycle, the phenomena is called *Restrike.* (Ref. sec. 3.20)

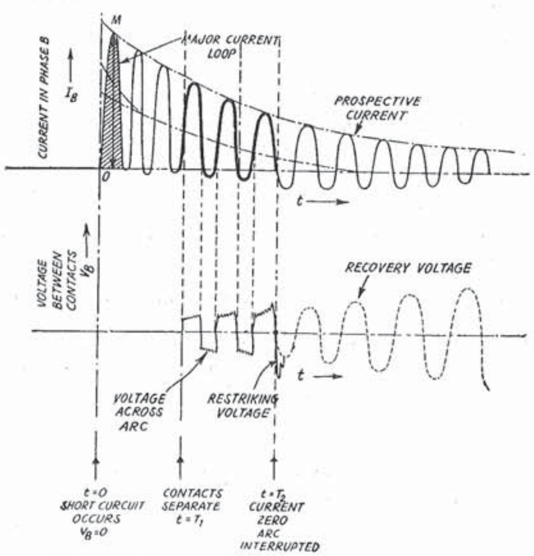


Fig. 3.7. Oscillogram of current and voltage during fault-clearing.

3.7. TRANSIENT RECOVERY VOLTAGE (TRV)

In altenating current circuit-breaker, the current interruption takes place invariably at the natural zero of the current wave.

After a current zero, the arc gets extinguished if the rate of rise of transient recovery voltage between the contacts less than the rate of gain of the dielectric strength. The voltage appearing between the breaker contacts at the moment of final current zero has a profound influence on the arc extinction process. The voltage appearing across contacts after current zero is a trasient voltage of higher natural frequency (restriking voltage). superimposed on the power frequency system voltage (recovery voltage). The trasient component vanishes after a short time of the order of less than 0.1 mill-sec and the normal frequency system voltage is established voltage. After current zero the voltage appearing across the contacts is composed of transient restriking voltage and power frequency recovery voltage.

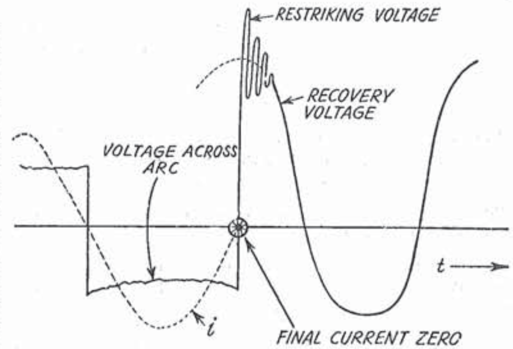


Fig. 3.8 (*a*) Voltages after final current zero (TRV) (Simplified). (Ref. Fig. 3.8*b*)

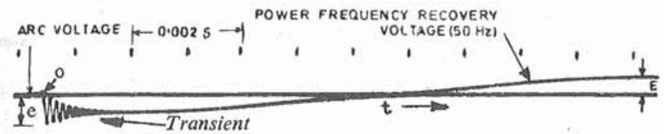


Fig. 3.8 (*b*) Shape of TRV waveform as seen from Cathode-ray oscillographic record.

"Recovery voltage is the voltage which appears across the terminals of a pole of a circuit-breaker after the breaking of current. It refers to the breaker-pole first to clear."

The transient recovery (TRV) or Restriking Voltage is the recovery voltage during the time in which it has a significant transient character. TRV lasts for a few tens or hundreds of microseconds. (Ref. Fig. 3.8*b*)

— It may be oscillatory or non-oscillatory or a combination, depending upon the characteristics of the circuit and the circuit-breaker.

— It is the voltage across the first pole to clear, the same is generally higher than across the two poles which clear later.

Power Frequency Recovery Voltage is the recovery voltage of power frequency (50 Hz.) appearing after the transient voltage has been subsided.

The transient Recovery Voltage refers to the voltage across the pole immediatley after arc extinction. Such voltage has a power-frequency component plus an oscillatory trasient component. The oscillatory trasient component due to the inductance and capacitance in the circuit. The power frequency component is due to the system voltage (Ref. Fig. 3.8). The transient oscillatory component subsides after a few micro-seconds and the power frequency component continuous. The frequency of transient component is given by

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

where f_n = frequency of transient recovery voltage, Hz

L = equivalent industance, hency.

C = equivalent capacitance, farad.

In actual systems the waveform of the transient recovery voltage has several component frequencies ranging from a few hertz to several thousand hertz, depending upon the values of the circuit parameters.

3.7.1. Effect of natural frequency of TRV

Fig. 3.9 illustrates the slopes of tangents to three TRV waveforms of different frequencies (f_n, f_{2n}, f_{4n}). With increase in the natural frequency, the rate of rise of TRV at current zero increases.

The rate of rise of trasient recovery voltage across circuit-breaker pole causes voltage stress on the contact-gap tending to continue the arc. With higher frequency (say f_{4n}), relatively less time is available for the building of dielectric strength of the contact gap. Hence higher frequency is associated with greater stresses.

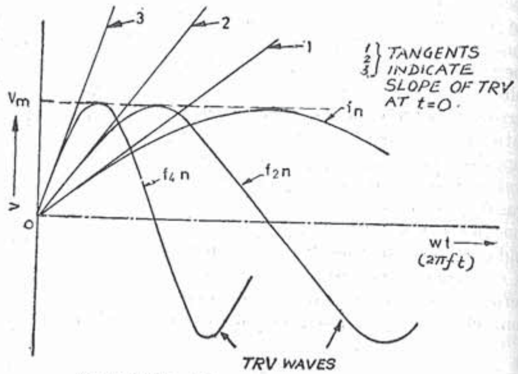


Fig. 3.9 Effect of frequency of TRV on the RRRV.

The breaking capacity of a circuit-breaker (r.m.s. value of current, which the circuit-breaker can interrupt) is related with the rate if rise TRV, and, therefore, natural frequency of TRV. The breaking capacity reduces with increase in natural frequency (Ref. Sec. 3.10. Eq. 3.26).

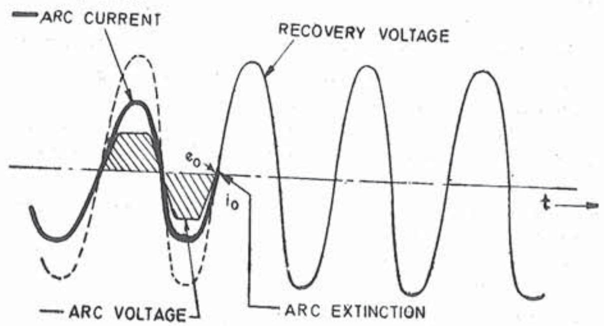


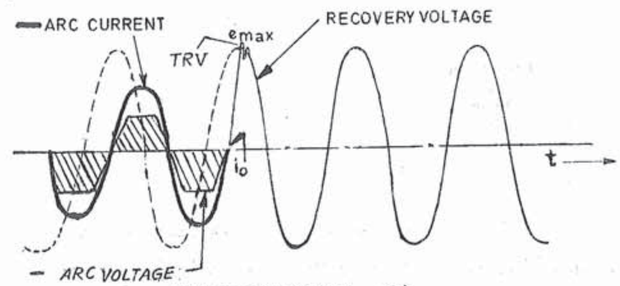
Fig. 3.10. (a) Unity power factor: e_0 *at* i_0.

3.7.2. Effect of Power-Factor on TRV

The voltage appearing across the circuit-breaker pole at the instant of final current zero is influenced by the power-factor of the current. (Fig. 3.10). The arc gets extinguished at current zero. The power-frequency voltage appears across the circuit-breaker pole. The instantaneous value of the voltage at the instant of current zero depends upon the phase angle between current and voltage. For unity power-factor loads, the voltage and current are in phase and both are zero at the same instant. For zero power-factor currents, the peak of the voltage (E_{max}) is impressed on the circuit-breaker pole at the instant of current zero. Such sudden application of voltage give rise to severe transient and has a high rate of rise of TRV. Hence interrrupting currents of low power-factor is a difficult switching duty.

3.7.3. Effect of Reactance-drop on power-frequency Recovery Voltage

Suppose V_1 is voltage at the location of the circuit-breaker berfore fault. During the fault the increased current cause an increase in the voltage drop in the reactance. As a result the voltage appearing at the location of the fault, immediatly after fault clearance say V_2 is slightly less than V_1. It takes some time for the system voltage to regain the original value V_1. Hence the power frequency recovery voltage is slightly less than the normal power frequency system voltage.



(*b*) Zero power-factor : e_{max} at i_0.

Fig. 3.10 Effect of power factor on instantaneous value of voltage at current zero.

3.7.4. Effect of Armature Reaction on Recovery Voltage

The short-circuit currents are at lagging power factor and, therefore, have a demagnetising armature reaction in altenators. As a result, the induced e.m.f. of alternators reduces during short-circuit currents. The e.m.f. requires some time to regain its original value. Hence the power frequency component of recovery voltage is slightly less than the normal value of system voltage.

3.7.5. Effect of the First-Pole-to-Clear

Refer to Fig 3.11 illustrating a three phase fault not involving the earth. The voltage across the circuit-breaker pole, first to clear is 1.5 times the phase voltage. In three-phase a.c. circuit-breakers, arc extinction in the three poles is not simultaneous as currents in three phases are mutually 120° out-of-phase. Hence, the power-frequency recovery voltage of the phase in which the arc gets extinguished first, is about 1.5 times the phase voltage. In practice the recovery voltage of the pole, first-to-extinguish the arc is of the order of 1.2 to 1.5 times. If the neutral is grounded through reactor and if the fault involves earth, the recovery voltage at the location of the circuit-breaker is influenced by the equivalent system reactance and can be calculated by the method of symmetrical components.

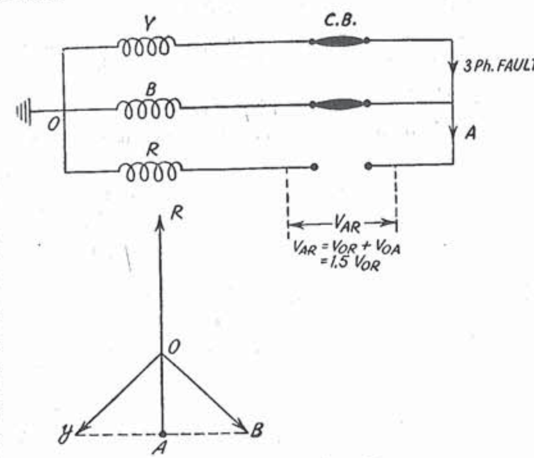


Fig. 3.11. Voltage across the phase, first-to-open.

3.7.6. The First-Pole-to-Clear Factor

To consider, the effect of the first-pole-clear on the power frequency component of the recovery voltage, the following factor has been defined in the standards on high voltage a.c. circuit breakers.

