Chapter (4)

Transient recovery voltage (TRV)

1. Introduction

Transient is associated with every change of state of a circuit. Transient recovery voltage thus is the transient across a circuit breaker. Transient recovery voltages are contingent upon the circuit conditions and parameters of the circuit. Thus making it extremely essential to study them for application of circuit breakers.

Generally, circuit breakers in a system are applied based on available short circuit capability at that point in the circuit. But, when circuit is interrupted it results in a TRV, this has deleterious effects on the circuit breaker. TRV manifests in different way depending on circuit configuration, hence the object of this report is to study the various parameters causing and affecting the TRV.

2. Transient Recovery Voltages on Systems

2.1. What is Transient Recovery Voltage?

It is ascertained that TRV is resultant of the change in state of circuit. Thus TRV can be defined as voltage appearing across a circuit breaker after a switching action. Typical of every transient TRV also has high amplitude and high frequency. The figure below shows example of TRV.

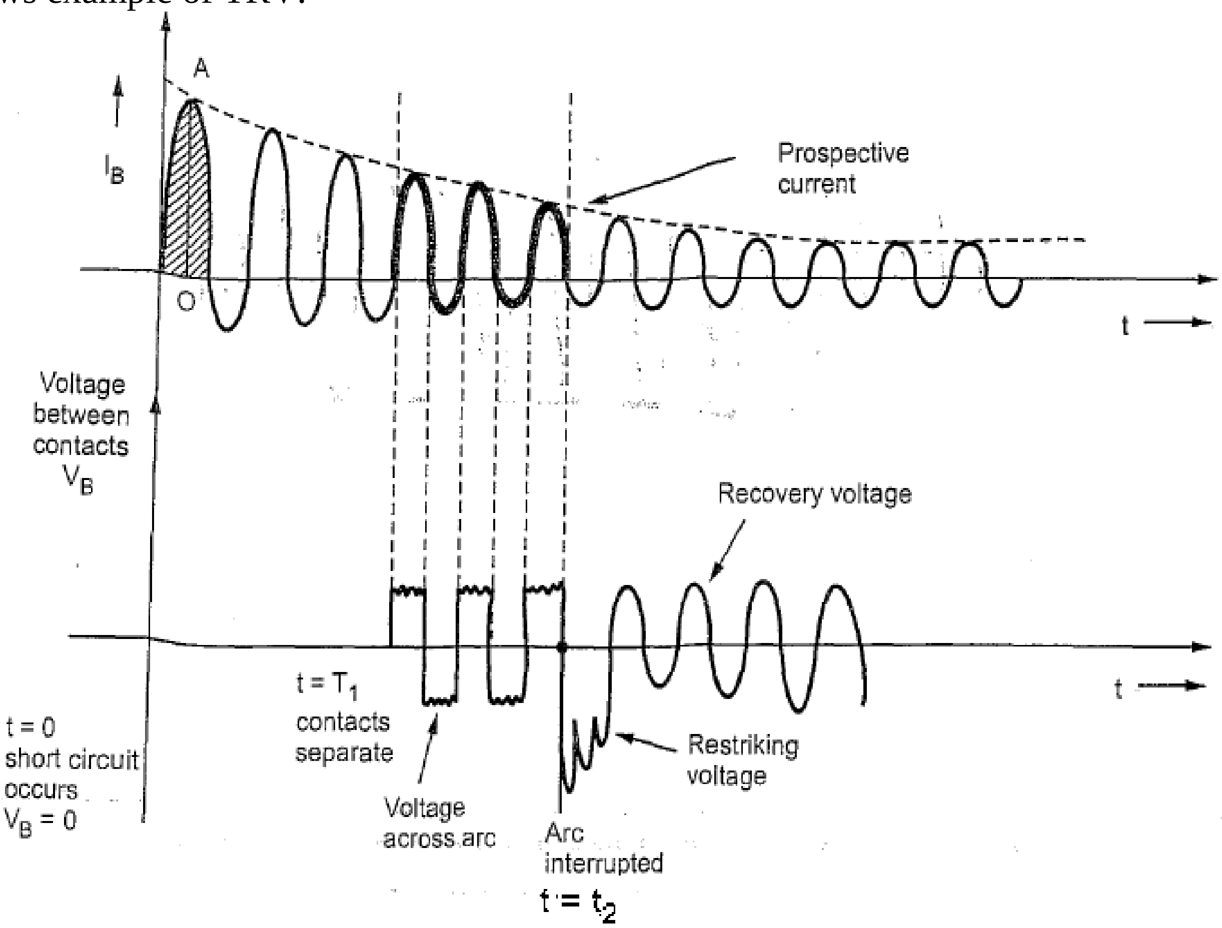

Fig. 4.1 Current and voltage during fault clearing

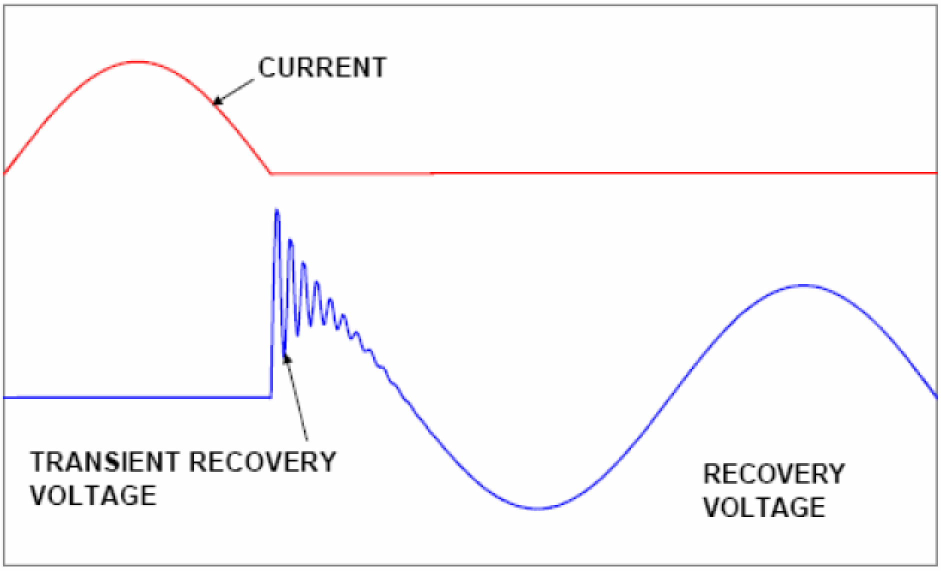

Figure-4.2 Transient Recovery Voltage

TRV is a point by point difference of voltage at the incoming side and at the outgoing side of a circuit breaker. When a circuit breaker interrupts, incoming side or the side to bus or supply is connected tries to return to power frequency voltage level and the outgoing side depending on what is connected also oscillates. The difference between these voltages is recovery voltage.

TRV is associated with every interruption, but the ones resulting because of interruption of fault current are the most ominous TRV. Thus the choice of circuit breakers or introduction of means and methods for safeguarding the circuit and circuit breaker has to be considered.

2.2. Factors affecting TRV

Transient recovery voltage is affected by various parameters of the system. Prominent among them are listed below:-

1. Inductance and capacitance in the system
2. Fault current level of the system at point of study of TRV.
3. Bushing capacitance of circuit breakers, voltage transformers etc
4. Number of transmission lines terminating at a bus and their characteristics impedance.
5. Internal factors of the circuit breaker like the first pole to clear a fault etc.
6. System grounding.

2.3. Types of TRV wave shapes

Transient recovery voltages manifesting across any circuit breaker in a system are seen to have some typical shapes. Wave shapes are classified into types:

1. Cosine: Observed in case of transformer fed or reactor fed faults.
2. Exponential cosine: Observed when transformer fed faults on breaker terminals with transmission lines connected on the incoming side of circuit breaker.
3. Triangular or Saw-tooth wave shape: Observed on line side when short transmission lines are connected.
4. Initial TRV: Observed when bus work of substation is involved.

