Unit-IV Theory of Arc Quenching.

Ionization Of gases:-

In circuit breakers, the contact space is ionized by the Following ways.

Thermal ionization:-

* At normal temperature, molecules of gas are moving at various velocities in various directions & possess kinetic energy as $\frac{1}{2} Mv^2$.
* With increase in temperature, the molecules break up in simpler Form as atoms.
* At high temperature, more & more collision takes place which will produce free electrons, thus produces ionization by heat is called thermal ionization.

Thermal emission From surface of contacts:-

* with the separation of contacts in circuit breakers there decreases the area of contact which will increase the current density & consequently the temperature of the surface increases & will cause emission of electrons which is called thermal electron emission.

Ionization by collision:-

* Any particle (atom, molecule or electron) at higher velocity may strike another particle so that energy of moving particle is imparted to other one. This energy is sufficient to remove electrons from atoms.

Secondary Emission at contact surface:-

under the strong influence of electric field between the contacts, the electrons move from one contact to other producing emission from contact surface.

Field emission

As the contacts open, the voltage gradient at the contact surface is high which is sufficient to remove electrons from the surface of electrodes. It causes the breakdown of gas. This is called Field emission.

Photo emission:-

The electron emission from contact surface due to incident of light energy is called Photo emission.

Initiation of Arc:-

There must be some electrons for initiation of an arc, when circuit breaker contacts starts separating from each other. Electrons are emitted by two methods.

1. By high voltage gradient at the cathode, resulting in field emission.
2. By rise of temperature, resulting in thermionic emission.

Maintenance of an arc:-

The electrons while travelling towards anode collide with another electrons to dislodge them & thus the arc is maintained. The ionizing is facilated by

1. High temperature of the medium around the contacts due to high current densities. Thus the kinetic energy gained by moving electrons is increased.
2. The increase in kinetic energy of moving electrons due to voltage gradient which dislodge more electrons from neutral molecules.
3. The separation of contacts of circuit breaker increases the length of path which will increase the neutral molecules. This will decrease the density of gas which will increase free path movement of the electrons.

Deionization:-

It is an important process as it supports Arc extinction. It occurs in the following ways:-

Recombination:-

If a gas contains positive ions & electrons, then there is tendency between them to combine & form a neutral atom. This is called recombination. This wi' asist arc extinction.

Diffusion:-

- The electrons from high, ionized space diffuse to the surrounding weakly ionized space which is an important process in building up dielectric strength.

Conduction of Heat:-

Particles in high temperature travel to the space at low temperature. Thus kinetic energy is removed from the space which is ionized between the contacts.

Arc Extinction:-

It is essential that arc should be extinguished as early as possible. The two methods of Arc Extinction are:

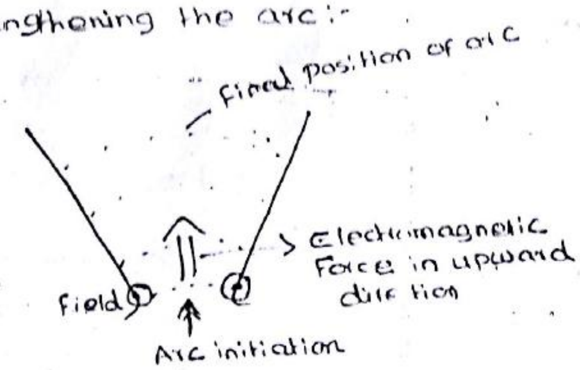
1. High Resistance Method
2. Low Resistance method of current zero method.

1. High Resistance Method:-

* In this method, the arc resistance is increased with time. This will decrease the current to such a value which will be insufficient to maintain the arc. Thus the arc is interrupted & the arc is extinguished. This method is employed only in dc circuit breakers.

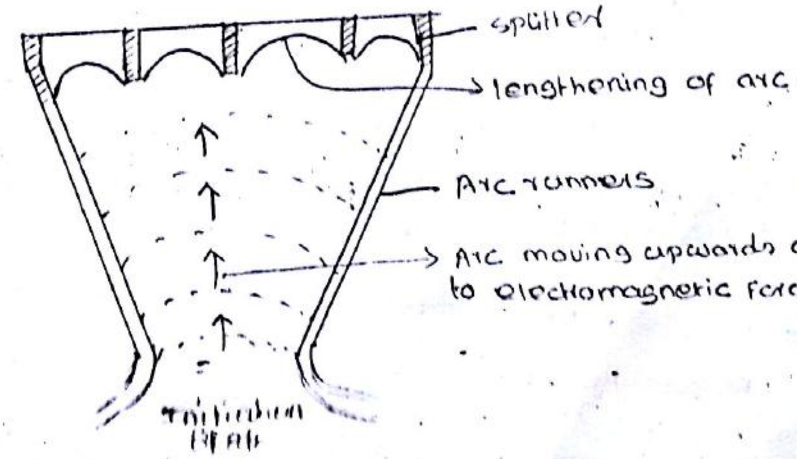
The resistance of the arc is increased by lengthening the arc, cooling the arc, reducing the cross-section of the arc & splitting the arc.

a) Lengthening the arc:-



- In this method, arc length is increased by using arc runners which are horn like blades of conducting material. The arc runners are connected to arcing contacts & it is in the shape of letter 'V'. The arc is initiated at the bottom & blows upwards due to electromagnetic force. Due to this arc length increases & consequently arc is extinguished.

b) splitting of Arc:-



In this method, the enlongation of arc is done & the arc is split using arc splitters which are specially made plates of resin bonded fibre glass. These plates are placed in perpendicular path to arc so that it will be pulled towards it by electromagnetic force.

When the arc is pulled upwards, it gets enlongated then splited & cooled due to which it gets extinguished.

c) Cooling of Arc:-

The recombination of ionized particles can be done by cooling the arc which removes heat from the arc. This is done by bringing the arc in contact with cooled air. Due to cooling the arc diameter decreases which will increase its resistance. This will help in arc extinction.

2. Low Resistance or zero point Extinction:-

* This method is used in a.c arc interruption.
* The current becomes zero two times in a cycle. so at earch current zero point, the arc vanishes for small instant & again it appears.
* In a.c circuit breakers, the arc is interrupted at current zero point.
* The space between the contacts is deionized quickly if there is fresh unionized medium such as oil or fresh air or SF_6 gas between the contacts at the current zero point. This will make dielectric strength of the contact space to increase such that arc will be interrupted & discontinued after current zero.
* This action produces high voltage across the contacts which is sufficient to reestablish the arc Thus the dielectric strength must be build more than the restriking voltage for faithful interruption of arc. Then the arc is extinguished at next current zero.
* While designing a circuit breaker, care is taken so as to remove the hot gases from the contact space immediately after the arc, so that it can be filled by fresh dielectric medium having high dielectric strength.

In summary, we can say that the arc extinction process is divided into 3 parts:

1. Arcing phase
2. current zero phase
3. Post arc phase.

In <u>arcing phase</u>, the temperature of contact space is increased due to the arc. The heat produced must be removed quickly by providing radial & axial flow to gases. The arc cannot be broken abruptly but its diameter can be reduced by the passage of gas over the arc.

When a.c current wave is near its zero, the diameter of the arc is very less & consequently arc is extinguished. This is <u>current zero phase</u>.

Now inorder to avoid the reestablishment of arc, the contact space must be filled with dielectric medium having high dielectric strength. This is <u>post arc phase</u> in which hot gases are removed & fresh dielectric medium is introduced.