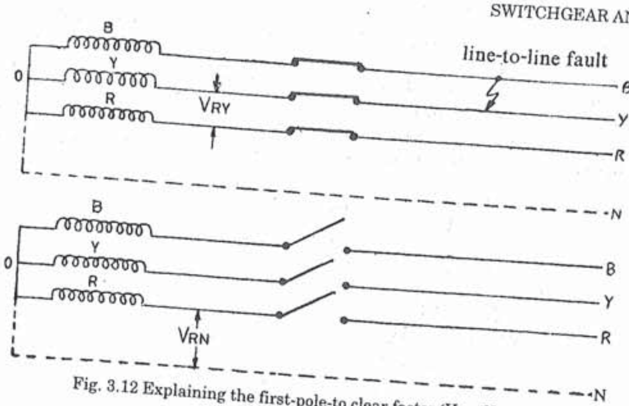


Fig. 3.12 Explaining the first-pole-to clear factor (V_{RY}/V_{RN})..

The first pole to clear factor $= \dfrac{\text{R.m.s. voltage between healthy phase \& faulty phase}}{\text{Phase to netural voltage with fault removed}}$

at the location of the circuit-breaker during a phase-to-phase fault.

Ref. Fig. 3.12, first-pole-to-clear factor is the ratio of the

$$\frac{\text{Voltage between healthy and faulty phase } (V_{RY})}{\text{Normal phase voltage } (V_{RN})}$$

at the location of the circuit-breaker for a phase-to-phase fault (Fig. 3.12).

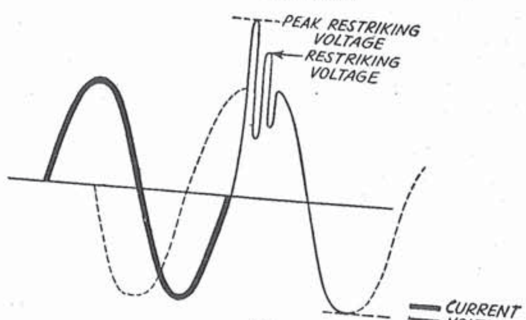
3.8. SINGLE FREQUENCY TRANSIENT

The single frequency restriking voltage transient is produced in the circuit illustrated in Fig. 3.13 (*b*). The frequency of oscillation is given by the natural frequency of the circuit.

i.e.

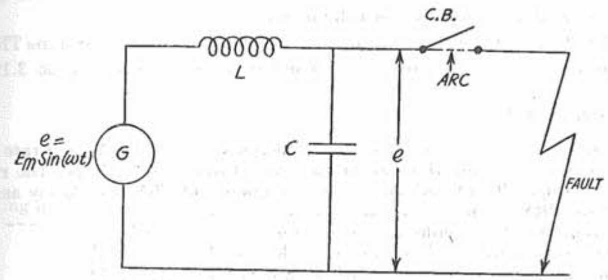
$$f_n = \frac{1}{2\pi\sqrt{LC}} \text{ Hz}$$

where L = Inductance, henry ; C = Capacitance, farads.



(*a*)

These frequencies are of the order of 10 to 10,000 Hz depending upon the value of L and C. The actual power system is composed of distributed capacitance and inductance. The circuit configuration is also complex. The TRV for such circuits can have several component frequencies ranging from a few Hertz to several kilohertz. A typical single frequency transient is illustrated in Fig. 3.13 (*a*). Such a transient is obtained while opening on a terminal fault. In such cases the reactance between the fault and the circuit-breaker is negligible.

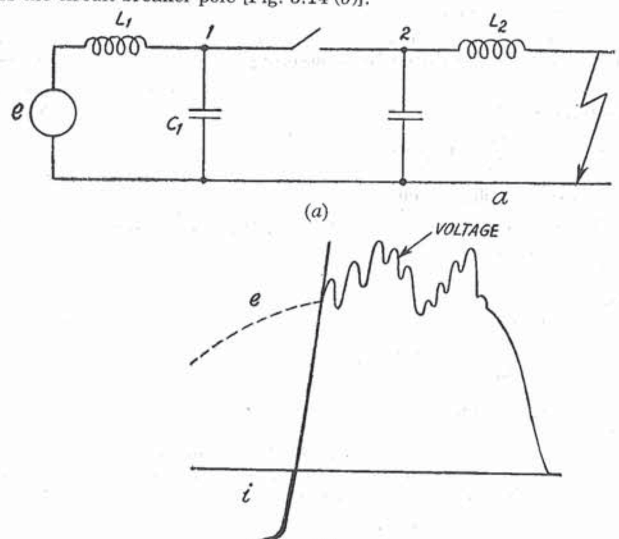


(*b*) Single frequency transient.

Fig. 3.13. Explaining single frequency transient of TRV.

3.9. DOUBLE FREQUENCY TRANSIENTS

The circuit may have L and C on both sides of the circuit-breaker as shown in Fig. 3.14. Before clearing the fault, both the terminals, 1 and 2 are at the same potential. After arc extinction both the circuits oscillate at their own natural frequencies and a composite double frequency transient appears across the circuit breaker pole [Fig. 3.14 (*b*)].



(*b*)

Fig. 3.14. Double frequency transient of TRV.

In general the frequencies and waveform, rate of rise and peak value of the TRV depends upon several aspects such as

— net work configuration — type of fault — type of neutral earthing.

The TRV wave can be defined by various methods such as

— specifying the peak and time to reach the peak.

— specifying the TRV wave by defining the segment of lines which enclose the TRV waveform.

The latter method has been now universally adopted and is described in sec. 3.19.9.

3.10. RATE OF RISE OF TRV

The rate of rise of restriking voltage usually abbreviated by R.R.R.V. is a rate expressed in volts per micro-second, represents the rate of increase in restriking voltage. The rate of rise of Trasient Recovery Voltage. (TRV) and the natural frequency of TRV are closely associated. The rate of the rise of TRV depends on the system parameters. The circuit breaker should be capable of interrupting its rated short-circuit breaking current under the specified conditions of TRV. Hence the follwing characteristics of TRV are significant:

— Peak of TRV, time to reach the peak. Hence the rate of rise of TRV

— frequency of TRV

— Initial rate of rise

The term rate of rise of restriking voltage is explained as follows :

If e is restriking voltage volts

$$\text{R.R.R.V.} = \frac{de}{dt} \text{ volts}/\mu \text{ sec.}$$

where t is in μ seconds, e is in volts.

The peak restriking voltage is defined as the maximum instantaneous value attained by the restriking voltage (e_m).

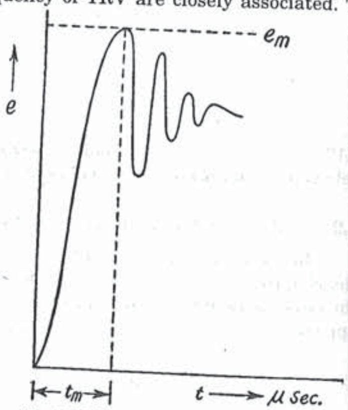


Fig. 3.15. Measurement of single frequency transient.

Referring to Fig. 3.15, R.R.R.V is given by

$$\text{R.R.R.V.} = \frac{e_m}{t_m} \ldots \text{V}/\mu \text{ sec.}$$

where e_m = peak restriking voltage, volts

t_m = time between voltages zero and peak restriking voltage in μ sec

E_m = peak recovery voltage.

$$\text{Amplitude factor} = \frac{e_m}{E_m}$$

$$\text{Natural frequency} = \frac{10^3}{2t_m} \text{ kilo cycles/second} \qquad \ldots(3.18)$$

Since $f = \dfrac{1}{2t_m}$ for any sinusoidal waveform.

Derivation of Restriking Voltage. Consider the circuit shown in Fig. 3.13 when current reaches zero at final arc extinction, a voltage e is suddenly impressed across capacitor and therefore, across the $c.b.$ contacts. The current i which would flow to the fault is not injected in the capacitor and inductor. Thus

$$i = i_L + i_c$$

$$i = \frac{1}{L}\int e\,dt + C\frac{de}{dt}$$

$$\therefore \quad \frac{di}{dt} = \frac{e}{L} + C\frac{d^2e}{dt^2}$$

Assuming zero time at zero currents when $t = 0$, and further

$$e = E \cos \omega t$$

$$i = \frac{E_m}{\omega L} \sin \omega t \text{ before opening of c.b.}$$

$$\frac{di}{dt} = \frac{E_m}{\omega L} \times \omega \cos \omega t$$

$$t = 0; \left| \frac{di}{dt} \right| = \frac{E_m}{L}$$

Substituting in Eq. (3.18), we get

$$\frac{E_m}{L} = \frac{e}{L} + C\frac{d^2e}{dt^2} \qquad \ldots(3.19)$$

The solution of this standard equation is

$$e = E_m\left(1 - \cos\frac{t}{\sqrt{LC}}\right) \qquad \ldots(3.20)$$

This is an expression for restriking voltage in which

E_m = Peak value of recovery voltage, phase to neutral volts

t = Time in seconds

L = Inductance in henrys

C = Capacitance, farads

e = Restriking voltage, volts.

Note. Rate of rise of restriking voltage

$$= \frac{de}{dt}$$

$$= \frac{E_m}{\sqrt{LC}} \sin\frac{t}{\sqrt{LC}} \qquad \ldots(3.21)$$

R.R.R.V. is maximum when it derivative is zero (from maxima theorem of differential calculus) .

$$\frac{de}{dt} \text{ is maximum when } \frac{d^2e}{dt^2} = 0$$

i.e. $$\frac{E_m}{LC}\cos\frac{t}{\sqrt{LC}} = 0$$

or when $$\frac{t}{\sqrt{LC}} = \frac{\pi}{2}$$

i.e. $$t = \sqrt{LC}\,\frac{\pi}{2}$$

The maximum R.R.R.V. is the value of de/dt at

$$t = \sqrt{LC}\,\frac{\pi}{2}$$

i.e. $$\text{R.R.R.V.}_{max} = \frac{E_m}{\sqrt{LC}} \qquad \ldots(3.23)$$

Further, peak restriking voltage occurs when e is maximum

i.e. when $$\frac{de}{dt} = 0$$

i.e. when $$\frac{t}{\sqrt{LC}} = \pi, \; i.e., \; t = \pi\sqrt{LC}$$

and peaking restriking voltage is equal to

$$e = E_m(1 - \cos \pi) = 2E_m \qquad \ldots(3.24)$$

SUMMARY OF EXPRESSIONS

$$e = E_m\left(1 - \cos\frac{t}{\sqrt{LC}}\right) \quad ...(3.20)$$

$$\text{R.R.R.V.} = \frac{E_m}{\sqrt{LC}}\sin\frac{t}{\sqrt{LC}} \quad ...(3.21)$$

$$e_{\max} = 2E_m \text{ at } \frac{t}{\sqrt{LC}} = \pi \quad ...(3.24)$$

$$\text{R.R.R.V.}_{max} = \frac{E_m}{\sqrt{LC}} \text{ at } t = \sqrt{LC}\,\frac{\pi}{2} \quad ...(3.22)$$

$$f_n = \frac{1}{2\pi\sqrt{LC}} \quad ...(3.25)$$

It is observed from Eqs. 3.22 and 3.25 that

$$\text{R.R.R.V.}_{max} = 2\pi E_m f_n \quad ...(3.26)$$

The Maximum Rate of Rise of Restriking voltage is proportional to the natural frequency of the circuit.