3. Ratings important for TRV

The above is general rating structure and is provided on nameplate of every circuit breaker. Rating that are important from the point of view of Transient recovery voltages depend on the voltage level it is used at and application. IEEE C37.011 is a application guide for transient recovery voltage for AC high voltage circuit breakers. In addition the to the peak of the recovery voltage the following ratings are referred to

1. Peak TRV in KV
2. Time to Peak of TRV In μs.
3. Rate of Rise of Recovery Voltage (RRRV)

4. Effects of Transient Recovery Voltages on Circuit Breaker

Transient recovery voltages appear on the system for a very short duration of time and assume very high values. These rapid changes have deleterious effects on the devices in the system.

<u>4.1 Insulation Failures</u>

TRV is voltage which appears across the circuit breaker on the system when it interrupts current, and are especially dangerous when short circuits are interrupted. TRV causes the insulation of the circuit breaker to be stressed and can result in breakdown. The classical examples of the breakdown of insulation are external flashover between phase and ground, or between a phase and another. TRV causes the air around to be stressed to higher levels thus resulting in breakdown.

<u>4.2 Re-ignition and Re-strikes</u>

When the circuit breaker is interrupting a fault, it results in arcing in the interrupting medium. During the process of interruption the arcing medium is trying to regain its insulation property. For the interruption to be successful the interrupting medium should withstand this fast rising recovery voltage.

Thus, there is a race in the interrupting medium to go from conducting state to insulating state, with the TRV, if the rate of rise of TRV is more than speed with which the medium returns to insulating state the arcing medium breakdown causing current to continue to flow in the circuit breaker, if speed of medium is higher the interruption is successful. This process of establishment of current is called re-ignition and refers to re-ignition of arc in the circuit breaker.

Re-ignition generally occurs almost immediately after the current zero, is generally because the arc plasma containing conducting ions reestablishes current.

TRV, if it very high will result in the arcing medium which has returned to insulating state to stressed. If this field created across the contacts is very high a dielectric breakdown may take place causing the interrupting medium to become conducting and carry current. This process of establishing current is called restrike. This generally occurs about a half cycle later to the current interruption. This phenomenon occurring internally to the circuit breaker is akin to insulation failure external to the circuit breaker.

5. Calculation of Transient Recovery Voltages of Circuit Breaker

At the rated voltage circuit breakers are expected to interrupt rated short circuit current in a system where the TRV doesn't exceed the rated TRV envelope. System may be grounded or ungrounded.