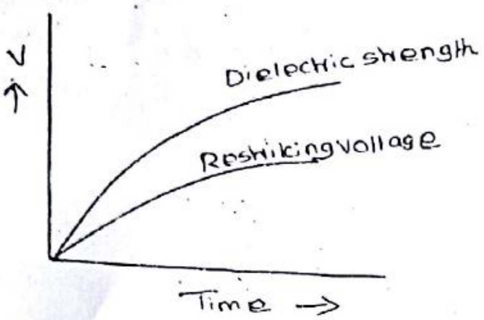
Arc Interruption theories:-

There are two main theories explaining current zero interruption.

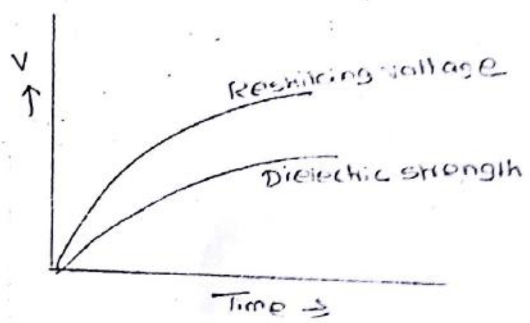
1. Recovery Rate theory or slepian's theory
2. Energy balance theory or cassie's theory

Slepian's theory:-

* slepian described the process as a race between the dielectric strength & restriking voltage.
* The arc is a column of ionised gases.
* To extinguish the arc, the electrons & ions are to be removed from the gap immediately after the current reaches a natural zero.
* Ions & electrons can be removed either by recombining them into neutral molecules (or) by sweeping them away by inserting insulating medium (gas or liquid) into the gap.
* The arc is interrupted if ions are removed from the gap at a rate faster than the rate of ionisation.
* In this method, the rate at which the gap recovers its dielectric strength is compared with the rate at which the restriking voltage (transient voltage) across the gap rises.
* If dielectric strength increases more rapidly than the restriking voltage, the arc is extinguished.
* If the restriking voltage rises more rapidly than the dielectric strength, the ionisation persists & breakdown of the gap occurs, resulting in an arc for another half cycle.



Arc extinguishes



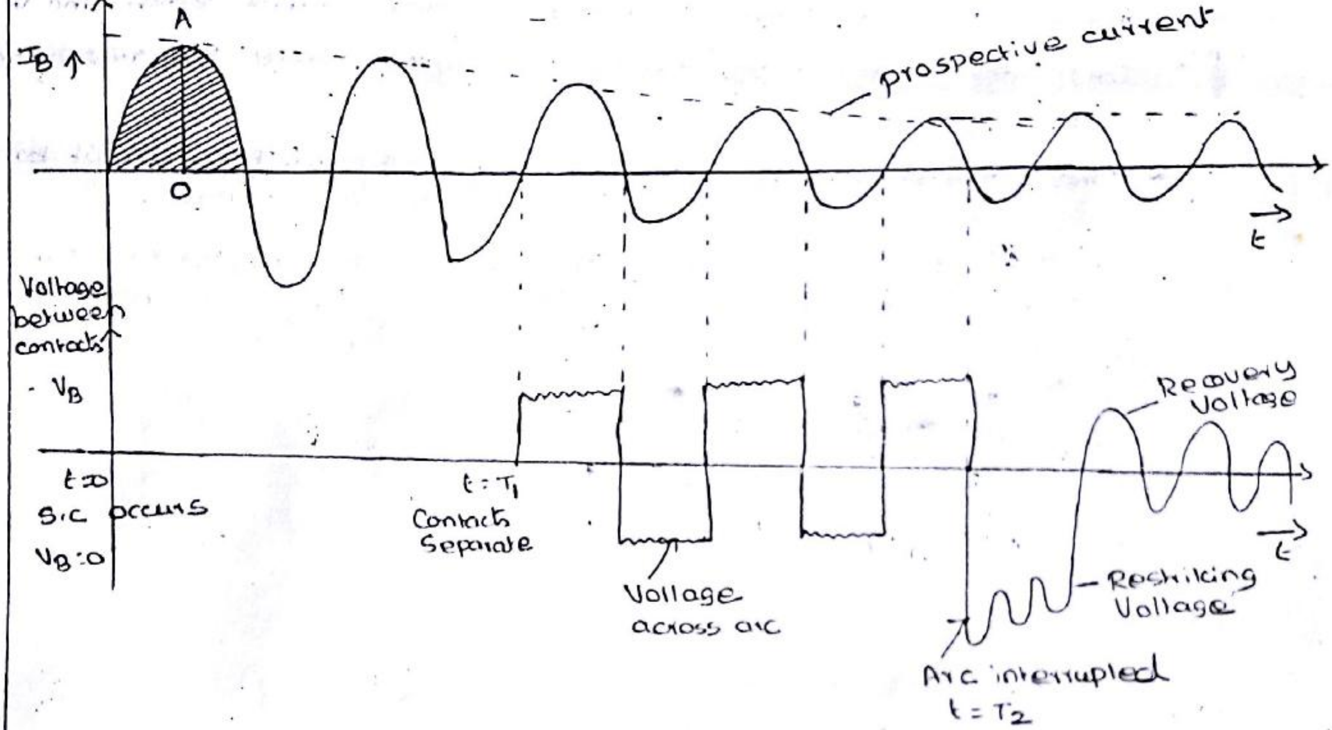
Arc does not extinguishes

Energy balance theory :-

* The space between the contacts contains some ionised gas immediately after current zero & hence it has a finite post-zero resistance.
* At the current zero moment, power is zero because restriking voltage is zero.
* When the arc is finally extinguished, power again becomes zero, the gap is fully deionised & the resistance is infinitely high.
* In between these two limits, first the power increases & reaches a maximum value, then decreases & finally reaches zero value.
* Due to the rise of restriking voltage and associated current, energy is generated in the space between the contacts.
* That energy appears in the form of heat.
* The circuit breaker is designed to remove this generated heat as early as possible by cooling the gap, giving a blast of air or flow of oil at high velocity & pressure.
* If the rate of removal of heat is faster than the rate of heat generated, the arc is extinguished.
* If the rate of heat generation is more than the rate of heat dissipation, the space breaks down again resulting in an arc for another half cycle.

Current Interruption in A.C. Circuit Breakers

* A.c circuit breakers generally employ zero point interruption technique.
* Let us consider an alternator on no load to which a circuit breaker is connected. The circuit breaker is in open position with its other side short circuited.
* When the voltage of phase B with respect to neutral is zero, the circuit breaker is closed. Under this condition the "B" phase current will have maximum d.c. component & its current waveform will be unsymmetrical about normal zero axis.



* The current is zero before t=0 as the alternator is on no load.
* The short circuit is applied at t=0 & current increases to very high value (10 to 25 times the load current) during first quarter cycle.
* The peak of first current loop which is the maximum instantaneous value of current during short circuit is OA. It is called making current which is expressed as kA peak.
* Circuit breakers will open its contact after few cycles say $t = T_1$. The rms value of short circuit current at that instant of contact separation is called breaking current.
* When circuit breakers contacts separate, an arc is struck between the contact & the arc current varies sinusoidally for few cycles. At $t = T_2$, the arc [illegible] interrupted as the dielectric strength of arc space builds sufficient [illegible] the [illegible] the arc will be [illegible]

* With Voltage waveform, before the instant $t=0$, the contacts are closed, so the voltage between them is zero. At the instant $t=T_1$, the contacts starts separating & the voltage across them starts increasing. This voltage is the drop across the arc.