This is an important conclusion. The circuit with high natural frequency give a high rate of TRV and produce severe dielectric stress on the contact space of the circuit-breaker.

Hence High $f_n \rightarrow$ High rate of rise of TRV

Examples on Restriking Voltage*

Example 3.3. *A 50-cycles, 3-phase alternator with grounded neutral has inductance of 1.6 mH per phase and is connected to busbar through a circuit-breaker. The capacitance to earth between the alternator and the circuit-breaker is 0.003 μF per phase. The circuit breaker opens when r.m.s. value of current is 7500 A. Determine analytically the following :*

(a) Maximum rate of rise of restriking voltage.

(b) Time for maximum rate of sise of restriking voltage.

(c) Frequency of oscillations.

Neglect First-Pole-to-clear factor.

Solution. Frequency of oscillation is given by

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

where L in henry, C is in farads, f_n is in Hz.

$$\therefore \quad f_n = \frac{1}{2\pi\sqrt{1.6 \times 10^{-3} \times 0.003 \times 10^{-6}}}$$

$$= \frac{1}{2\pi\sqrt{4.8 \times 10^{-12}}} = \frac{1}{2\pi \times 2.2 \times 10^{-6}} = 72{,}400 \text{ c/s.}$$

The recovery voltage can be calculated from the known values of current I and ωL.

$$E = I \times \omega L = I \times 2\pi f \times L$$

$$= 7500 \times 314 \times 1.6 \times 10^{-3} = 3780 \text{ volts r.m.s.}$$

$$E_m = \sqrt{2} \times E_{rms} = 3780 \times \sqrt{2} = 5340 \text{ volts}$$

Expression for restriking voltage

$$e = E_m\left(1 - \cos\frac{t}{\sqrt{LC}}\right) = 5340\left(1 - \cos\frac{t}{2.2 \times 10^{-6}}\right)$$

where e is in volts, t is in sec.

* In this derivation and in Examples on Restriking Voltage, First Pole to Clear Factor is neglected.

Maximum rate at rise of restriking voltage occurs when

$$\frac{d^2e}{dt^2} = 0$$

i.e. when

$$t = \sqrt{LC}\,.\,\frac{\pi}{2} = 2.2 \times \frac{\pi}{2} = 3.45\ \mu\text{-sec.}$$

Maximum R.R.R.V. is given by $= \dfrac{E_m}{\sqrt{LC}} = \dfrac{5340}{2.2} = 2420$ volts/μ-sec.

[Ans. (*a*) 2420 V/μ-sec., (*b*) 3.45 μ-sec., (*c*) 72,400 c/s.]

Example 3.4. *A three phase altenator has the line voltage of 11 kV. The generator is connected to a circuit-breaker. The inductive reactance upto the circuit breaker is 5 ohm per phase. The distributed capacitance upto circuit-breaker between phase and neutral is 0.01 μF. Determine the following :*

Neglect First Pole to clear factor

(a) Peak restriking voltage across the c.b.

(b) Frequency of restriking voltage transient.

(c) Average rate of restriking voltage upto peak restriking voltage.

(d) Maximum R.R.R.V.

Solution. $2\pi f L = 5\Omega$

$$\therefore \quad L = \frac{5}{314} = 0.0159 \text{ H}$$

$$V_r = 11 \text{ kV}$$

$$V_{ph} = \frac{11}{\sqrt{3}} = 6.35 \text{ kV r.m.s.}$$

$$E_{\max} = \sqrt{2} \times 6.35 = 9 \text{ kV.}$$

Expression for striking voltage

$$e = E_m\left(1 - \cos\frac{t}{\sqrt{LC}}\right)$$

$$= 9\left(1 - \cos\frac{t}{\sqrt{0.0159 \times 0.01 \times 10^{-6}}}\right)$$

$$= 9\left(1 - \cos\frac{t}{12.6 \times 10^{-6}}\right)$$

Peak restriking voltage $= 2 \times E_{\max} = 2 \times 9 = 18$ kV

Time for peak restriking voltage:

$$\frac{t}{\sqrt{LC}} = \pi$$

$$t = \sqrt{LC} \times \pi = 12.6 \times \pi = 39.5\ \mu\text{-sec.}$$

Average rate of restriking voltage $= \dfrac{e_{\max}}{t_m} = \dfrac{18}{39.5} = 0.456$ kV/μ-sec.

Frequency oscillations $\quad f_n = \dfrac{1}{2\pi\sqrt{LC}} = \dfrac{1}{2\pi \times 12.6 \times 10^{-6}} = 12{,}637$c/s

$$\text{Max. R.R.R.V.} = \frac{E_m}{\sqrt{LC}} = \frac{9 \times 10^3}{126} = 714\text{V}/\mu\text{-sec.}$$

Example 3.5. *In a system the r.m.s. voltage is 19.1 kV, L is 10 mH, C is 0.02 mF. Determine the average rate of rise of restriking voltage, when the circuit breaker opens.*

Solution.
$$e = E_{max}\left(1 - \cos\frac{t}{\sqrt{LC}}\right)$$

Inserting the numerical values $e = \sqrt{2} \times 19.1\left(1 - \cos\frac{t}{\sqrt{10 \times 10^{-3} \times 0.02 \times 10^{-6}}}\right)$

$$= 27\left(1 - \cos\frac{t \times 10^5}{1.414}\right)\text{kV}$$

Time to reach maximum restriking voltage

$$t = \pi\sqrt{LC} = \pi \times 1.414 \times 10^{-5} \text{ sec.} = 44.4 \ \mu\text{-sec.}$$
$$e_{max} = 2E_m = 2 \times 27.0 = 54 \text{ kV}$$

Average rate of restriking voltage $= \frac{e_{max}}{t_m} = \frac{54{,}000}{44.4} = 1220 \text{ V}/\mu\text{-sec.}$

Example 3.6. *In a short-circuit test on a 3 pole, circuit-breaker power factor of fault was 0.4, the recovery voltage was 0.95 times full line value. The breaking current was symmetrical. The frequency of oscillation of restriking voltage was 15,000 c/s. Estimate the average rate of rise of restriking voltage. The neutral is grounded and fault involves earth. Neglect First Pole to clear factor.*

Solution. The maximum restriking voltage is given by $2E_{max}$, where E_{max} is the instantaneous value of power frequency voltage at the time of current zero.

Line to line voltage = 110 kV r.m.s.

Line to phase voltage $= \frac{110}{\sqrt{3}}$ kV r.m.s.

$$\text{Peal } E_{max} = \frac{110}{\sqrt{3}} \times 2 = 90 \text{ kV}$$

The power factor $= 0.4$

Hence p.f. angle $\theta = 66.4°$

$\sin\theta = 0.92$

Recovery voltage is 0.95 times peak value.

From equation instantaneous value of recovery voltage is $E = kE_{max}$

where $k = k_1 \times k_2 \times k_3$ (Ref. Sec. 3.7)

k_1 = multiplying factor due to power factor angle

$= \sin\theta = 0.92$

k_2 = multiplying factor due to system voltage = 0.95

k_3 = Factor depends on circuit conditions

= 1 in this case since the fault involves earth

$\therefore \quad k = k_1 k_2 k_3 = 0.92 \times 0.95 \times 1 = 0.875$

$\therefore \quad E = 0.875 \times 90 = 78.75$ kV (instantaneous)

The time to reach the first peak of restriking voltages can be estimated from Eq. (3.18).

$$f_n = \frac{10^3}{2 \times t_m}, \text{ where } f \text{ is in kc/sec.} \qquad ...(3.19)$$

$$f_n = \frac{1}{2 \times t_m}, \text{ where } f \text{ is in c/s.}$$

$$t_m = \frac{1}{2f_n} \text{ sec.}$$

$$t_m = \frac{1}{2 \times 15{,}000} = 0.33 \times 10^{-4} \text{ sec.} = 0.33 \times 102 \ \mu\text{-sec.}$$

Average $\quad \text{R.R.R.V.} = \frac{2E_{max}}{0.33 \times 10^2} = \frac{2 \times 78.75}{33} = 4.8 \text{ kV}/\mu\text{-sec.}$

Example 3.7. *In a short-circuit test on a circuit-breaker, the following readings obtained on a frequency transient:*

(a) time to reach the peak restriking voltage 70 μ-sec.

(b) the peak restriking voltage 100 kV.

Calculate the average rate of rise of restrking voltage and the natural frequency of the circuit.

Solution. Average rate of rise restriking voltage

$$= \frac{\text{Peak restriking voltage } (E_m)}{\text{Time to reach the peak } (t_m)} = \frac{100 \times 10^3}{70} = 1430 \text{ V}/\mu\text{-sec.}$$

Natural frequency f_n is given by

$$f_n = \frac{10^3}{2t_m} \text{ c/s}$$

$$f_n = \frac{10^3}{2 \times 70 \times 10^{-6}} = 7143 \text{ c/s.}$$

3.11. RESISTANCE SWITCHING, DAMPING OF TRV, OPENING RESISTORS

A deliberate connection of a resistance in parallel with the contact space (arc) is called *Resistance switching.* Resistance Switching is used in circuit-breakers having high post zero resistance of contact space (Air blast C.B.) Let us see the effect of such a resistance on the frequency of restriking voltage transient (Ref. Fig. 3.19).

Considering the current loop, we get

$$e = iR + L\frac{di}{dt} + \frac{1}{C}\int i_c dt \qquad ...(3.26)$$

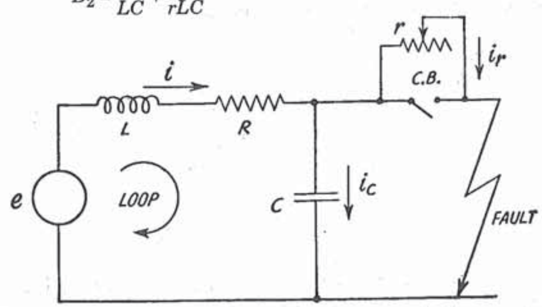
$$\frac{1}{C}\int i_c dt = i_r r$$

$$i = i_r + i_c, \ e = 0$$

$$\frac{d^2 i}{dt^2} + B_1\frac{di_r}{dt} + B_2 i_r = 0 \qquad ...(3.27)$$

where
$$B_1 = \frac{R}{L} + \frac{1}{rC} \qquad ...(3.28)$$

$$B_2 = \frac{1}{LC} + \frac{R}{rLC} \qquad ...(3.29)$$



(1) r is resistance connected in parallel with the c.b. (resistance switching opening resistance—ohm

(2) R series resistance of circuit per phase—ohm

(3) C capacitance between phase and earth per phase—farad

(4) L inductance per phase—henry ; i_r current in resistance switching ; i_c current in capacitor ; i total current

Fig. 3.19. Resistance switching.