5.1 Envelope Specification and Calculation

TRV rating of circuit breaker is defined by an envelope of rated withstand capability Parameters that define the envelope are based on the characteristics of actual system. According to the standard various wave shapes are observed for circuit breakers on the system, illustrated in section 3. Applicable envelope of TRV depends on the application and voltage rating of the circuit breaker.

Two envelopes are defined, one for circuit breakers rated 100KV and below and other for above 100KV.

Circuit breaker is generally used in conjunction with transformers and transmission lines. As noted earlier the transformer fed faults are known to produce 1-cosine wave, which is also characteristics of under damped system. Transmission lines, depending upon number of lines in parallel, are known to add damping to the system and hence produce exponential waveform. Thus the two envelopes are:-

1. Two parameter envelope used for circuit breakers rated 100KV and below and for above 100KV, if fault current is less than 30% of rated short circuit current.
2. Four parameter envelope for circuit breakers used above 100KV.

Voltage (E2) can also be calculated using formulae specified in standard and stated as under

$$E_2 = k_a \times k_{pp} \times \frac{\sqrt{2}}{\sqrt{3}} \times V$$

$$E_1 = k_{pp} \times \frac{\sqrt{2}}{\sqrt{3}} \times V$$

k_a : transient amplitude factor

k_{pp} : first pole to clear factor

V : System rated voltage

5.2 Factors affecting Transient Recovery Voltage

Transient recovery voltage appearing across a circuit breaker is affected by various factors like fault current, first pole to clear factor, out of phase switching, system inductance and capacitance etc…TRV may also be affected by the applications a breaker is used for.

5.2.1 Faults Current

Calculation of transient recovery voltage Eq.1,2,4 &6 indicates that all forms of TRV are greatly dependent on the fault current. Short circuit at a point in system depends on the devices paralleled like the transmission lines, transformers etc. It is observed that TRV peak increases and time to peak reduces as short circuit reduces. This also causes the RRRV to increase. Figure below shows the TRV envelopes.

5.2.2 Circuit Parameter

Circuit inductance and capacitance plays a vital role in the TRV peak and time to peak. Eq.1, 2, 4&6Thus the TRV values can be controlled and reduced using the inductance and circuit capacitance. Generally system capacitance is considerably less; hence TRV is controlled by addition of additional surge capacitance.

5.2.3 Out-of-phase Switching

Out of phase switching results in higher values of TRV and is analyzed in a similar way as the generator circuit breaker analysis. Rated values for out of phase switching are specified for 900 phase shift.

5.2.4 First Pole to Clear Factors

First pole to clear factors are a function of the system grounding arrangements. It is defined as ratio, Eq.9.

$$K_{pp} = \frac{V_{IP-60Hz}}{V_{3P-60Hz}} ---(9)$$

$V_{IP-60Hz}$: - Voltage appearing across interrupting pole, when other poles have not interrrupted

$V_{3P-60Hz}$: - Voltage appearing across all poles after interruption

K_{PP} is 1.5 for ungrounded systems and 1.3 for effectively grounded system. First pole to clear factor is seen to be dependent on the zero sequence and positive sequence impedance of the system and is given by [2]

$$K_{pp} = \frac{3X_0}{X_1 + 2X_0} ---(10)$$

For effectively grounded system

$X_0 = 3X_1$ hence $K_{pp} = 1.3$

For ungrounded system

$X_0 >> X_1$ hence $K_{pp} = 1.5$

5.2.5 Applications

TRV depends on the application of circuit breaker. Some important applications are:

1. Transformer fed faults: - Standard capability curve is specified as two parameter curve. Severe TRV conditions may result if the fault is immediately after transformer, without appreciable capacitance in between transformer and circuit breaker. In such cases the TRV peak and RRRV may exceed the values specified in C37.06-2000; in such circumstances values specified in C37.06.1-2000 are used. These values correspond to fast time to peak values.
2. Series Reactor limited faults: - Series reactors are used to limit short circuit current in a line. Use of series reactors on line side can cause high Rate of rise TRV values.
3. Shunt reactor switching: When a shunt reactor is switched circuit breaker interrupts very small currents. This kind of circuit results in load side oscillating with frequency of 1/√LC, L being shunt reactor and C being capacitance associated with it. This can result in very high frequencies sometimes in the range of 1 to 5 KHz.
4. Generator Circuit breakers: - These circuit breakers are required to have special characteristics as these are installed between the transformer and generators. Faults

associated with this can result in TRV values higher than the values ones given inC37.04 and C37.06. For system-source faults these can be 3-5 times higher.