* The current & voltage across arc are in phase as the arc is resistive in nature.

* Due to increased arc resistance the voltage across the contacts increases in the next cycle. Finally at $t=T_2$, the arc is extinguished.

* A high frequency transient voltage appears across the contacts which is superimposed on power frequency voltage. This high frequency voltage tries to restrike the arc. Hence it is called Restriking Voltage (or) Transient Recovery Voltage. It is responsible for restriking of arc.

* The power frequency system voltage between the circuit breaker contacts after arc extinction is called Recovery Voltage.

* The prospective current shown in the waveform may be defined as the current that would flow in the circuit if circuit breakers were replaced by solid conductor.

Transient Recovery Voltage :-

* It has an effect on the behaviour of circuit breaker. This is the voltage which appears between the contacts immediately after final arc interruption.

* This causes high dielectric stress between the contacts.

* If the dielectric strength of the medium between the contacts does not build up faster than the rate of rise of the transient recovery voltage, then the breakdown takes place which will cause restriking of arc.

* Thus it is very improtant that the dielectric strength of the contact space must build very rapidly, so that the interruption of current by the circuit breaker takes place successfully.

* The rate of rise of transient voltage depends on circuit parameters & type of switching duty involved.

* The rate of building up of dielectric strength depends on the effective design of the interrupter & the circuit breaker.

Reignition :-

* If circuit breaker is designed to break the capacitive currents, while opening the capacitor banks, there may appear a high voltage across the contacts which can cause reignition of the arc after initial arc extinction.

* Thus if contact space breaks down within a period of one fourth of a cycle from initial arc extinction, the phenomenon is called Reignition.

* If moving contacts of circuit breakers move a very small distance from the fixed contacts, then reignition may occur without overvoltage.

* The arc gets extinguished in the next current zero by the time the moving contacts should be moved by sufficient distance from fixed contacts.

* This reignition is not harmful as it will not lead to any overvoltage beyond permissible limits.

Restrike:-

* If the breakdown occurs after one fourth of a cycle, the phenomenon is called Restrike.

* In this high voltage appears across the circuit breaker contacts during capacitive current breaking.

* In successive restrikes, voltage will goes on increasing which may lead to damage of circuit breakers.

* Thus the circuit breakers used for capacitors should be free from Restrike (or) they should have adequate rating.

Effect of Different parameters on Transient Recovery Voltage (TRV)

* After the final current zero, high frequency transient voltage appears across the circuit breaker poles which is superimposed on power frequency system voltage & tries to restrike the arc.

* It will last for a few tens or hundreds of μsec.

* Shape of TRV may be oscillatory or non-oscillatory or a combination of two depending upon the characteristics of the circuit & C.B.

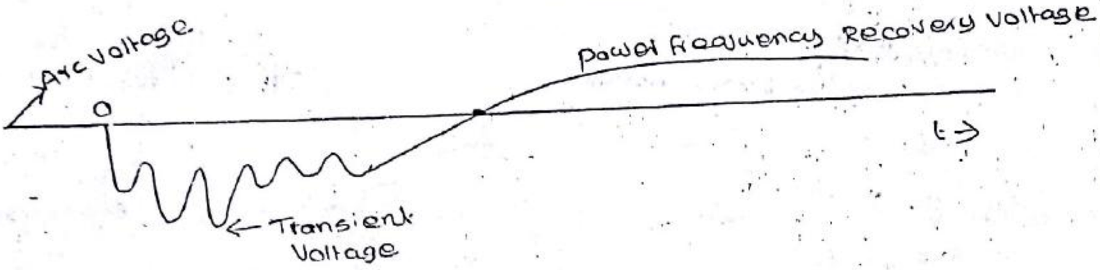
* This transient voltage has a power frequency component & an oscillatory transient component.

* The power frequency component is due to system voltage.
* The oscillatory component is due to L & C in the circuit.
* The transient oscillatory component lasts for few μsec after which power frequency voltage remains.
* The transient component has frequency given by

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

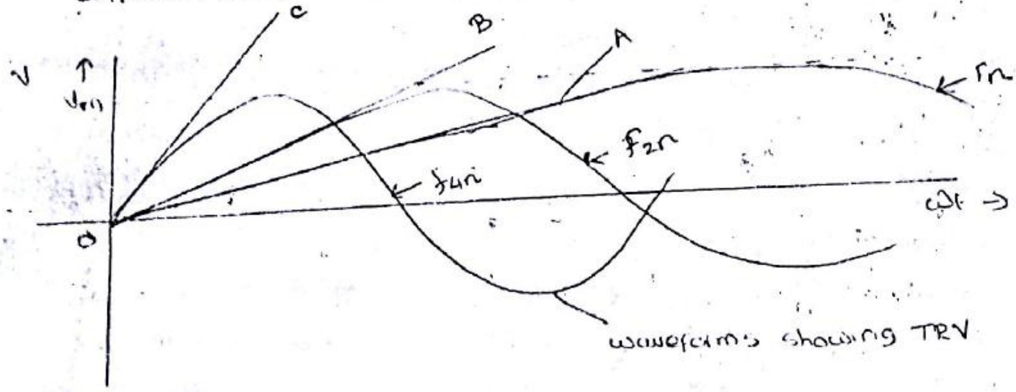
where f_n - frequency of transient recovery voltage
L - Equivalent inductance
C - Equivalent capacitance.

Shape of transient recovery voltage



Effect of Natural frequency on TRV :-

* With increase in natural frequency the rate of rise of TRV at current zero increases.
* The rate of rise of transient recovery voltage is represented by the slopes of the tangents to the 3 waveforms drawn at different frequencies.



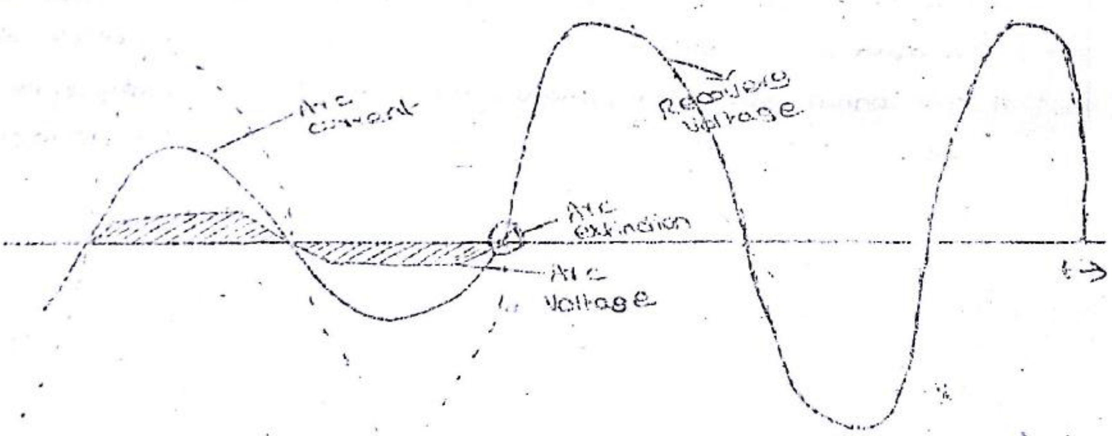
A, B, C → Tangents indicate slope of TRV at t = 0.

* Rate of Rise of TRV causes voltage stress on the contact gap which will continue the arc.
* If frequency is increased, then relatively small time is available for building of dielectric strength of contact gap. Hence increase in frequency causes greater stresses.