The roots are complex and the frequency of transient is given by

$$f_n = \frac{1}{2\pi}\sqrt{\frac{1}{LC} - \frac{1}{4}\left(\frac{R}{L} - \frac{1}{rC}\right)^2}$$

and attenuation

$$p = \frac{1}{2}\left(\frac{R}{L} + \frac{1}{rC}\right)$$

if

$$R \le L$$

$$f_n = \frac{1}{2\pi}\sqrt{\frac{1}{LC} - \left(\frac{1}{2rC}\right)^2} \qquad \ldots(3.30)$$

From Eq. 3.30, it is clear that if parallel resistance 2 across contacts is less than

$$\frac{1}{2}\sqrt{\frac{L}{C}}$$

the frequency reduces to zero as shown below

$$f_n = \frac{1}{2\pi}\sqrt{\frac{1}{LC} - \frac{1}{4C^2} \times \frac{4C}{L}}$$

$$= \frac{1}{2\pi}\sqrt{0} = 0 \text{ if } r < \frac{1}{2}\sqrt{\frac{L}{C}}$$

The value of resistance r at which the frequency of TRV becomes zero is called "Critical Damping Resistance'. The resistance connected in parallel with the circuit-breaker for opening operation is called 'Opening Resistance'.

The frequency of transient restriking voltage vanishes and the rate of rise of restriking is kept within the capability of the breaker. In the resistance switching resistance is connected in shunt with the arc (Fig. 3.19) so as to reduce the restriking voltage frequency. The resistance also diverts part of the arc current.

In the plain break oil circuit-breakers (tank type) the post zero resistance of the contact space is low. Hence resistance switching is not necessary. However, the resistance switching assists the circuit-breaker in interrupting the magnetising currents and capacitive currents.

The post-zero resistance of air-blast circuit-breaker is high. This may result in severe voltage transients due to current chopping (interruption of current before natural zero). Hence the resistance switching is adopted.

The magnitude of opening resistance for resistance switching is given by

$$r = \frac{1}{2}\sqrt{\frac{L}{C}}$$

Assuming

$$I_{sc} = \frac{E}{\omega L}$$

$$L = \frac{E}{I_{sc}\,\omega}$$

$\therefore$

$$r = \frac{1}{2}\sqrt{\frac{E}{I_{sc}\omega C}} = K\frac{1}{\sqrt{I_{sc}}}$$

Hence magnitude of resistance depends on the fault current.

Example 3.8. *In a system of 132 kV, the circuit phase to ground capacitance is 0.01 mF, the series inductance is 6H. Calculate the voltage appearing across the pole of a.c.b. if a magnetizing current of 10 amp. is interrupted (instantaneous). Calculate the Value of resistance to be used across contact space to eliminate the restriking voltage transient.*

Solution. $L = 6\text{H}$; $C = 0.01\ \mu\text{F}$

$$\frac{1}{2}Li^2 = \frac{1}{2}Cv^2$$

$$v = i\sqrt{\frac{L}{C}}$$

$$= 10\sqrt{\frac{6}{0.01 \times 10^{-6}}} = 10\sqrt{6 \times 10^8}$$

$$v = 245{,}000 \text{ V}.$$

The magnitude of resistance r for resistance switching is given by

$$r = \frac{1}{2}\sqrt{\frac{L}{C}}$$

$$= 0.5\sqrt{6 \times 10^8} = 0.5 \times 2.45 \times 10^4$$

$$= 1.225 \times 10^4\ \Omega = 12.25\ \text{k}\Omega.$$

Hence the critical damping resistance = 12.25 kΩ.

3.12. INTERRUPTION OF LOW MAGNETIZING CURRENT, CURRENT CHOPPING

The necessity of interrupting small inductive current arises while disconnecting transformers on no-load. No-load currents of transformer, *i.e.* magnetizing currents are almost at zero power factor lag. The current is smaller than normal current rating of the breaker. The breaking of such a low current presents a sever duty on the circuit-breaker. (Sec. 15.23)

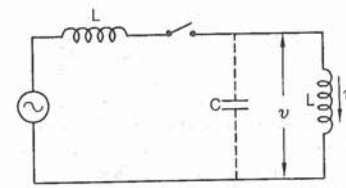


Fig. 3.20 Circuit diagram illustrating interruption of low inductive current.

When interrupting low inductive currents such as magnetizing currents of transformer, shunt reactor, the rapid deionization of contact space and blast effect may cause the current to be interrupted before its natural zero. This phenomenon of the interruption of current before its natural zero is called current chopping. As shown in example 3.6 the energy stores in inductance for value of current it is diverted to the capacitance at the moment of current interruption, i.e.

$$\frac{1}{2}Li^2 = \frac{1}{2}Cv^2 \text{ joules}$$

$$v = i\sqrt{\frac{L}{C}}$$

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

Such a transient voltage having high RRRV appears across the contacts, unless the arc continues. If it restrikes a further, chop may occur or several chops may occur before the current is finally interrupted, circuit-breaker may fail to clear the fault.

If the restrike does not occur, the severe voltage appears across the c.b. contact and on the system.

Resistance switching is adopted to overcome the effect of over-voltages due to current

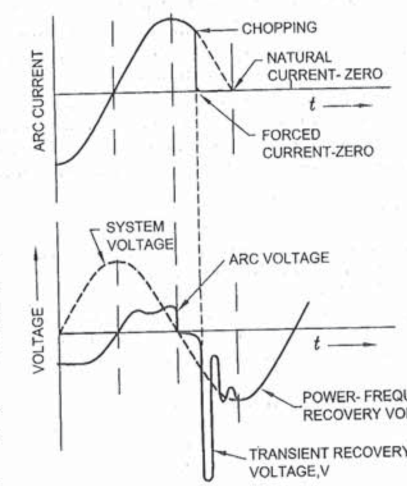


Fig. 3.21. Interruption of low magnetizing currents.

chopping. The value of resistance used for resistance switching is of the order of 15,000 ohms for switching off a 132 kV 45 MVA transformer.

The currents to be interrupted may be small, but interrupting such currents may result in very high voltages. For example consider disconnection of a 110 kV, 20 MVA tranformer.

$$\text{Rated current} = \frac{20 \times 10^6}{\sqrt{3} \times 110 \times 10^3} = 105 \text{ A.}$$

The magnetising current was 2 A.

$$X_0 = \frac{110 \times 10^3}{\sqrt{3} \times 2} = 31.7 \times 10^3 \text{ ohm}$$

$$L_0 = \frac{X_0}{2\pi f} = \frac{31.7 \times 10^3}{314} = 101 \text{ henry.}$$

Assuming current is interrupted at instantaneous value $\sqrt{2} \times 2 = 2.82$ A.

$$i^2 = (2.82)^2 = 8$$

The capacitance between phase and ground is found to be 5000 pF equating energies we get

$$\frac{1}{2} Li^2 = \frac{1}{2} Cv^2$$

$$v = i\sqrt{\frac{L}{C}} = 2.82\sqrt{\frac{101}{5000 \times 10^{-12}}} = 400 \text{ kV Peak}$$

Thus voltage of 400 kV appears across breaker pole. If the dielectric strength of the contact space is low or if resistance or capacitor is provided in shunt, the excessive voltage is discharged and therefore, does not appear on the system. Thus a circuit-breaker in which the dielectric strength of contact space grows at a slower rate, the problem of restriking voltage disturbance is less severe because the gap-breaks down and absorbs the magnetic energy in successive restrikes, circuit-breakers with internal extinguishing source such as oil circuit-breakers are, therefore suitable for such applications. On the contrary in air blast circuit-breakers, post arc dielectric strength is high, severe voltage transients can be expected. Hence resistance switching is adopted.

Another difficult duty for which the circuit-breakers should be desinged is breaking of inductive currents such as breaking of reactors or transformers loaded with reactors. Resistance switching is resorted to. Resistance switching comprises non-linear resistors which are brought into the circuit, parallel to the arc between contacts, during arc interruption. The current flows in the shunt resistor until it is interrupted by the resistor switch. In medium voltage systems upto 36 kV, RC surge absorbers with R = 100 ohms and $C = 0.1\ \mu F$ are connected phase to ground between the breaker and the inductive load. The surges are absorbed by the RC combination.

3.13. USE OF OPENING RESISTORS

'Opening resistors' also called 'switching resistors' are fitted parallel with main break in series with a resistance switch. The opening resistors come into the circuit prior to the opening of the main break (1) by closing of the resistors switch (II). The resistance switch (II) may be formed by the moving parts in the interrupter or striking of an arc depending upon the design of the circuit-breaker.

During the arc-interruption process in the main-break, the resistor switch (II) remains closed. The resistance switch (II) opens with a certain delay after the opening of the main break.

The magnitude of opening resistances depend upon the type of circuit-breaker and the switching duty involved.

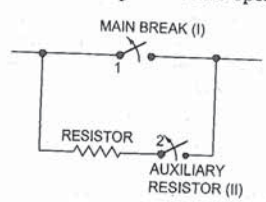


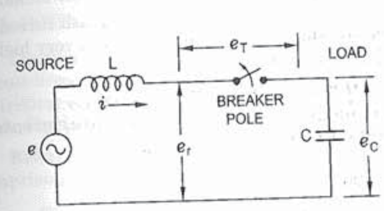
Fig. 3.22. Use of opening Resistor in Circuit-Breaker.

In air-blast circuit-breakers the problems or current chopping is generally more severe due to the fact that the blast is of same high pressure even if the breaking current is low. The opening resistors and the resistor switch are designed for values of currents of the order of 30% of the rated breaking current. The typical value of the opening resistors may be of the order of 300 to 500 ohms in case of 145 kV air-blast circuit-breakers. In oil-circuit-breakers the energy required for arc extinction is proportional to the current in the arc. Hence the opening resistors need not carry high value of current; the typical values being in the range of 5 to 10% of the rated breaking current (Ref., sec., 18.8 for Closing Resistors).

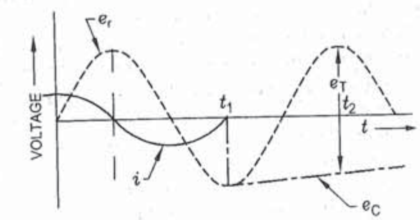
The SF_6 circuit breakers generally do not need opening resistors as the arc interruption generally takes place at natural current zero and the dielectric strength of the medium between the contacts builds up very rapidly.

3.13.1. Switching of Capacitor Banks (Ref. Sec. 15.26)

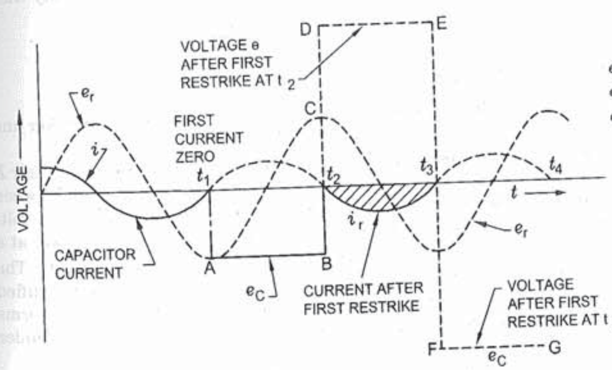
While opening capacitor banks the reginition and 'restriking' can occur in an interrupter (Ref. Sec. 3.6) Capacitor banks are connected in the network to provide reactive power at leading power factor. The voltage across a capacitor cannot change instantaneously. The currents supplied to the capacitor is generally of small order and the circuit-breaker can interrupt such currents invariably at the first current zero. Due to the 90° phase difference, the voltage across the Capacitor is at maximum value (e_c) at this instant (t_1) and the capacitor remains charged at this voltage (e_c). After



(a) Single phase Representation of star connected 3 ph. Capacitor Bank



(b) Waveform of Clean interruption without restrike (at t_1 current i is interrupted)



e_r = Source side sinusoidal voltage
e_c = Voltage across capacitor C
e_r = Voltage across breaker pole

(c) Waveform for restrikes

Fig., 3.23 Switching of capacitive currents for opening operation.

half cycle (t_2) the recovery voltage of approximate magnitude of (e_{rmax}) appears across the circuit-breakers and the total voltage across the circuit-breaker is the sum of two voltages *i.e.*

$$e_{Tmax} = e_{rmax} + e_c$$

where e_{Tmax} = Maximum voltage across breaker

e_{rmax} = Max. value of power frequency recovery voltage

e_c = Voltage across capacitor.