6. Effect of Different Parameters on Transient Recovery Voltage (TRV)

As seen from the previous section, after the final current, zero high frequency transient voltage appears across the circuit breaker poles which is superimposed on power frequency system voltage and tries to restrike the arc. This voltage may last for a few tens or hundreds of microseconds. If the shape of this TRV is seen on the oscilloscope then it can be seen that it may be oscillatory, non-oscillatory or a combination of two depending upon the characteristics of the circuit and the circuit breaker. The waveform is as shown in the Fig. 4.3

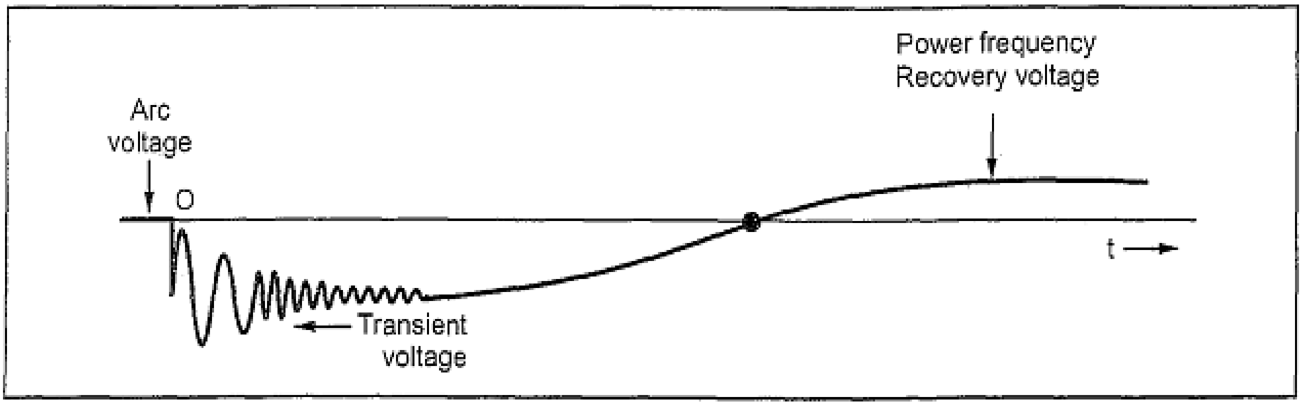

Fig. 4.3 **Shape of transient recovery voltage**

This voltage has a power frequency component and an oscillatory transient component. The oscillatory component is due to inductance and capacitance in the circuit. The power frequency component is due to the system voltage. This is shown in the Fig. 4.4

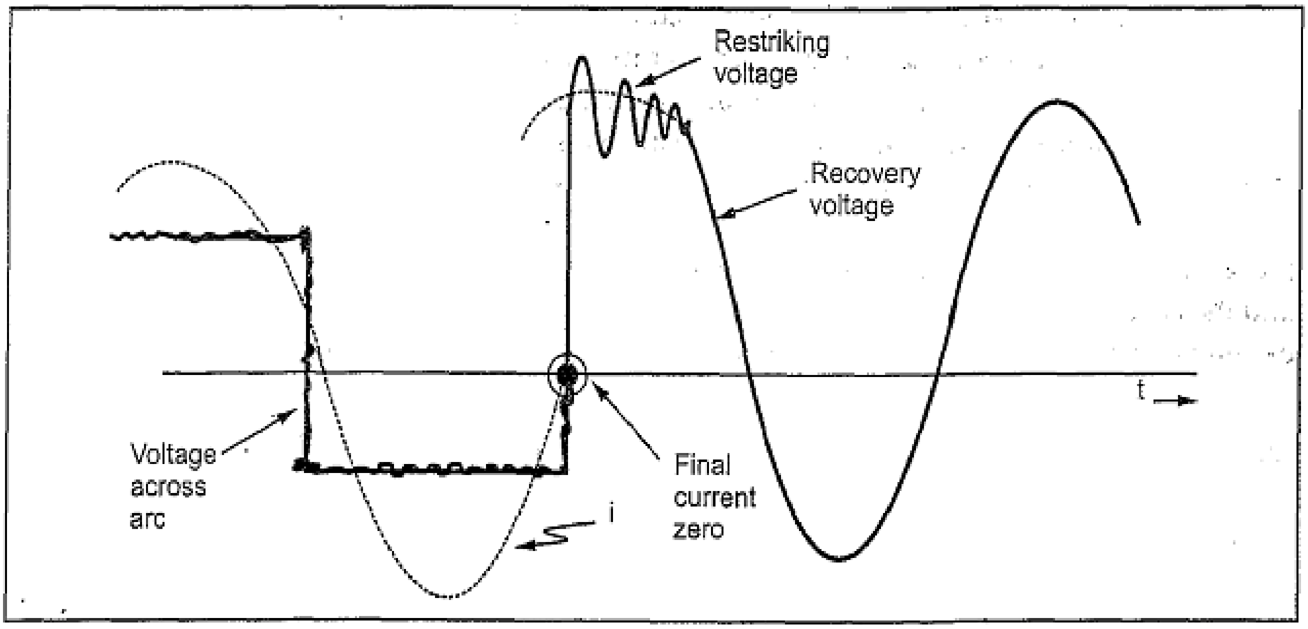

Fig. 4.4 **Voltages after final current zero**

The transient oscillatory component lasts for few microseconds after which power frequency voltage remains. The transient component has frequency given by,

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

where f_n = Frequency of transient recovery voltage
L = Equivalent inductance
C = Equivalent capacitance

6.1 Effect of Natural Frequency on TRV

With increase in the natural frequency the rate of rise of TRV at current zero increases. This is shown in the Fig. 4.5. The rate of rise of transient recovery voltage is represented by slopes of tangents to the three waveforms drawn at different frequencies.