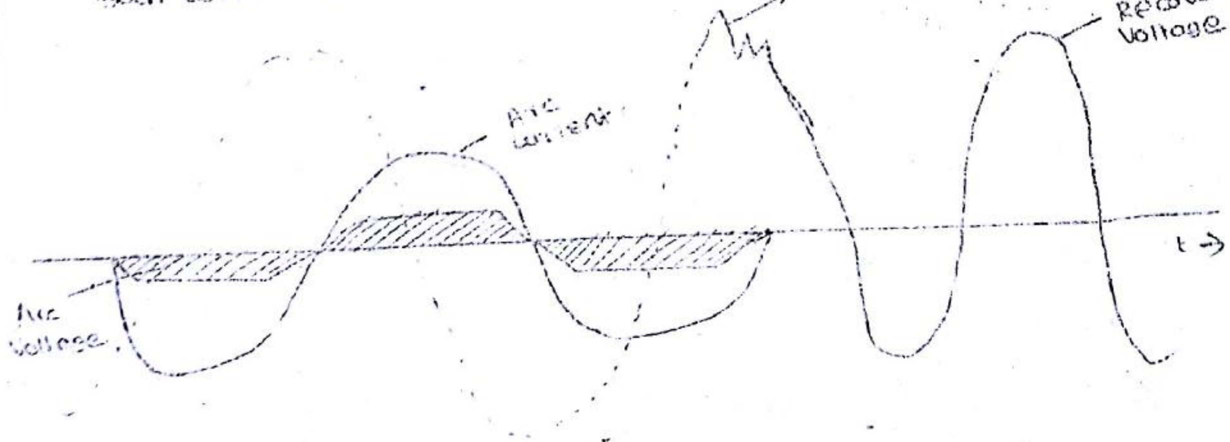
* The rate of rise of TRV is related with the breaking capacity [illegible] of TRV is dependent [illegible]
* As natural freq of TRV is increasing, [illegible] the breaking capacity decreases.

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 recovery voltage appears across the circuit breaker.
* The instantaneous value of the voltage at current zero depends on phase angle between the current & voltage.
* For unity P.f load, both voltage & current are in phase & are zero at the same instant.



* For zero powerfactor currents, the peak voltage Emax is impressed on the C.B contacts at the current zero instant.
* This instantaneous voltage gives more transient & provides high rate of rise of TRV. Hence if the p.f is low, then interrupting of such current is difficult.



Recovery Voltage:-

It is the voltage having normal power frequency which appears after the transient voltage.

Effect of Reactance Drop on Recovery Voltage:-

* Before fault occurs, the voltage appearing across the C.B is V_1.
* Due to fault, the fault current increases, the voltage drop in reactance also increases.
* After fault clearing, the voltage appearing across the C.B is V_2.

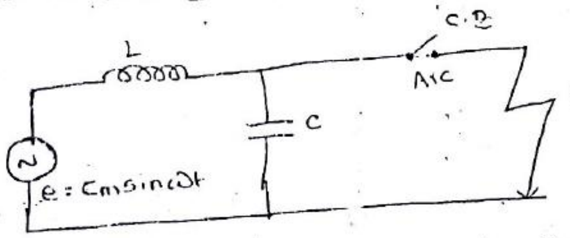
$$V_2 < V_1$$

* The system takes some time to regain to its original value.

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.

Single Frequency Transient:-



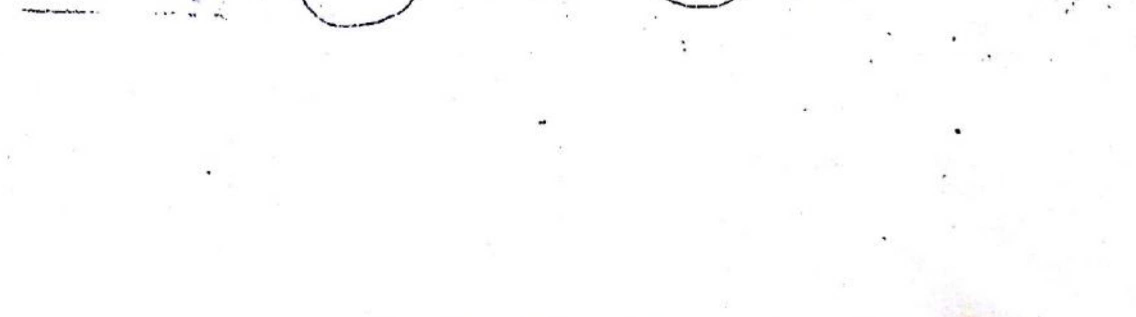
This circuit produces the single frequency restriking voltage transient.

The natural frequency of oscillation is given by

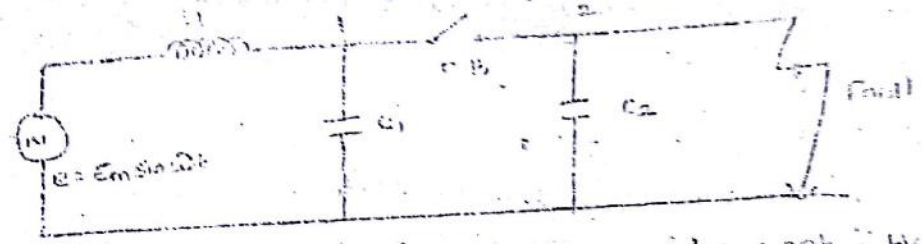
$$f_n = \frac{1}{2\pi\sqrt{LC}}$$

L - inductance in henry
C - capacitance in farads.

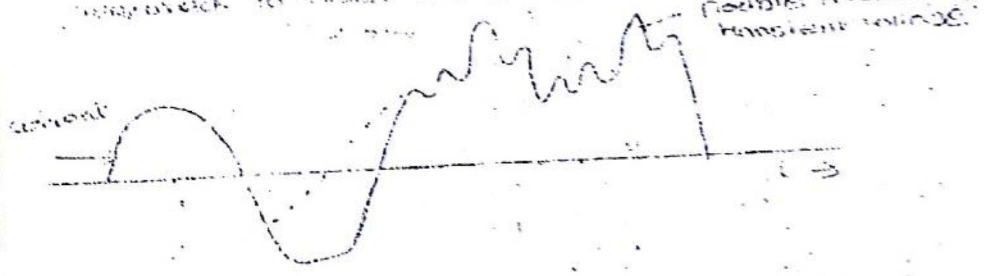
Depending upon the values of L & C, the frequency ranges from 10 Hz to 10 kHz.



Double Frequency Transient :



* This circuit produces double frequency transient. Here L & C are on both sides of C.B.
* The points 1 & 2 are equipotential points before clearing the fault.
* After arc extinction there will be two circuits which may oscillate at their own natural frequencies & thus a composite double frequency transient appears across C.B.
* The circuit configuration, the type of fault & the type of neutral earthing are the important factors which will decide the frequency, rate of rise & peak value of the TRV
* The TRV curve is defined by specifying the peak value & time required to reach the same.