Thus the recovery voltage of the order of $2E_{max}$, (where $E_{max} = \sqrt{2}\, E_{ph}$) appears across the circuit-breaker pole at the instant t_2, after 1/2 cycle of current zero. Therefore, a restrike is possible. If a restrike occurs, the LC circuit will oscillate at a frequency given by $f_n = 1/2\sqrt{LC}$. This current tries to maintain the arc. The voltage across the interrupter rises upto 4 p.u due to one restrike and upto 6 p.u. with second restrike. The energy ($1/2\ Cv^2$) to be dissipated during such arcs is quite large and the interrupters may get damaged in the process after a restrike. Hence, the circuit-breakers used for capacitors duty should be 'Restrike free'. It should have adequate rating for capacitive current switching.

While closing the circuit breaker of parallel capacitor banks, the pre-arcing between contacts can have damaging. The pre-arcing taken place before the contact touch. The frequecny of arc current is given by $f_n = 1/2\sqrt{LC}$. The energy in the arc is converted into heat. Every circuit-breaker has a limit of making capacity depending upon the frequency and magnitude of the inrush current. While paralleling one capacitor bank with another, the frequency of inrush currents is very high. Suitable reactor (L) should be provided in series. (Ref. Sec. 15.26)

3.13.2. Switching of Unloaded Transmission Lines and Unloaded Cables

Unloaded transmission lines and unloaded under ground power-cables take capacitive currents. The magnitude of capacitive currents encountered in practice are:

Unloaded lines: Charging currents : Up to 10 A

Underground cables : Charging currents: Up to 100 A

Capacitor Banks: Current up to 1400 A

During the opening operation, the restrike phenomenon is possible in above cases (described in Sec. 3.14.1)

The circuit-breaker used for a particular application should be capable of performing opening and closing operations without getting damaged and with overvoltages within specified limits. The circuit-breaker should have adequate rating and should be type tested for the relevant duty (Ref. Secs. V 3.19.20; 11.10)

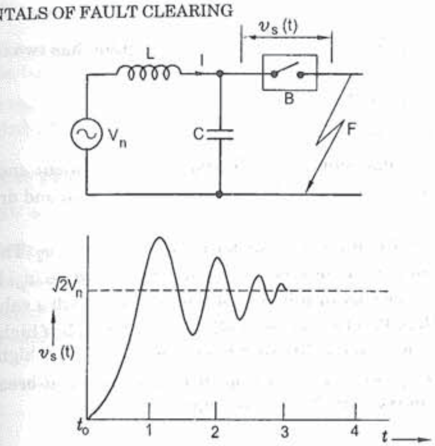
Vacuum CB, SF_6 CB and ABCBs are suitable for capacitors switching duty.

3.14. INTERRUPTING THE TERMINAL FAULTS

The Terminal Fault is defined as a fault occurring very near to terminal of circuit-breaker and that the reactance between the fault point and breaker is negligible.

Fig. 3.24 shows a single phase repesentation of a terminal fault condition. Consider breaker B 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 current I is governed by voltage of the source V_n and impedance of source ωL. The current I is interrupted by the breaker at a current zero. After the arc interruption, the voltage $Vs\ (t)$ appears across the breaker pole. The circuit being predominantly inductive, the power factor of current is low (0.1). The simplified waveform of transient recovery voltage is shown in Fig. 3.24. 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-56.2, the rated characteristics of a circuit-breaker include rated transient recovery voltage for terminal faults. The rated short-circuit breaking current is specified with references to the rated TRV for terminal faults.



B = Breaker
V_n = Voltage of source
L = Inductance on source side
F = Fault at terminal of B
$V_s\ (t)$ = Voltage across breaker
t = Time in microsec
C = Shunt capacitance on source side.

Simplified TRV form

Fig. 3.24 Conditions representing Terminal Fault (t in μs).

3.15. INTERRUPTING SHORT LINE FAULTS (Kilometric Fault)

The fault occurring between a distance of a few kilometers to a few tens kilometers from the circuit-breaker arc called short line faults. Such faults are characterised by high frequency of restriking voltage of the order of 10 to 100 kHz depending upon length of line and location of the fault. Fig. 3.25 represents a condition of a shortime fault and simplified TRV form.

Referring to Fig. 3.25 supply voltage cause short circuit current I to flow through the circuit comprising the following impedances :

ωL = impedance of source = $2\pi fL$

λ_1 = impedance of 1 km length of line

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

λ = impedance per km length of line.

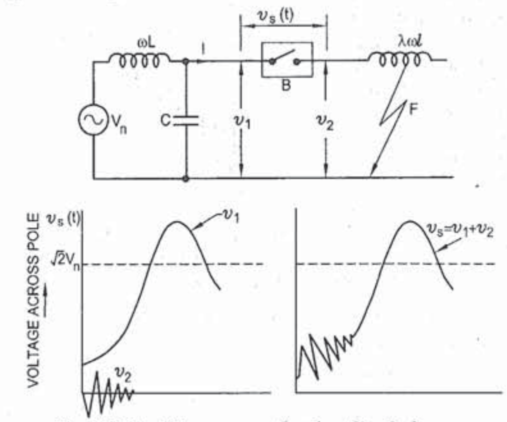


Fig. 3.25. Condition representing short-line fault (kilometric fault) (t in microsec).

The voltage appearing across breaker pole after final current interruption has two components v_1 and v_2. (Fig. 3.25)

– v_1 is the voltage at the terminal from supply side.

– v_2 is the voltage at the terminals from line side.

The voltage v_1 has power frequency component and high frequency component and reaches a peak value $\sqrt{2}V_n$ as illustrated in the figure. Whereas v_2 has saw-tooth waveform and drops to zero after a few microseconds.

The trasient recovery voltage v 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 $v_p/41$ where (v_p) is propagation velocity on the line and λ is the impedance per unit length of line. F_1 may reach a value between 10 to 100 kHz depending upon the 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 transient recovery voltage for short line appearing across circuit-breaker pole is the vector sum of the voltage from the source and the line voltage $V_S - V_L$.

3.16. PHASE OPPOSITION SWITCHING

When two systems are to be sychronised, it may happen that the breaker opens on non-synchronous condition. In Fig. 3.26, if V_1 and V_2 are not in sychronism during opening of breaker the likely waveform of transient recovery voltage is as shown in Fig. 3.27. Under certain conditions the voltage across pole may reach three times phase voltage or in extreme cases it may reach twice to line voltage.

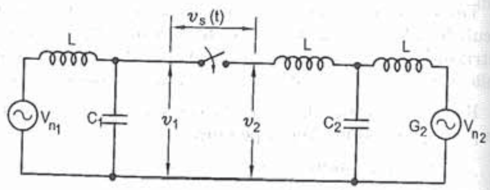


Fig. 3.26 Out-of phase switching.

The circuit-breakers used for synchronising, 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° out of phase, given by :

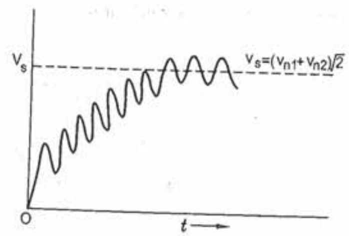


Fig. 3.27 Waveform of voltage across the breaker pole during out-of-shape opening (t in microsec.)

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

where, V_s = Maximum value of power frequency recovery voltage

V_1 = Component from source side.

V_2 = Component from line side.

Summarising. The circuit-breaker should be capable of performing variety of switching duties. The current and voltage severities during these conditions are quite different. The studies on these switching conditions are simulated on

— Transient Network Analyzer
— Field testing
— Analogue Computer
— Short-circuit testing

To test the performance of circuit-breaker for various switching conditions, the tests are now recommended for high voltage circuit-breakers.

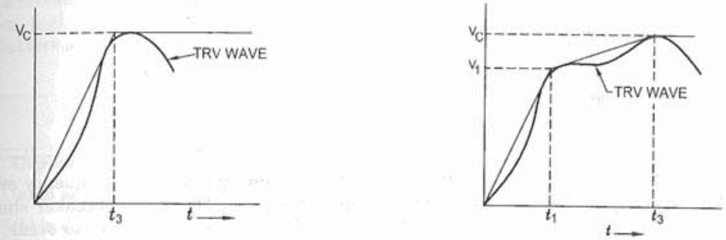
3.17. SPECIFYING THE TRV WAVE

The TRV waveform can be specified by various methods (Fig. 3.28) such as

— Specifying the peak value and time to reach the peak.

This methods was used earlier

— Specifying the parameters which determine the line segments enveloping the TRV wave (Fig. 3.28) (two parameter method and four-parameter method).



(a) Two-parameter method, V_C, t_3 (b) Four-parameter method, V_l, V_C, t_1, t

Fig. 3.28 Possible methods defining TRV waveform (t in μs).

3.18. RATED CHARACTERISTICS OF CIRCUIT-BREAKERS

The ratings of a circuit-breaker denote its capabilities under specified conditions of use and behaviour. The following paragraphs are generally based on the recommendations of IEC, Publication IEC-56: "High Voltage Alternating Current Circuit-Breakers" and IS-2516 : "Specifications of Alternating Current Circuit-Breakers."

The capabilities of a circuit-breaker of a particular type are proved by conducting type tests as per the recommendation of the standards.

The following rated characteristic (1-9) are generally specified for all high voltage a.c. circuit-breakers rated above 1000 V (For specifications of low voltage c.b.—Ref. Sec. 15.7).

3.18.1. Rated Voltage

The rated voltage of a circuit-breaker corresponds to the higher system voltage for which the circuit-breaker is intended. The standards values of rated voltages are given in Table 3.1. The rated voltage is expressed in $kV_{r.m.s.}$ and refer to phase to phase voltage for three-phase circuit. The earlier practice of specifying the rated voltage of a circuit-breaker as nominal system voltage is no more followed.