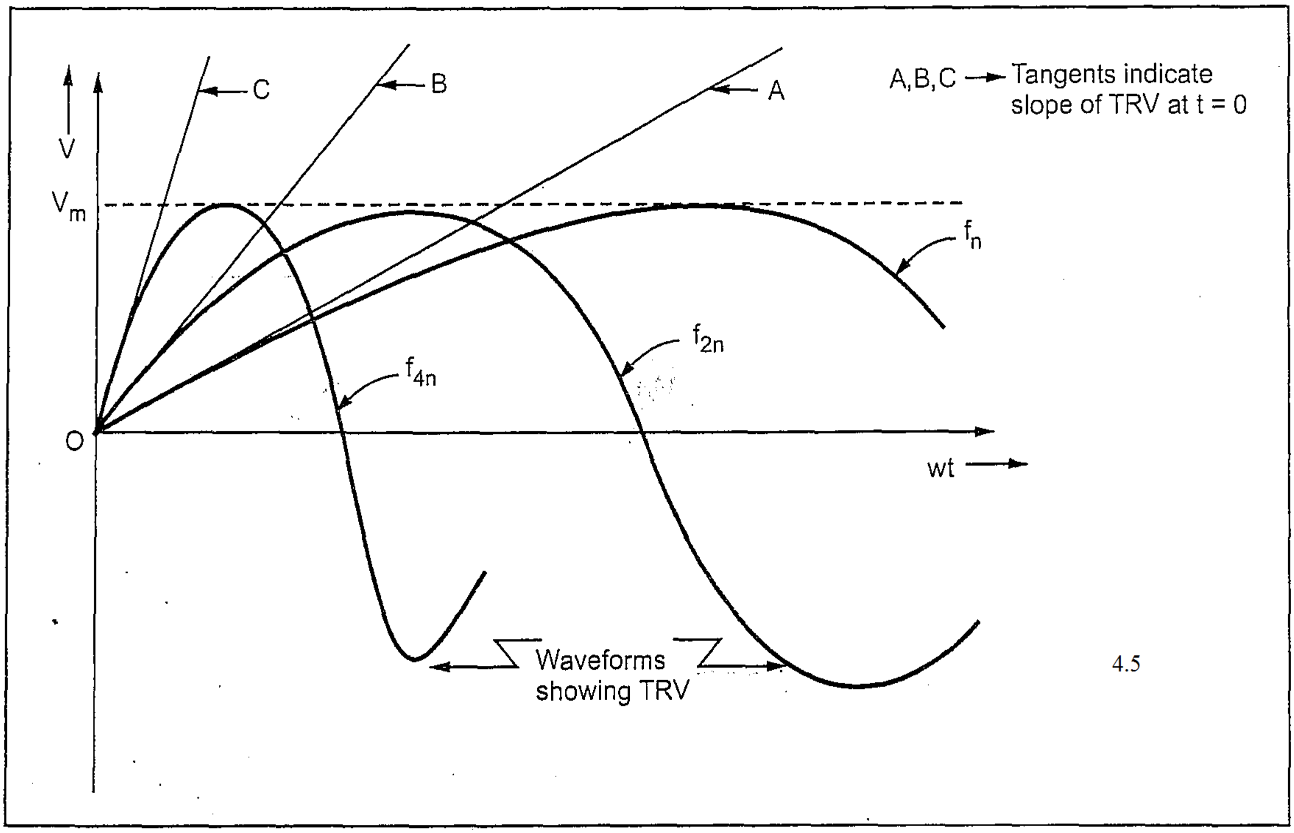

Fig. 4.5 Effect of frequency of TRV

Rate of rise of TRV causes voltage stress on the contact gap which will continue the arc. If the frequency is increased then relatively small time is available for building of dielectric strength of contact gap. Hence increase in frequency causes greater stresses. The rate of rise of TRV is related with the breaking capacity of a circuit breaker. Thus it also means rate of rise of TRV is dependent on natural frequency of TRV. As frequency increases the breaking capacity reduces.

6.2 Effect of Power Factor on TRV

At the instant of final current zero the voltage appearing across the C.B. contacts is affected by the p.f. of the current. At current zero the arc is extinguished. After this power frequency voltage appears across the circuit breaker. The instantaneous value of the voltage at current zero depends on phase angle between the current and voltage.

For unity p.f. load as shown in the Fig. 4.6 both voltage and current are in phase and are zero at the same instant.