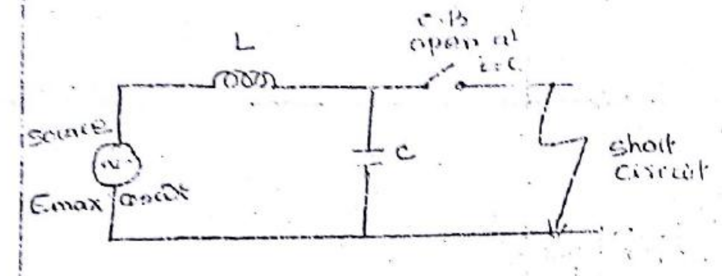
Definition of Rate of Rise of TRV:

The Rate of Rise of restriking Voltage (RRRV) will represent the rate at which transient recovery Voltage is increasing. It is expressed in Volts/μsec. The RRRV is dependent on system parameters.

$RRRV = \frac{de}{dt}$ volts/μsec with e as restriking voltage in volts.

The maximum instantaneous value attained by the restriking voltage is called peak restriking voltage.

The peak value of TRV, time to reach the peak, frequency of TRV & initial rate of rise are some of the important properties of TRV.



L - Total inductance between C.B & source

c - capacitance to earth of the circuit.

circuit resistance is neglected.

* A short circuit is applied directly at the terminals of C.B, remote from source.

Initially C.B is closed & at that time : current flowing through it is 'i'

$$i = \frac{E_m}{\omega L}\cos(\omega t - 90^\circ)$$

$$i = \frac{E_m}{\omega L}\sin\omega t$$ (the effect of 'c' can be neglected as it is short circuited by the breaker switch)

When C.B is opened, then if current is to be interrupted this can be simulated by assuming a cancelling current equal & opposite to original current, being injected at C.B.

The voltage necessary to cause this current is then the voltage that appears across C.B contacts immediately after interruption.

Looking at circuit from the breaker terminals L & C appear in parallel & the equation of cancelling current is

$$i = \frac{1}{L}\int e\,dt + c\frac{de}{dt} \quad \text{— (1)}$$

where e - Voltage across breaker terminals nothing but restriking voltage.

Differentiating eqn (1)

$$\frac{di}{dt} = \frac{e}{L} + c\frac{d^2e}{dt^2} \quad \text{— (2)}$$

The solution of 'e' will thus depend on the current & if interruption takes place at current zero (ie) when t=0 then,

$$i = \frac{E_m}{\omega L}\sin\omega t$$

& after opening of C.B

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

$$= \frac{E_m}{L}\cos\omega t \quad \text{at } t = 0$$

[illegible] this in eqn (2)

$$\frac{E_m}{L}\cos\omega t = \frac{e}{L} + c\frac{d^2e}{dt^2}$$

This is standard equation & solution of this equation is

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

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.

Expression for maximum value of restriking voltage e_m & corresponding time t_m.

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

If 'e' is to be maximum,

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

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

∴ Time at which maximum restriking voltage occurs is,

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

& Peak value of restriking voltage,

$$e_m = 2E_m$$

where E_m is equal to active recovery voltage (i.e) instantaneous value of recovery voltage at current zero.

Expression for RRRV & maximum RRRV

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

$$RRRV = \frac{E_m}{\sqrt{LC}}\sin\frac{t}{\sqrt{LC}}$$

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

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

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

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

Frequency of oscillation of Restriking voltage (Transient)

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

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

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

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

Restriking Voltage under Various conditions

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

where V_{ar} - active recovery voltage i.e) the instantaneous value of recovery voltage at current zero &

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

E_m - peak value of system voltage

K_1 - Factor which accounts for the effect of circuit p.f & $K_1 = \sin\phi$

K_2 - Factor which accounts for the effect of armature reaction on recovery voltage.

K_3 - phase factor or First pole to clear factor.

First pole to clear factor:

$$\text{First pole to clear factor} = \frac{\text{R.M.S voltage between healthy phase \& faulty phase}}{\text{Phase to neutral voltage with fault removed.}}$$

* In 3ϕ systems if fault does not involve ground (earth) the voltage across the C.B pole first to clear is 1.5 times the phase voltage.

* If fault involves earth:
  i) $k_3 = 1$ if neutral is earthed & fault is the earthed.
  ii) $k_3 = 1.5$ if neutral is grounded & fault is not involved of earth.

1. In short circuit test on a 3 phase, 132kV C.B., 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 16kHz. Assume neutral is grounded & fault is not grounded. Determine average RRRV.

Soln:

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

$V_{or} = k_1 k_2 k_3 E_m$

$k_1 = \sin\phi = \sin[\cos^{-1} 0.4] = 0.9165$

$k_2 = 0.9$

$k_3 = 1.5$

Peak value of voltage (ω) line to ground

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

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

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

$$= 2\pi \times 16\times10^3$$

$$= 1\times10^5$$

Time to reach maximum restriking voltage

$$t_{max} = \pi\sqrt{LC} = \frac{\pi}{1\times10^5}$$

Maximum restriking voltage $= 2V_{or}$

$$= 2k_1k_2k_3E_m = 2\times0.9165\times0.9\times1.5\times107.77\times10^3$$

$$= 2.66682\times10^5 \text{ V}$$

Average RRRV.

$$\frac{\text{Maximum restriking voltage}}{\text{Time to reach maximum restriking voltage}} = \frac{2.66682\times10^5}{\pi/1\times10^5} = 8.48\times10^9 \text{ V/sec}$$

$= 8.48\times10^6$ kV/sec

$= 848$ kV/ms

2. In a short circuit test on a 180kV, 3 phase system, the breaker gave the following results: p.f of fault 0.45, recovery voltage 0.95 times full line voltage, breaking current symmetrical & restriking transient had a natural frequency 16kHz. Determine average RRRV. Assume fault is grounded.

Soln:

$$E_m = \frac{\sqrt{2} \times 180}{\sqrt{3}} = 106.144 \text{ kV}$$

$V_{ar} = k_1 k_2 k_3 E_m$

$= 0.8930 \times 0.95 \times 1 \times 106.144$

$= 90.047262 \text{ kV}$

$k_1 = \sin\phi = 0.8930$

$k_2 = 0.95$

$k_3 = 1$

Maximum $e = 2V_{ar} = 180.09452 \text{ kV}$

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

$\therefore$ Maximum $t = 1/2f_n = \frac{1}{2 \times 16 \times 10^3}$

$\therefore$ Average RRRV $= \frac{\text{Maximum } e}{\text{Maximum } t} = \frac{180.09452}{1/2 \times 16 \times 10^3} = 5.76302 \text{ kV}/\mu\text{sec}$

3. Calculate the RRRV of 132kV circuit breaker with neutral earthed. S.C data as follows: Broken current is symmetrical, restriking voltage has frequency 20kHz, p.f 0.15. Assume fault is also earthed.

Soln:

$k_1 = \sin\phi = \sin(\cos^{-1} 0.15) = 0.9886$

$k_2 = 1$

$k_3 = 1$

$$E_m = \frac{\sqrt{2} \times 132}{\sqrt{3}} = 107.77755 \text{ kV}$$

$V_{ar} = k_1 . k_2 . k_3 E_m$

$= 106.54889 \text{ kV}$

$\therefore$ Maximum $e = 2 V_{ar}$

$= 213.09778 \text{ kV}$

$t_m = \pi\sqrt{LC}$

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

Maximum $t_m = \frac{1}{2 \times 20 \times 10^3}$ sec

$$RRRV = \frac{e_{max}}{t_{max}} = \frac{213.09778}{[1/(20 \times 10^3 \times 2)]} = 8.52 \text{ kV}/\mu\text{sec}$$

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

i) Maximum Voltage across the C.B contacts

ii) Frequency of oscillations

iii) RRRV average upto first peak of oscillations.