3.18.2. Rated Insulation level

The rated insulation level of a circuit-breaker refers to the power frequency withstand voltage and impulse voltage withstand values which characterise the insulation of the circuit-breaker. (Ref. Table 12.1)

TABLE 3.1.
Rated Voltage of Circuit-Breaker

Nominal System Voltage $kV_{r.m.s.}$	*Rated Voltage of Circuit-breaker $kV_{r.m.s.}$*
0.240	0.264
0.415	0.440
3.3	3.6
6.6	7.2
11	12
22	24
33	36
66	72.5
132	145
220	245
400	420
500	525
750	765

The circuit-breakers connected in a power-system are subjected to power-frequency over voltages due to regulation, Ferranti effect, higher tap-setting, etc. The circuit breaker should be capable of withstanding the power frequency over-voltages which are likely to occur. These capabilities are varified by conducting power frequency voltage withstand tests and impulse-voltage withstand tests. The circuit-breaker is subjected to impulse over-voltage due to causes like lighting surge and switching surge.

During single-line to ground faults, the voltage of healthy lines to earth increases to $\sqrt{3}$ time to normal value in systems with insulated neutral. Hence higher values of insulation are recommended for circuit-breaker connected in non-effectively earthed systems. The following insulations are provided in the circuit-breaker:

— Insulation between live parts and earth for each pole external and internal.
— Insulation between poles.
— Insulation between terminals of the same pole-external and internal.

The design of these insulation depends upon the structural form of the circuit-breaker and the rated insulation level desired Ref. Ch. 12 for further details.

3.18.3. Rated frequency

The standard frequency for a three pole circuit-breaker is the frequency of the power system (50 Hz). The characteristics like normal current breaking capacity etc. are based on the rated frequency.

The frequency of the current influences the circuit-breaker behaviour as follows :

— The temperature rise of current-carrying parts and neighbouring metallic parts is influenced by eddy-current heating. The increase in frequency results in increased eddy currents. Hence, with specified limits of the temperature rise the rated current of a circuit-breaker needs de-rating for application on higher frequency.
— The frequency corresponds to the number of current-zeros per second. Since the breaking time of the circuit-breaker is associated with the time for half cycles during the arc extinguished process, the breaking time is influenced by the frequency of current. The breaking time increases with reduction in frequency.

— The increase in frequency influences the TRV and rate-of-rise TRV. Hence a circuit-breaker desinged and rated for a certain frequency cannot be recommended for other frequencies unless its capabilities are proved for those frequencies.
— The d.c. circuit-breakers generally adopt a different principle of arc-extinction and have different construction than a.c. circuit-breakers.

3.18.4. Rated Normal Current (Rated Current)

The rated normal current of a circuit-beaker is the r.m.s. value of the current which the circuit-breaker can carry continuously and with temperature rise of the various parts within specified limits.

Preferred Values of Rated Currents A rms

400, 630, 800, 1250, 1600, 2000, 2500, 3150, 4000, A rms

The design of contacts and other current carrying parts in the interrupter of the circuit breaker are generally based on the limits of temperature rise. For a given cross-section of the conductor and a certain value of current, the temperature rise depends upon the conductivity of the material. Hence, high conductivity material is preferred for current carrying parts. The cross-section of the conductors should be increased for materials with lower conductivity.

Table 3.2. Permissible Temperature Rise*

Item	*Maximum value of temperature °C*	*Temperature rise at ambient temperature of 40°C*
1. Copper contacts		
(*a*) in air with silver plating	105	65
(*b*) in air without silver plating	75	35
(*c*) in oil with silver plating	90	50
(*d*) without silver plating in oil	80	40
2. Oil		
in oil circuit-breakers	80	40
3. Terminals or the Circuit-breakers (*a*) With Silver plating	105	65
(*b*) Without silver plating	90	50
4. Metal part in contact	100	60
With class E insulation in oil.		

* Ref. Sec. 10.2.2 Temperature Tests.

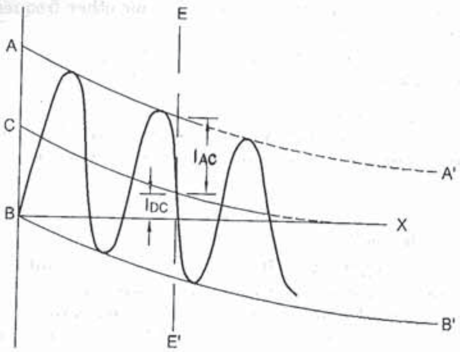
The use of magnetic materials in close circuits should be avoided to prevent heating due to hysteresis loss and eddy currents. The rated current of a circuit-breaker is verified by conducting temperature rise tests.

3.18.5. Rated Short Circuit-Breaking Current

The rated short-circuit breaking-current of a circuit-breaker is highest rms value of short-circuit current which the circuit-breaker is capable of breaking under specified conditions of transient recovery voltage and power frequency voltage. It is expressed in kA r.m.s. at contact separation.

Referring to Sec. 3.6, Fig. 3.6 the short-circuit current has a certain value at the instant of contact separation, ($t = T_1$). The breaking current refers to value current at the instant of the contact separation.

The transient recovery voltage refers to the transient voltage appearing across the circuit-breaker pole immediately after the arc interruption. The rated values of transient recovery voltage are specified for various rated voltages of circuit-brekers. For specified conditions of rated TRV and



$\left.\begin{matrix} AA' \\ BB' \end{matrix}\right]$ Envelope of current wave
BX = Normal zero axis of wave
CX = Displaced zero axis of wave
EE = Instant of contact separation
I_{AC} = Peak value of A.C. component at EE
I_{DC} = D.C. component of current at EE
$\dfrac{I_{DC} \times 100}{I_{AC}}$ = Percentage of D.C. component at the instant EE
$\dfrac{I_{AC}}{\sqrt{2}}$ = r.m.s. value a.c. component.

Fig. 3.29. Determination of breaking current.

rated power frequency recovery voltage, a circuit-breaker has a certain limit of breaking current. This limit is determined by conducting short-circuit type tests on the circuit-breaker. The waveforms of short-circuit current are obtained during the breaking test. The evaluation of the breaking current is explained in Fig. 3.29.

The breaking current is expressed by two values :

(1) the r.m.s. value of a.c. component at the instant of contact separation EE, given by

$$\frac{I_{AC}}{\sqrt{2}}$$

(2) the percentage d.c. component at the instant of contact separation given by

$$\frac{I_{DC} \times 100}{I_{AC}}$$

The r.m.s. values of a.c. components are expressed in kA, the standard values being

8, 10, 12.5, 16, 20, 25, 31.5, 40, 45, 63, 80 and 100 kA.

The earlier practice was to express the rated breaking capacity of a circuit breaker in terms of *MVA* given as follows:

$$MVA = \sqrt{3}\ \text{kV} \times \text{kA} \qquad \ldots(3.31)$$

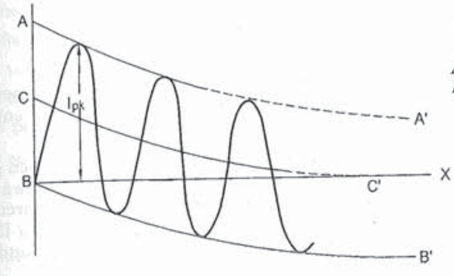
where MVA = Breaking capacity of a circuit-breaker
kV = Rated voltage
kA = Rated breaking current.

This practice of specifying the breaking capacity in terms of *MVA* is convenient while calculating the fault levels. However, as per the revised standards the breaking capacity is expressed in kA for specified conditions of TRV, and this method takes into account both breaking current and TRV.

While selecting the circuit-breaker for a particular location in the power system the fault level at that location is determined. (Section II of the book). The rated breaking current can then be selected from the standard range.

3.18.6. Rated Short-circuit Making Current

It may so happen that circuit-breaker may close on an existing fault. In such cases the current increase to the maximum value at the peak of first current loop. The circuit-breaker should be able to close without hesitation as contacts touch. The circuit-breaker should be able to withstand the high mechanical forces during such a closure. These capabilities are proved by carrying out making



$\left.\begin{matrix} AA' \\ BB' \end{matrix}\right]$ = Envelope of current wave
BX = Normal zero axis
CC = Displaced zero axis
I_{pk} = Peak making current.

Fig. 3.30. Determination of peak making current.

current test. The rated short-circuit making current of a circuit-breaker in the peak value of first current loop of short-circuit current (I_{pk}) which the circuit-breaker is capable of making at its rated voltage (Ref. Fig. 3.7, Sec. 3.6).

The rated short-circuit making current should be least 2.5 times the r.m.s. value of a.c. component of rated breaking current.

$$\text{Rated making current} = 1.8 \times \sqrt{2} \times \text{Rated short-circuit breaking} \qquad \ldots(3.32)$$
$$= 2.5 \times \text{Rated short-circuit breaking current.}$$

In Eq. 3.32 the factor $\sqrt{2}$ converts the r.m.s. value to peak value. Factor 1.8 takes into account the doubling effect of short-circuit-current (Ref. Sec. 3.6) with consideration to slight drop in current during the first quarter cycle.

3.18.7. Rated duration of short-circuit (Rated short time current)

The short time current of a circuit-breaker is the r.m.s. value of current that the circuit-breaker can carry in a fully closed position during a specified time under prescribed conditions of use and behaviour. It is normally expressed in terms of kA for a period of one second. Adjacent poles experience mechanical force during this test.

The rated duration of short circuit is generally 1 second and the circuit breaker should be able to carry short-circuit current equal to its rated breaking-current for one second. During the short-time current test, the contacts should not get damaged or welded. The current carrying parts and insulation should not get deteriorated. Generally the cross-section of conductors based on normal current rating requirements is quite adequate for carrying the rated short-circuit current for the duration of 1 second.

3.18.8. Rated Operating Sequence (Duty Cycle)

The operating sequence denotes the sequence of opening and closing operations which the circuit-breaker can perform under specified conditions. The operating mechanism experiences severe mechanical stresses during the auto-reclosure duty. As per IEC, the circuit-breaker should be able to perform the operating sequence as per one of the following two alternatives:

(*i*) *O–t–CO–T–CO*

where, O = opening operation
C = closing operation
CO = closing followed by opening
t = 3 minutes for circuit-breaker not to be used for rapid auto-reclosure
t = 0.3 second for circuit-breaker to be used for rapid auto-reclosure
T = 3 minutes

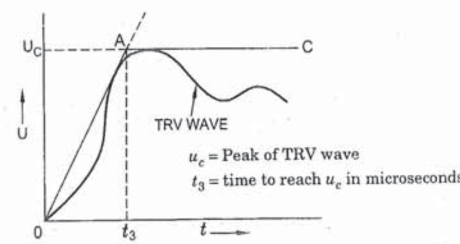


Fig. 3.31 (*a*) Representation of TRV wave by two parameter method.

(*ii*) *CO–t′–CO*

where t'–15 second for circuit-breaker not to be used for rapid auto-reclosure.

3.18.9. Rated Transient Recovery Voltage for Terminal Faults

The methods of specifying a TRV wave were briefly discussed in Sec. 3.18. As per new standards on circuit-breakers, the circuit-breakers should have rated TRV. The breaking current test is carried out on circuit-breaker with specified TRV.

The standard parameters such as voltage co-ordinate time coordinates have been given in the standards. Based on these parameters the line segments can be drawn. The TRV wave can then be drawn within the segments. Thus the circuit-breaker should be tested for short-circuit-breaking current test with TRV waveform above the standard waveform. IEC 56.2, 1971 and IS 2516 Part I/sec. 3, 1972 recommended the following two alternative methods for specifying standard TRV.