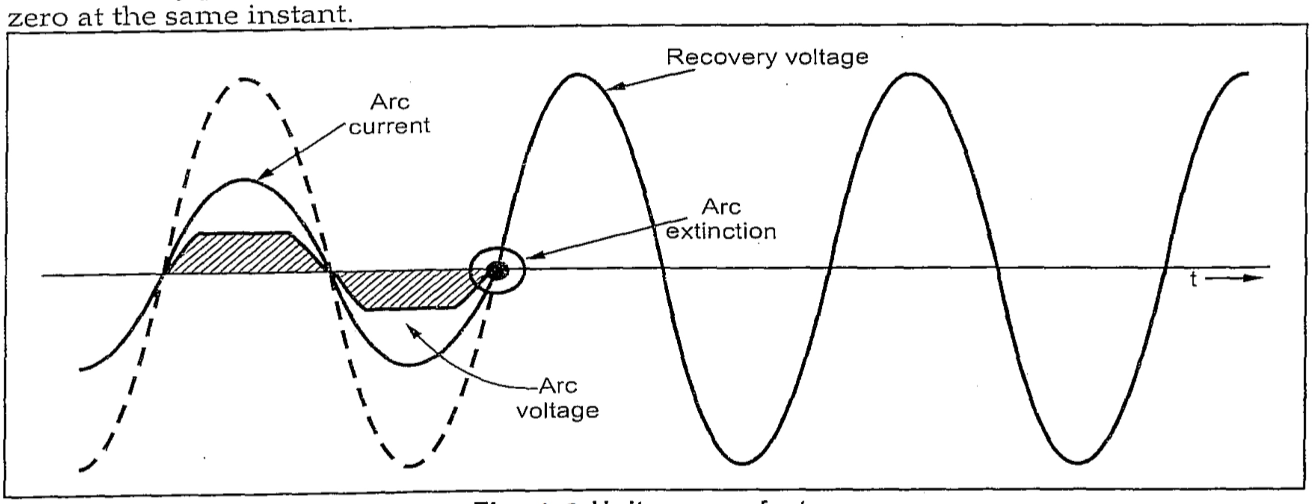

Fig. 4.6 Unity power factor

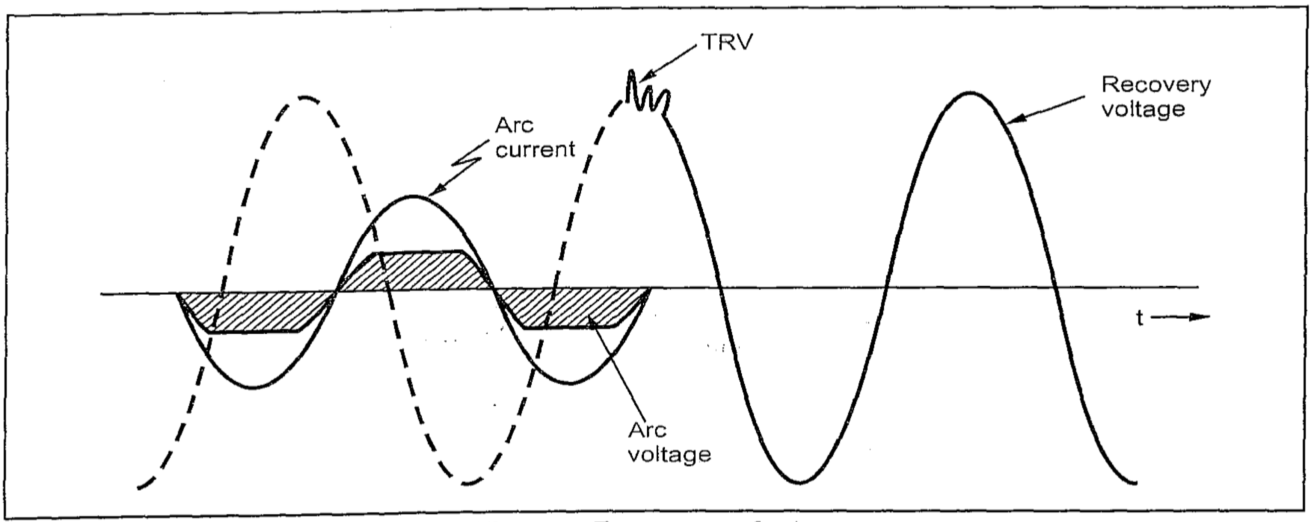

Fig. 4.7 Zero power factor

If we consider zero power factor currents, the peak voltage E_{max} is impressed on the circuit breaker contacts at the current zero instant. This instantaneous voltage gives more transient and provides high rate of rise of TRV. Hence if the p.f. is low then interrupting of such current is difficult.

7. Recovery Voltage

As seen previously it is the voltage having normal power frequency which appears after the transient voltage.

7.1 Effect of Reactance Drop on Recovery Voltage

Before fault is taking place let us consider that the voltage appearing across circuit breaker is V_1. As the fault current increases, the voltage drop in reactance also increases. After fault clearing the voltage appearing say V_2 is slightly less than V_1. The system takes some time to regain the original value.

7.2 Effect of Armature Reaction on Recovery Voltage

The short circuit currents are at lagging power factor. These lagging p.f. currents have a demagnetizing armature reaction in alternators. Thus the induced e.m.f. of alternators decreases. To regain the original value this e.m.f. takes some time. Thus the power frequency component of recovery voltage is less than the normal value of system voltage.