Solu:-

$$X = 2\pi f L = 4\ \Omega$$

$$L = 4/2\pi\times50 = 0.0127\ H$$

$$E_m = \sqrt{2}\times7.5 = 10.606\ kV$$

i) Maximum Voltage $= 2\times E_m$

$$= 2\times10.606 = 21.212\ kV$$

ii) $$f_n = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{0.0127\times0.01\times10^{-6}}}$$

$$= 14.1227\ kHz.$$

iii) $$\text{Average RRRV} = \frac{\text{Maximum Voltage}}{t_m}$$

$$t_m = \pi\sqrt{LC} = \frac{1}{2f_n} = \frac{1}{2\times14.1227\times10^3}\ sec$$

$$\therefore \text{Average RRRV} = \frac{21.212}{\left[1/(2\times14.1227\times10^3)\right]} = 0.599\ kV/\mu sec$$

5. In a system having 220kV, the line to ground capacitance 0.015 μF, inductance 3.5H. Determine voltage appearing across pole of circuit breaker if a magnetising current of 6.5A instantaneous, is interrupted. Determine also the value of resistance to be used across the contacts to eliminate the restriking voltage.

Solu:

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

$$\tfrac{1}{2}Li^2 = \tfrac{1}{2}Ce^2$$

$$e = i\sqrt{L/C}$$

$$= 6.5\sqrt{\frac{3.5}{0.015\times10^{-6}}}$$

$$= 99.3\ kV$$

To eliminate restriking voltage & critical damping condition,

$$R = 0.5\sqrt{L/C} = 0.5\sqrt{\frac{3.5}{0.015\times10^{-6}}} = 7.635\ k\Omega.$$

6. A 50HZ, 3 Φ alternator has rated voltage 13.5KV, connected to circuit breaker, inductive reactance 4Ω/ph, c = 2 μF. Determine maximum RRRV, peak restriking voltage, frequency of oscillations.

<u>Solu:-</u>

$$E_m = \frac{\sqrt{2} \times 13.5}{\sqrt{3}} = 11.0227 \text{ kV}$$

$$X = 2\pi f L$$

$$L = \frac{4}{2\pi \times 50} = 0.0127323 \text{ H}$$

$$C = 2 \mu F$$

$$f_n = \frac{1}{2\pi\sqrt{LC}} = 0.997 \text{ HZ}$$

Maximum restriking voltage $= 2E_m$

$= 22.0454 \text{ KV}$

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

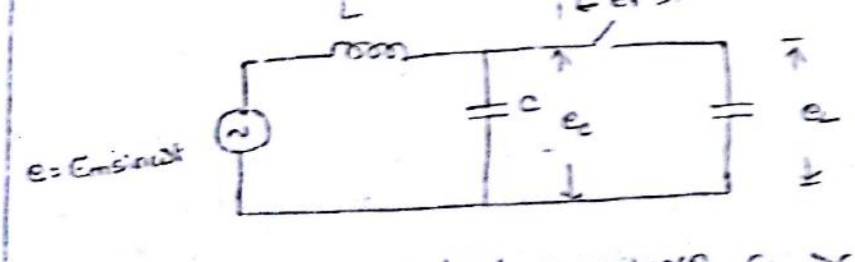
Maximum RRRV $= \frac{E_m}{\sqrt{LC}}$ $= 2\pi f_n E_m$

$= \pi \times 0.997 \times 10^3 \times 22.0454 \text{ kV/sec}$

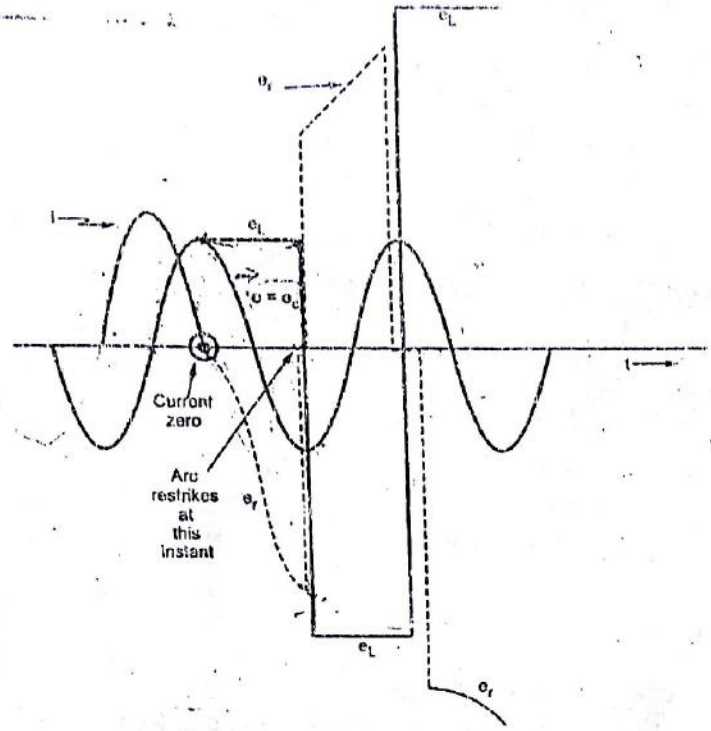
$= 0.06907 \text{ KV}/\mu\text{sec}$

Interruption of capacitive currents:-

* In power system capacitor banks are used in the network which supplies reactive power at leading P.F.
* There are various conditions such as opening a long transmission line on no load or disconnecting a capacitor bank etc. in which it is required to interrupt the capacitor currents which is a difficult task for the circuit breakers.
* To understand this difficulty consider a simple circuit



* The value of load capacitance $C_L > C$.
* Voltage across a capacitor cannot change instantaneously.
* The currents supplied to the capacitor are generally small & interruption of such currents takes place at first current zero.



* At the beginning, the rate of rise of recovery voltage is low & increases slowly.
* So whenever such circuit is opened, a charge is trapped in the capacitance C_L.
* The voltage e_L across the load capacitance will hold the same value when circuit was opened, & that voltage value will be peak of supply voltage, as p.f angle is nearly 90° leading.
* Voltage across V_c gets oscillates but due to small value of capacitance, it is attained close to supply voltage.
* Recovery voltage e_r is the difference between e_c & e_L

$$e_r = e_L - e_c$$

* It's initial value is zero & will starts slowly increasing, in negative direction, since e_L remains constant & e_c will get charge in reverse direction.
* This value reaches twice the normal peak value when current waveform reaches zero. That time due to insufficiency of dielectric strength between the circuit breaker contacts, an arc may restrike again. Due to this the circuit will be reclosed & e_L oscillates at a high frequency, since the supply voltage at this instant will be at its negative peak
* At the instant of restriking the arc, recovery voltage e_r is zero, the voltage across load capacitance (e_L) reaches -3 times the peak value of normal supply voltage.

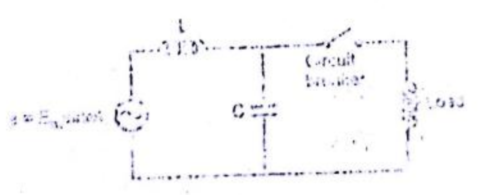
* once again the recovery voltage starts increasing. The again restriking of arc takes place, high frequency oscillation of e_c takes place.
* Such several repetitions of the [illegible] cycle [illegible] the voltage across load capacitance to a dangerously high value.
* In practice its value is limited to 4 times the normal peak of the voltage.
* Since voltage across capacitor goes on increasing due to successive restriking, energy [illegible] $\frac{1}{2}CV^2$ is quite large & it damages the circuit breaker.
* Hence circuit breakers used for capacitors must be free from restriking & should have adequate rating for capacitive current switching so that severe voltage transients can be avoided.
* If circuit breakers are closed while switching capacitor banks in parallel, the pre-arcing (ie) the arc struck before contacts touch together takes place. This may damage the contacts as the energy in the arc is converted into heat. Thus while switching with capacitor banks suitable reactor (L_s) must be used in series to limit high frequency inrush current.