— Method of two parameters.

— Method of four parameters.

3.18.10. Representation of a TRV waveform by four parameter method [Ref. Fig. 3.31 (*b*)]

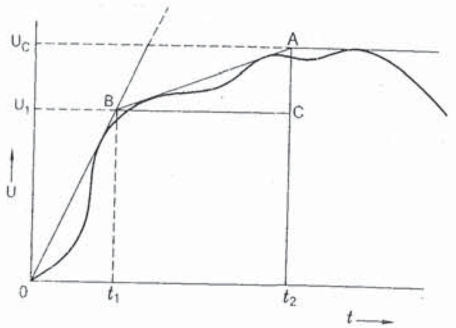
In the systems rated above 100 kV or locations where the short-circuit currents are relatively heavy compared to the maximum short circuit current in the system (Ref. Sec. 3.7.), the TRV wave has initial period of high rate of rise followed by later period of low rate of rise. Such waveforms can be represented by four parameter method. The four parameter are the following :

u_1 = first reference voltage kV.

t_1 = time to reach u_1 μ sec.

u_c = second reference voltage, Peak value of TRV. kV

t_2 = time to reach u_c, μ sec.



u_1 — first reference point of TRV wave
t_1 — time to reach u_1 in microseconds
u_c — peak of TRV
t_2 — time to reach u_c in microseconds

Fig. 3.31. (*b*) Representation of TRV wave by four parameter method. (Ref. Fig. 3.8 (*b*) A portion of TRV shown therein is magnified here)

The values of four parameters μ_1, t_1, u_c, t_c have been specified in the standards for various values of rated voltages. Based on these values the segments can be plotted as shown in Fig. 3.31 (*b*) and the student TRV wave can be drawn such that it is contained in the three segments. The parameters u_c and u_1 can be calculated from rated phase to phase r.m.s. voltage u_1 as follows:

(*a*) For systems with non-effective earthing (Ref. Sec. 18.6)

$$u_1 = \frac{1.5 \times \sqrt{2} \times u_r}{\sqrt{3}}$$

(*b*) For systems with effective earthing (Ref. Sec. 18.6)

$$u_1 = \frac{1.3 \times \sqrt{2} \times u_r}{\sqrt{3}}$$

where u_r = rated voltage of circuit-breaker (highest system voltage), phase to phase r.m.s. kV

u_1 = first reference kV

t = time to reach u_1, μs

t_2 = time to reach u_c, μs

u_c = peak value of TRV wave

t_1 and t_2 are specified in standards for various rated voltages of circuit-breakers.

Factors 1.3 or 1.5 in equation given above is called *First pole to clear factor* (Ref. Sec. 3.10; Sec. 18.6)

$$\text{Amplitude factor} = \frac{u_c}{u_1} \text{ (Ref. Sec. 3.10)}$$

$$\text{Natural frequency} = \frac{10^3}{2t_2} \text{ kHz (Ref. Sec. 3.10)}$$

3.18.11. Representation of TRV waveform by two-parameter method

The wavaform of TRV in systems rated below 100 kV or locations where short-circuit current is low compared with the maximum short-circuit current in the system can be approximately represented by a single frequency transient. Such a waveform can be defined by method of two parameters as follows:

u_c = peak of TRV wave, kV

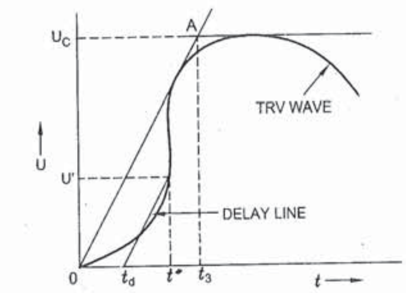
t_3 = time to reach peak, μs

The standard values of u_c and t_3 have been given in IEC-56-2 and IS2615-I/3 for various rated voltage of circuit-breaker. From these values the segments of line can be plotted and the TRV waveform contained in these segments can be defined [Ref. Fig. 3.31 (*a*)].

U_c can be calculated as described in the method of four parameters.

The delay line. The initial rate of rise of TRV wave contained within segments drawn according to the method of two parameters and four parameters is defined the delay line.

(Ref. Fig. 3.8. (*b*). The portion of TRV therein is magnified here).



The TRV wave should cross the delay line only once and should not recross it.
Fig. 3.32 The Delay Line.

The parameters u', t', and t_d are specified in the standards for various rated voltages. From these parameters, the delay line can be drawn. The TRV waveform should cross the delay line only once and should not recross it. By this method the initial rate of rise of TRV wave is defined.

Initial TRV. (ITRV) to TRV for one or two microseconds after current zero.

Example of Rating of a 145 kV Circuit Breaker

Rated Voltage..................145 kV rms

Rated Frequency.....................50 Hz

Rated Insulation Level

— 1 Min. Power Frequency Withstand............275 kV rms

— Impulse Withstand...........650 kV_p

Rated Normal Current...............1600 A rms

Rated Short-Circuit Breaking Current........25 kV

Rated Operating Sequence.........O—0.3 sec—CO—3 min—CO

Rated Duration of Short Circuit........1 sec

Rated Short Circuit Making Current..........62.5 kA_p

Total Break Time (maximum)..........3 cycles.

3.18.12. Rated Peak Withstand Current

The rated peak withstand current is the instantaneous value (peak value) of short-circuit current which the circuit-breaker in closed position is capable of withstanding. The closed circuit-breaker may be subjected peak short-circuit current during every short-circuit beyond a circuit-breaker. (Fig. 3.30 Ipk). The adjacent phases are subjected to maximum mechanical force at the instant of adjacent phases are subjected to maximum mechanical force at the instant of this peak (Sec. 17.18). These forces are inversely proportional to the distance between adjacent poles. In LV and HV circuit-breakers upto rated voltage of 72.5 kV, the phase to phase clearances are relatively small and the forces during peak short-circuit current are high. The circuit-breaker should be capable of withstanding these stresses without damage.

As per IEC-56 the assigned value of rated peak withstand current is equal to the rated short-circuit making current. It is expressed in terms of kA, instantaneous.

For making current test the breaker is closed on existing short-circuit. For peak withstand current test the short-circuit with maximum asymmetry in one phase is applied to a closed breaker. Peak withstand current test is combined with the short-time current test (Sec. 11.6).

TABLE 3.3

Preferred Ratings of High Voltage circuit-breakers Selection Chart

Rated Voltage kV, rms	*(L.V.) 0.460*	*(H.V.) 3.6*	*7.2*	*12*	*36*	*72.5*	*145*	*245*	*420*
1 Minute p.f. withstand kV rms		21	27	32	75	140	230/275	395/460	680
Impulse withstand kV peak		45	60	75	170	325	550 650	900 1050	1425
Rated normal current A rms	400-4000								
Rated S.C. breaking current kA rms	8-60	8-40	8-40	8-40	20-31.5	20-31.5	25-40	25-50	25-60
Rated S.C. making current kA, peak	*	*	*	*	*	*	*	*	*
Rated duration of S.C. sec	3 sec	1/3	1/3	1	1	1	1	1	1
Rated operating sequence	(O—3m—CO—3m—CO) (CO—15 Sec—CO)				(O—0.3 Sec—CO—3m—CO)				

Reference standards :

(1) IS 2516, IEC-56 for Ratings and Testing of High Voltage a.c. current breakers.

(2) IEC 60, IEC 71 for High Voltage Testing and Insulation Co-ordination.

(3) ICE 157 for Low Voltage Switchgear and Controlgear.

(4) Total breaking time varies between 80-120 ms for circuit breakers up to 12 kV and 40-80 ms for circuit breakers above 36 kV. It is less than 60 ms for 145 kV, less than 50 for 420 kV circuit breakers.

3.18.13. Rated Quantities for Auxiliary Circuits and Operating Mechanisms for opening and closing

In addition to the specified ratings for the main circuit and poles, the performance of auxiliary supply circuits and operating mechanisms is also important. The auxiliary circuits which supply voltage to the trip-coil and closing coil should have certain minimum voltage. Below this limit the tripping mechanism and closing mechanism may not operate even after getting a command. In case of AC auxiliary supply, the frequency should be between specified range to ensure correct operation of AC trip coils and AC electromagnetic operating mechanisms (if any).

The following ratings are mentioned in IEC 56 (1987).

— Rated supply voltage of closing and opening devices and auxiliary circuits.

— Rated supply frequency of closing and opening devices and auxiliary circuits.

No load operation tests are carried out on a circuit-breaker (s) before carrying out main short-circuit duty tests and main short circuit duty tests.

These comprise O, C, CO operations on no-load with

— Closing of auxiliary energized at 105%, 100%, 85% of rated supply voltage of auxiliary closing devices.

— Shunt opening release (trip coil) energized at 110%, 100%, 85%, rated auxiliary supply voltage in the case of AC and 110%, 100% and 70%, in the case of DC supply voltage.

3.18.14. Rated Pressure of supply for pneumatic and hydraulic operating devices

Air-blast circuit-breaker and some single pressure SF_6 circuit breakers use pneumatic operating mechanisms. Some SF_6 circuit-breakers use hydraulic operating mechanisms. The minimum rated maximum pressures of air pressure and hydraulic pressure are specified.

The no-load tests short circuit test duties with rated operating sequency (0-0.3S—CO-3m—CO) are performed with certain conditions of these pressures.

The pressure switches are fitted in the auxiliary-systems of the operating mechanism.

3.18.15. Rated Pressure of Interrupting Medium and Insulating medium (If applicable)

Fir Air-blast circuit-breakers and SF_6 circuit-breakers these quantities are specified along with lowest, normal and highest permissible value. The type tests are performed as per rules. The settings of limit switches are also decided accordingly.

Satisfactory performance of circuit-breakers during various type tests and during switching operation in service is with reference to minimum and maximum pressure of insulating medium in the breaker pole unit.

The dielectric type tests and short-circuit type tests are performed on new circuit-breaker filled with specified normal pressure of interrupting medium and insulating medium. Breaker should be leakage free.

During service, the pressure switches sound an alarm for lower pressure or upper pressure. In case pressure drops below safe limits, pressure which sends tripping command or locking command.

3.18.16. Summary of Rated Characteristics of HV (a.c.) Circuit-breakers

(A) Rated Characteristics to be specified for every circuit breaker.

Every high voltage a.c. circuit-breaker should have the following rated characteristics : (Ref. : Table 3.3). These are assigned for every circuit breaker supplied by manufacturer. The type test certificates are furnished for confirming these rated characteristics.

(1) Rated Voltage

(2) Rated Insulation Level

(3) Rated Normal Current

(4) Rated Frequency

(5) Rated duration of short-circuit or Rated short-time current

(6) Rated short-circuit breaking current
(7) Rated short-circuit making current
(8) Rated peak withstand current
(9) Rated TRV for terminal fault
(10) Rated Operating Sequence
(11) Rated supply voltage for closing and opening devices and auxiliary circuits.
(12) Rated pressure of compressed gas (Air or SF_6) for interruption (if applicable)
(13) Rated pressure of compressed gas or oil for pneumatic or hydraulic operating mechanism (if applicable)

(B) Additional Rated Characteristics to be specified in certain cases.