This equation is **expression for restriking voltage**

$$\boxed{e = E_m\left[1-\cos\left(\frac{t}{\sqrt{LC}}\right)\right]} \qquad \dots (A)$$

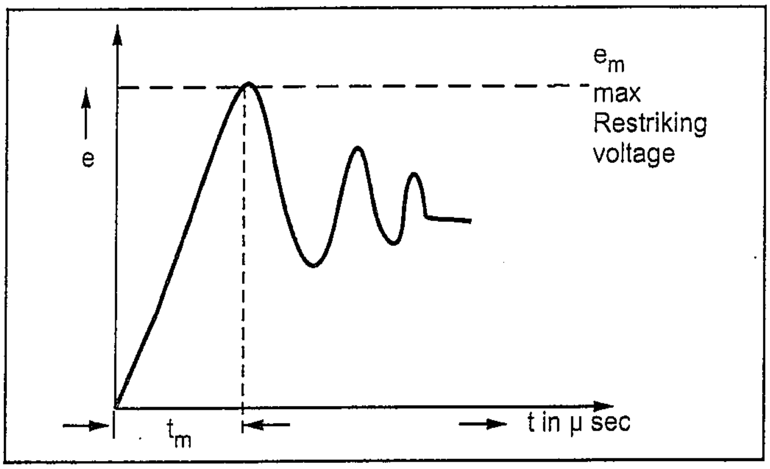

Fig. 4.8

This is an **expression for restriking voltage** in which,

E_m = Peak value of recovery voltage phase to neutral in volts.

t = time in sec.

L = inductance in henries

C = capacitance in farads

e = restriking voltage

First Pole to Clear Factor

The first pole to clear factor is given by,

$$\text{Factor pole to clear factor} = \frac{\text{RMS voltage between healthy phase and faulty phase}}{\text{Phase to neutral voltage with fault removed}}$$

In three phase systems if fault does not involve the earth, the voltage across the circuit breaker pole first to clear is 1.5 times the phase voltage. The arc extinction in the three poles of three phase circuit breakers is not simultaneous as currents are 120° out of phase. In practical systems the recovery voltage of the pole first to extinguish the arc is of the order of 1.2 to 1.5 times of the phase voltage.

If fault involves earth and the neutral is grounded through reactor, the recovery voltage is influenced by the equivalent system reactances.

Thus in 3 phase circuits $K_3 = 1$ if neutral is earthed and fault is also earthed. While $K_3 = 1.5$ if neutral is earthed and fault is insulated or neutral is insulated and fault is earthed.

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

where $V_{ar} = K_1 K_2 K_3 E_m$

K_1 takes into account p.f. effect

$= \sin\phi$

K_2 = takes into account armature reaction effect ≈ 0.9

K_3 = Phase factor or 1st pole to clear factor

= 1 for both neutral and fault grounded.

= 1.5 for any one of the two not grounded.

Expression for Maximum Value of Restriking Voltage E_m and Corresponding Time t_m

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

if 'e' is to be maximum $\frac{de}{dt} = 0$

$$\cos\left(\frac{t_m}{\sqrt{LC}}\right) = -1 \quad \text{where } t = t_m$$

$$\therefore \quad \frac{t_m}{\sqrt{LC}} = \pi$$

$\therefore$ Time at which maximum restriking voltage occurs is,

$$\boxed{t_m = \pi\sqrt{LC}}$$

And peak value of restriking voltage,

$$\boxed{e_m = 2\,E_m}$$

where E_m is equal to active recovery voltage

(i.e. instantaneous value of recovery voltage at current zero).

Expression for RRRV and Maximum RRRV

Now $$\text{RRRV} = \frac{de}{dt} = \frac{d}{dt}\left[E_m\left(\cos\left[\frac{t}{\sqrt{LC}}\right]\right)\right]$$

$$\therefore \quad \boxed{\text{RRRV} = \frac{E_m}{\sqrt{LC}}\sin\frac{t}{\sqrt{LC}}}$$

and $$\boxed{\text{maximum RRRV} = \frac{E_m}{\sqrt{LC}}}$$

when $$\sin\frac{t}{\sqrt{LC}} = 1$$

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

$$\therefore \quad \boxed{t = \frac{\pi\sqrt{LC}}{2}} \quad \text{for maximum RRRV}$$

Frequency of Oscillation of Restriking Voltage (Transient)

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

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

$$\therefore \quad \text{Maximum RRV} = \frac{E_m}{\sqrt{LC}} = 2\pi f_n E_m$$

$$\therefore \quad \boxed{\text{Maximum RRV} = 2\pi E_m f_n}$$

Restriking Voltage Under Various Conditions

The restriking voltage 'e' under various conditions will be,

$$e = V_{ar}\left(1 - \cos\left[\frac{t}{\sqrt{LC}}\right]\right)$$

where V_{ar} active recovery voltage i.e. the instantaneous value of recovery voltage at current zero and V_{ar} can be written as

$$V_{ar} = K_1 K_2 K_3 E_m$$

Here E_m is the peak value of system voltage where,

K_1 is factor which takes into accounts effect of circuit p.f. and $K_1 = \sin\phi$

So if $\phi = 90^\circ$, $K_1 = 1$

K_2 is factor which accounts effect of armature reaction on recovery voltage.

K_3 is phase factor or first pole to clear factor.

$$= 2.66682 \times 10^{5}$$

<u>Average RRRV,</u>

$$\text{Average RRRV} = \frac{\text{Maximum restriking voltage}}{\text{Time to reach maximum restriking voltage}}$$

Ex. 1. : *A 50 Hz generator has e.m.f. to neutral 7.5 kV (r.m.s.). The reactance of generator and the connected system is 4 Ω and distributed capacitance to neutral is 0.01 μF with resistance negligible . Find,*

i) maximum voltage across the circuit breaker contacts

ii) frequency of oscillations

iii) RRRV average upto first peak of oscillations.