Current chopping (Interruption of Low magnetising currents) :-

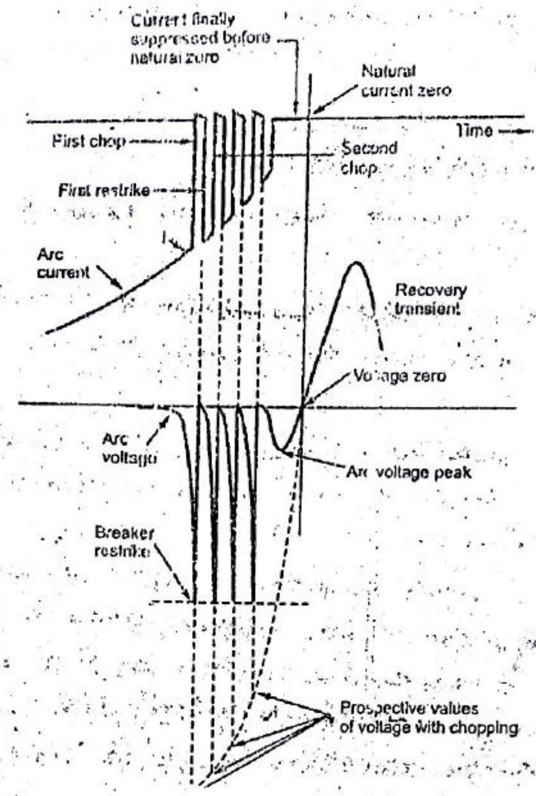
(ie) disconnecting transformers on noload

* There are certain circumstances in which it is necessary to interrupt small inductive currents.
* The noload current of a transformer is almost 90 zero p.f. lagging.
* This current is normally smaller than the normal current rating of the breaker.
* Interrupting of such currents causes [illegible] duty on the circuit breakers. This phenomenon is called current chopping

Consider the circuit shown in Fig.



* While interrupting low inductive current i_c, the rapid deionization of contact space & blast effect, may cause the current to reduce abruptly to zero even before the natural current zero. This current chopping causes very severe voltage oscillations.



* Let the arc current be i, when it is chopped down to zero value. The stored energy in the inductor $\frac{1}{2}Li^2$ will be discharged into the capacitor so that the capacitor is charged to a prospective voltage V such that

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

$$V = i\sqrt{L/C} \text{ volts}$$

* This prospective voltage is extremely high as compared to the normal system voltage. The frequency of natural oscillations is given by

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

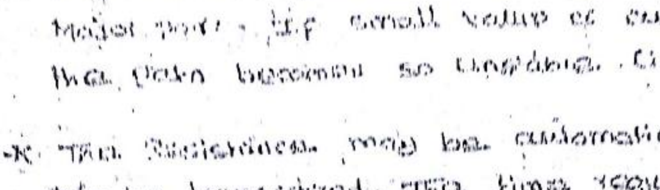
[eg: To understand this concept
220kV circuit breaker interrupting a I_μ of 10A r.m.s of transformer. Let the current be chopped at the instantaneous value of 7 A. L = 35 H &
C = 0.0020 μf.

$$e = 7\sqrt{\frac{35}{0.0020 \times 10^{-6}}} = 926 \text{ kV}$$]

* This voltage will appear across the circuit breaker contacts such a transient voltage having high RRRV appears across the contacts.
* There will be restriking of arc at some point.
* If the arc restrikes further, chop may occur.
* Thus before final interruption of current, there will be many chops & the circuit breaker will fail to clear the fault.
* Alternately if the restrike does not occur, the severe voltage stress will appear across circuit breaker contacts.
* The rise of voltage before restriking is an important factor. The lower is the rate of rise, more is the time required for deionization & high voltage will be reached.
* After first chopping the deionising force which is still in action acts & second chop of current takes place. But the arc current is now smaller than the previous one & the arc current collapses & restriking voltage is again build. Thus a sequence of chops will occur & arc will continuously decrease until a final chop brings arc current to zero. There will not be any further restriking as the gap is almost deionise.

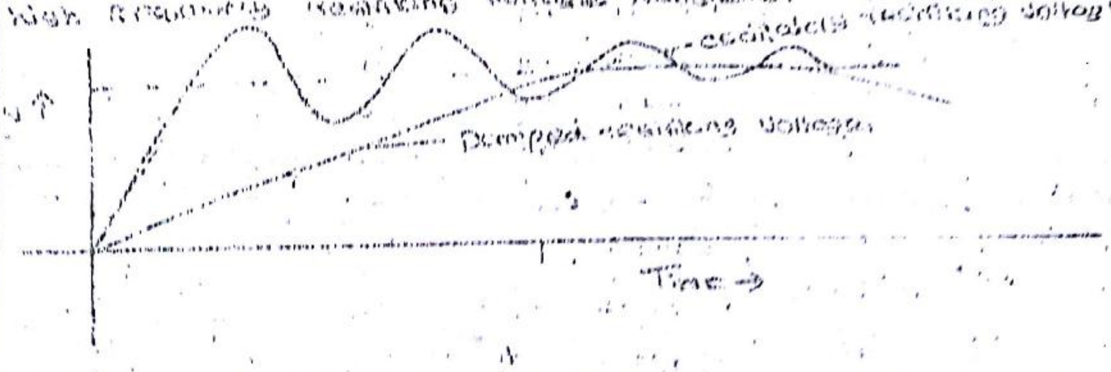
Resistance switching :-

* The interruption of low inductive currents, interruption of capacitive circuits also leads to severe voltage oscillations.
* These excessive voltage surges during circuit interruptions can be prevented by the use of shunt resistance 'R' across the circuit breaker contacts.
* This process is known as Resistance switching.
* When the resistance is connected across the arc, a part of the arc current flows through the resistance. This will lead to decrease in arc current & increase in rate of deionization of arc path & resistance of arc. This will increase the current through shunt resistance. This process continues until the current through the arc is diverted through the resistance either completely or in major part. If small value of current remains in the arc then the path becomes so unstable that it is easily extinguished.
* The resistance may be automatically switched in & arc current can be transferred. The time required for this action is very small.



Arc first appears across points A & B.
Then transferred across A & C.

The shunt resistance also ensures the effective damping of the high frequency restriking voltage transients.



* The analysis of resistance switching can be made to find out the critical value of shunt resistance to obtain complete damping of transient oscillations. Fig shows the equivalent electrical circuit for such an analysis.

Therefore if the value of the resistance, connected across the contacts of the circuit breaker is equal to or less than $\frac{1}{2}\sqrt{L/C}$, there will be no transient oscillation.

If $R > \frac{1}{2}\sqrt{L/C}$, there will be oscillation.