In addition to (A) above, following rated characteristics are assigned in following specific cases.

(14) Rated characteristic for short-line faults for CBs controlling overhead lines rated 52 kV and above.
(15) Rated line charging current for CBs controlling overhead lines rated 72.5 kV and above.

(C) Rated characterictics to be given on request by user or consultant

For special switching duties like capacitor switching, reactor switching, DC switches, inductive current switching etc. The circuit-breaker is subjected to unusual and severe stress. Each type of CB behaves differently *e.g.* MOCB is prone to restrict during capacitor switching. SF_6 is very good for interruption of low inductive currents. VCB is excellent for capacitor current switching etc. The severity of each special duty is different and each type of CB behaves differently. The suitability of circuit-breakers for following special duties should be varified by the user and the manufacturer before ordering.

The following rated characteristics are to be furnished on special request from user for particular intended application.

(16) Rated out-of-phase breaking current
(17) Rated cable-charging breaking current
(18) Rated single capacitor bank breaking current
(19) Permissible switching overvoltages
(20) Rated capacitor bank inrush overvoltages
(21) Rated small inductive breaking current
(22) Rated time quantities
(23) Repeated operating duty

The user requests the manufacturer for the specific assigned (16 to 23) and the ratings are mutually selected for particular application. Necessary circuit arrangements are made to limit the stresses in actual installation within assigned rating. This applies to the circuit-breaker in question and also all the associated CTs, VTs Surge Arresters, busbars etc. failure in an installation can occur in the weakest spot, internal or external. In case of special switching duties (16 to 23) particular investigations are essential for each installation before arriving a required rating of the circuit breakers and associated equipments in the installation.

3.18.17. Rated out-of-phase breaking current

Refer Sec. 3.17. Phase opposition switching the circuit breaker used for synchronising should be capable of opening under nonsynchronous condition. The recovery voltage across the circuit-breaker pole is higher than normal short circuit duties. The out-of-phase current is assigned to a circuit breaker to be used for synchronising. The rated out-of-phase current that the circuit-breaker shall be capable of breaking under the prescribed conditions of power frequency recovery voltage and transient recovery voltage.

The power frequency recovery voltage is 20 times rated voltage for earth neutral systems. The TRV is specified in the standards.The rated out-of breaking current is 0.25 times rated short-circuit breaking current. The circuit breaker should be capable of opening and closing. It is assumed that there is no fault on either sides of the breaker. Ref. Sec. 11.11 out-of-phase switching test.

3.18.18. Rated Cable-charging breaking current

Ref. Sec. 3.14.2 switching of unloaded cables. The circuit breakers to be used for high voltage cable switching should be capable of breaking cable charging current. Such circuit breakers are assigned the rated cable-charging breaking current. The rated cable-charging breaking current is the maximum cable-charging current that the circuit breaker shall be capable of breaking at its rated voltage. It is expressed in Amperes. Table 3.4 gives the standard values of rated cable-charging breaking current.

TABLE 3.4

Rated Voltage of CB (kV) r.m.s., ph. to ph.	3.6	7.2	12	36	72.5	145	245	420
Rated Cable Charging breaking current (A r.m.s.)	10	10	25	50	125	160	250	400

Ref. Sec. 11-13 cable-charging current test.

3.18.19. Rated Single Capacitor bank breaking current

Ref. Sec. 3.14.1. Switching of capacitor banks is a severe duty on circuit breaker. The circuit-breaker to be used for opening capacitor banks should have adequate rating for breaking capacitor current without giving restrikes. Single capacitor banks does not have a parallel capacitor bank. Hence there is no question of high frequency inrush current. The rated single capacitor bank breaking current is the maximum capacitor current that the circuit breaker is capable of breaking at its rated voltage.

This breaking current refer to the switching of a single shunt capacitor bank and with no other shunt capacitors, connected on source side of the circuit-breaker. Ref. Sec. 11.12 for single capacitor current breaking tests. The assigned current is given on the basis of type tests. Single capacitor bank tests may be made in the laboratory or on actual side. The breaker should be restrike-free.

3.18.20. Permissible Maximum Switching Over-Voltages When Interrupting Line-Charging, Cable-Charging and Single Capacitor bank Breaking Current.

As per IEC 56, the maximum switching over voltages occurring during interrupting capacitive currents have been specified as given in Table 3.5.

Switching overvoltage is defined in terms of instantaneous peak value of the transient recovery voltage. It is also defined in terms of power unit value with rated phase to ground voltage as the base.

3.18.21. Rated Capacitor Bank Inrush Making Current

When capacitor bank is to be connected in parallel with another capacitor bank, inrush high frequency inrush current flow through the breaker contact at the time of contact touch. These inrush currents produce severe stresses on circuit-breakers. Various breakers behave differently with such stresses. The breakers to be used for paralleling capacitor bank should have adequate rated capacitor bank inrush making current. The rated capacitor bank inrush making current is the peak value of the current that the circuit-breaker is capable of making at its rated voltage and with given frequency of inrush current.

— In service the frequency of the inrush current is normally in the range 2 to 5 kHz.
— The circuit-breaker is considered to be suitable for any frequency of the inrush current lower than that for which it has been tested.

3.18.22. Rated Small Inductive breaking current

Ref. Sec. 3.12. The requirements of switching low inductive currents. The testing requirements are covered in Sec. 11.13. The rated low inductive breaking current has not been covered in IEC and in under consideration. However for particular application such as motor switching no load transformer switching the manufacturer gives result of low inductive current tests. The switching over voltages due to current chopping if any should be lesser than the permissible values (Ref. Table 3.5)

A present permissible switching over voltage specified for switching capacitive currents. The same over voltages limits may be consider for switching low inductive currents. The standards give the specifications. Apart from the inductive load, the supply cable; surge capacitive, surge arresters, surge absorbers connected to breaker terminals limit the over voltages and the tests on particle installations are carried out with such devices, in the circuit,

Let U_n = Rated voltage of *CB*, phase-to-phase kV, r.m.s., r.m.s. value of phase to phase rated voltage of the *CB*

U' = r.m.s. value of phase to earth rated voltage $= \dfrac{U_m}{\sqrt{3}}$

U'_m = Peak value of rated phase to earth voltage $= \sqrt{2}\, U'$

Any voltage above U'_m is called switching over voltage U.

Switching overvoltage factor $K = U/U'_m$.

where U = Instantaneous value of overvoltage

U'_m = Peak value of rated phase to ground Voltage $= \sqrt{2}\, U'$

IEC 56-1987 gives the table which gives permissible values of switching overvoltage factor for capacitive current breaking. While testing the circuit-breaker for line charging, cable charging, single capacitor bank breaking current tests, the switching over voltage should be within specified limits.

3.19. REIGNITION AND RESTRIKE

Recall the definition described in the last part of Sec. 3.6; Reignition is the reappearing of arc after arc extinction within one-fourth of a cycle from final current zero. Reignition may occur by chance if the moving-contact travel was too small after arc extinction current zero. The contact gap breaks down and arc reignites without overvoltage. The arc gets quenched at the very next current zero by which time moving-contact should have moved sufficiently away from the fixed-contact to withstand the TRV. The reignition itself is not harmful as it does not give any overvoltage beyond permissible limit.

Restrike is defined as the reappearance of arc after one-fourth cycle from the arc extinction current zero. The phenomenon is explained in sec. 3.14.1. In Capacitor current Breaking, a single restrike gives an overvoltage of about 4 p.u. and a second restrike gives an overvoltage of about 6 p.u. resulting in internal and external flashovers, phase to phase as well as phase to ground. Restrikes were possible with MOCBs and OCBs used for Capacitor Switching. *For Capacitor switching, cable switching, switching of unloaded transmission lines, the restrike-free SF and Vacuum Circuit Breakers are not preferred.*

Summary

The sudden short-circuit in an a.c. system causes a rise in current in the short-circuited phases. The current increases to several times the normal current, during the first quarter cycle. Thereafter the amplitude of the waveform reduces successively, while passing through the sub-transient, trasient, and steady state. The waveform is asymmetrical about the normal zero axis. The value of current at the peak of the first major or current loop is called making current. The r.m.s. value at the intant of contact separation is called breaking current.

The voltage appearing across the circuit-breaker pole after final current zero is called recovery voltage. The recovery voltage containing the high frequency component is called Trasient Recovery Voltage (TRV). TRV tries to restrike the arc. The ability of the circuit-breaker to clear the short-circuit depends upon the rate of rise of dielectric strength of the gap, which should be more than the rate of rise of TRV.

Table 3.5

Recommended values of Maximum Permissible Swithching Overvoltage for Interruption of Capacitive Currents by CB

Rated Voltage of CB rms, ph to ph	*Rated Lightning Impulse withstand voltage*	*Maximum permissible switching overvoltage, phase to earth For line charging breaking current*		*For cable charging capacitor bank and back to back capacitor bank breaking current*	
		Peak value	*Switching overvoltage factor*	*Peak value*	*Switching overvoltage factor*
kV(rms)	*kV(peak)*	*kV(peak)*	*K*	*(p.u.)*	*(p.u.)*
3.6	20	8.8	3	7.3	2.5
3.6	40	13.2	4.5	7.3	2.5
7.2	40	17.6	3	14.7	2.5
7.2	60	26.4	4.5	14.7	2.5
12	60	29.5	3	24.5	2.5
12	75	39.5	4	24.5	2.5
36	145	88	3	73	2.5
36	170	112	3.8	73	2.5
72.5	325	207	3.5	148	2.5
145	550	356	3	297	2.5
145	650	415	3.5	297	2.5
245	850	540	2.7	400	2
245	950	600	3	400	2
245	1050	600	3	400	2
420	1300	790	2.3	688	2
420	1425	895	2.6	688	2
765	1800	1125	1.8	1125	1.8
765	2100	1250	2	1250	2

The rated characteristics of circuit-breaker include: the rated normal current, rated voltage, rated insulation level, rated transient recovery voltage, rated short-circuit breaking current, rated circuit making current, rated operating sequence etc. These ratings are assigned to a circuit-breaker after conducting the type tests. (Ref. Sec. 15.7 for low voltage circuit-breaker).

QUESTIONS

1. Define and discuss the following ratings of a.c. circuit-breakers : — rated short-circuit breaker current, rated short circuit making current.
2. Discuss the following : — two parameter method of defining TRV waveform

   — four parameter method of defining TRV waveform
3. Explain the fault clearing process by illustrating the oscillograph of short-circuit current and transient recovery voltage.
4. Explain the variation of short-circuit current through sub-transient, transient and steady state.
5. Explain the phenomena of transient recovery voltage and its influence on the behaviour of circuit-breaker performance.
6. A three phase alternator of rated line to line voltage of 13.5 kV is connected to a circuit-breaker. The inductive reactance up to the circuit-breaker is 4 ohms per phase. The distributed capacitance upto the circuit-breaker between phase to neutral is 0.2 μF. Determine the following neglecting First Pole to clear factor.