Sol. :

$$X = 2\pi fL = 4\ \Omega$$

$$L = 4 / 2\pi \times 50 = 0.0127\ \text{H.}$$

$$E_m = \sqrt{2} \times 7.5 = 10.606\ \text{kV}$$

1) Maximum voltage $= 2 \times E_m$

$$= 2 \times 10.606 = 21.212\ \text{kV}$$

2)

$$f_n = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{0.0127 \times 0.01 \times 10^{-6}}}$$

$$= 14.1227\ \text{kHz}$$

3) Maximum time to reach maximum voltage is,

$$t_m = \pi\sqrt{LC} = \frac{1}{2f_n} = \frac{1}{2 \times 14.1227 \times 10^3}\ \text{sec}$$

$$\therefore \text{Average RRRV} = \frac{\text{Maximum voltage}}{t_m}$$

$$= \frac{21.212}{[1/(2 \times 14.1227 \times 10^3)]}$$

$$= 0.599\ \text{kV}/\mu\ \text{sec}$$

Example 2. : *In short circuit test on a 3 pole, 132 kV circuit breaker, the following observations are made p.f. of fault 0.4, recovery voltage 0.9 times full line value, the breaking current symmetrical, frequency of oscillations of restriking voltage 16 kHz. Assume neutral is grounded and fault is not grounded. Determine average RRRV.*

Solution :
$$e = V_{ar}\left[1-\cos\left(\frac{t}{\sqrt{LC}}\right)\right]$$

where $V_{ar} = K_1 K_2 K_3 E_m$

K_1(takes into account p.f. effect) $= \sin\phi$

K_2 (takes into account armature reaction effect) ≈ 0.9

K_3 (Phase factor or 1st pole to clear factor)

$= 1$ for both neutral and fault grounded

$= 1.5$ for any one of the two not grounded.

In the problem,

$$K_1 = \sin\phi = \sin[\cos^{-1} 0.4] = 0.9165$$

$$K_2 = 0.9 \quad K_3 = 1.5$$

Peak value of voltage i.e. line to ground

$$E_m = \frac{132}{\sqrt{3}} \times \sqrt{2} = 107.77 \text{ kV}$$

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

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

$$= 2\pi \times 16 \times 10^3$$

$$= 1 \times 10^5$$

Time to reach maximum restriking voltage

$$\text{Maximum } t_m = \pi\sqrt{LC} = \frac{\pi}{1\times10^5}$$

Maximum restriking voltage,

$$= 2V_{ar}$$

$$= 2K_1 K_2 K_3 E_m = 2 \times 0.9165 \times 0.9 \times 1.5 \times 107.77 \times 10^3$$

$$= 2.66682 \times 10^5 \text{ V}$$

Average RRRV,

$$\frac{\text{Maximum restriking voltage}}{\text{Time to reach maximum restriking voltage}} = \frac{2.66682\times10^5}{\pi/1\times10^5}$$

$$= 8.48 \times 10^9 \text{ V/sec} = 8.48 \times 10^6 \text{ kV/sec} = 8.48 \text{ kV/}\mu\text{sec}$$

Recloser Type	PVDR	PVDR
Rated Maximum Voltage	15.5kV	27.0kV
Nominal Voltage	15.5kV	27.0kV
Frequency	60Hz	60Hz
Low Frequency Withstand		
60Hz dry for 1 minute	50kV	60kV
60Hz wet for 10 seconds	45kV	50kV
Fullwave Withstand - B.I.L.	110kV	125kV
Continuous Current Rating @ 60Hz	200A thru 1120A	200A thru 1120A
Standard Duty Cycle	0 + 0 sec + CO + 5 sec + CO	0 + 0 sec + CO + 5 sec + CO
Interrupting Time	5 cycles (3 cycles optional)	5 cycles
Closing Time	4.5 cycles	4.5 cycles
Rated Short Circuit (RMS)	2kA thru 16kA	2kA thru 16kA
Close and Latch Rating		
RMS Asymmetrical	3kA thru 26kA	25.6kA
Peak 5kA thru	43kA	42.5kA
3 Second Short Time Currect Rating (RMS)	2kA thru 16kA	16.0 kA
Reclosing Time	5 or 3 seconds	5 or 3 seconds
Permissible Tripping Delay	2 seconds	2 seconds
Capacitance Current Switching		
General Purpose Duty		
Line Charging Current	2A	2A
Isolated Cable Charging Current	250A	250A
Isolated Capacitor Bank Rating	250A	250A
Transient Recovery Voltage Peak	29kV	50.5kV
Time to Crest of Transient Recovery Voltage	36 microseconds	52 microseconds
Number of Operations		
Load Current Switching	2500 Before Servicing	2500 Before Servicing
Full Fault Unit Operations	18 Before Servicing	18 Before Servicing
Control Voltage	DC: 48V, 125V, 250V AC: 120V, 240V (60Hz)	DC: 48V, 125V, 250V AC: 120V, 240V (60Hz)

Circuit Breaker Nameplate Catalogue