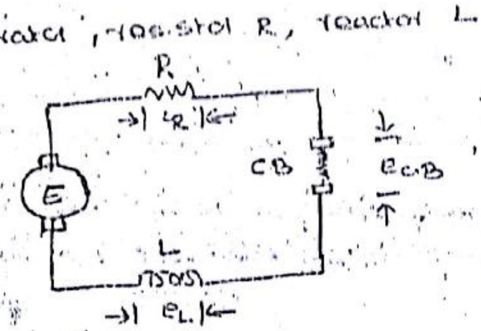
$R = \frac{1}{2}\sqrt{L/C}$ is known as critical Resistance.

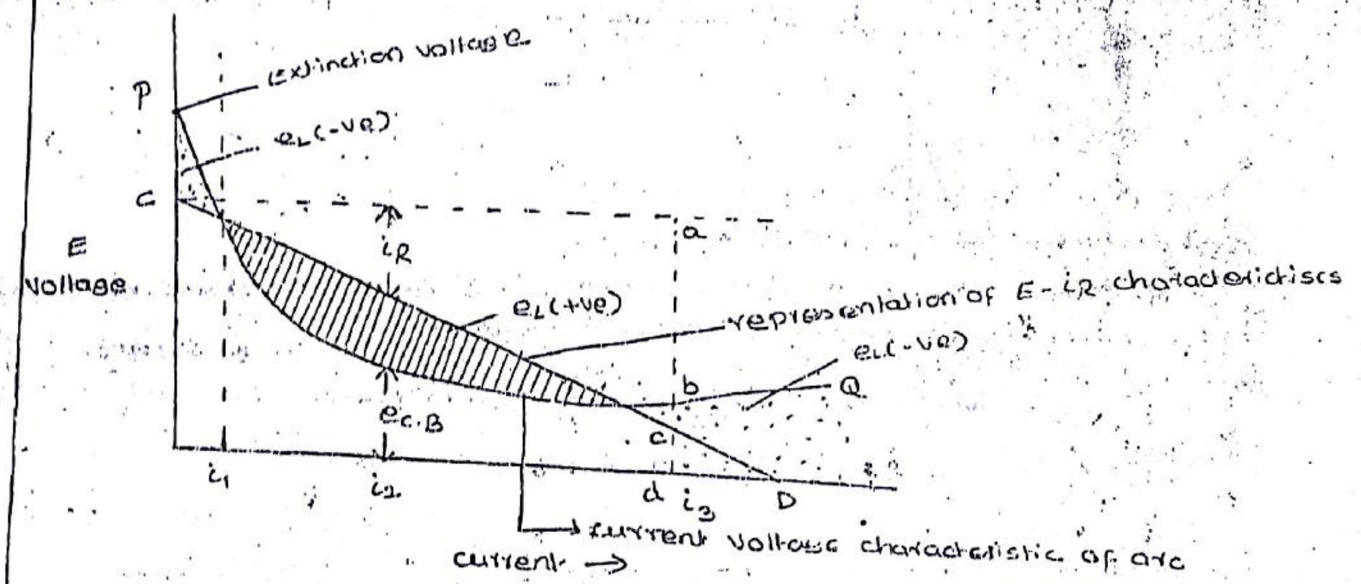
The frequency of damped oscillation is given by.

$$f = \frac{1}{2\pi}\sqrt{\frac{1}{LC} - \frac{1}{4C^2R^2}}$$

DC circuit Breaking:-

Consider the D.C circuit represented in Fig which consists of a generator, resistor R, reactor L & the circuit breaker (C.B).





* The curve CD represents the voltage (E-iR), where E is the generated e.m.f & i is the current at any instant.
* The curve PQ represents the voltage - current characteristics of the arc, for decreasing value of current & $e_{C.B}$, the instantaneous voltage across the arc.
* When the circuit breaker just opens, it carries full load fault current given as:

$$I = E/R$$

* When the fault current reduces to i_2, the voltage drop across the resistance 'R' is $i_2 R$ equal to ac & the arc voltage e.c.b is represented by bd, thus it is clear the voltage across the arc is greater than the voltage available.

* The arc is unstable between currents i_2 & I_2. The difference of the two voltages is supplied by inductance L, the voltage across which is given by

$$e_L = L\frac{di}{dt}$$

* This quantity is negative for decreasing values of current & according to Lenz's law it tries to maintain the arc.

* In the region of currents between i_1 & i_2, e_L is +ve as the arc characteristic lies below resistive drop line CD. In this range the current tries to increase, so the interruption of the fault current is not possible in this range.

* As the separation of contacts is increased, the arc is lengthened, which results into raising the arc voltage characteristics above the resistive voltage drop line CD.

* In D.C. circuit breakers, it is always sought to have the progressive lengthening of the arc which raises the characteristics above the line CD.

* The operation of the circuit breaker is said to be ideal if the characteristic is raised clear above the drop line CD even in the region of currents i_1 & i_2 as shown in Fig (1).

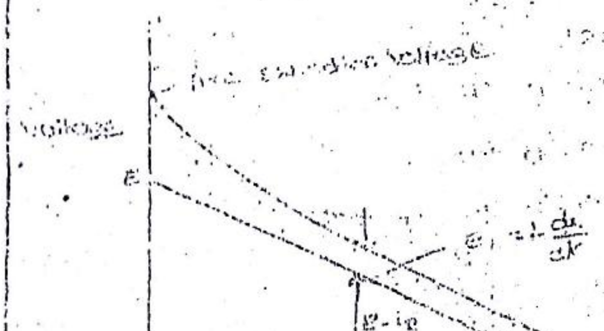
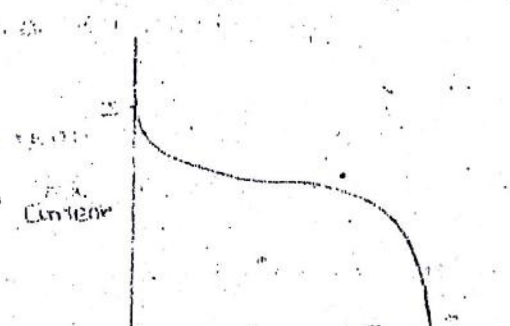
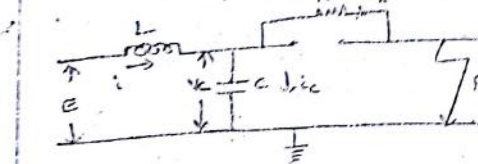


Fig (1)



Fig(2) Time

* Further it will be observed that the arc voltage is always greater than E - iR & the balance is supplied by e_L which is proportional to the rate of change of current $\frac{di}{dt}$ as shown in Fig (2)



The voltage equation is given by

$$L\frac{di}{dt} + \frac{1}{C}\int i_c\,dt = E \quad \& \quad i = i_c + i_R$$

$$L\frac{d(i_c + i_R)}{dt} + V_c = E$$

(or)

$$L\frac{di_c}{dt} + L\frac{di_R}{dt} + V_c = E \qquad \text{--- (1)}$$

$$i_c = \frac{dq}{dt} = \frac{d}{dt}(CV_c)$$

$$\frac{di_c}{dt} = \frac{d^2(CV_c)}{dt^2} = C\frac{d^2V_c}{dt^2}$$

$$\frac{di_R}{dt} = \frac{d(V_c/R)}{dt} = 1/R\,\frac{dV_c}{dt}$$

Sub the values of $\frac{di_c}{dt}$ & $\frac{di_R}{dt}$ in eqn (1)

$$LC\frac{d^2V_c}{dt^2} + L/R\,\frac{dV_c}{dt} + V_c = E$$

Taking Laplace transform

$$LCs^2V_c(s) + L/R\,sV_c(s) + V_c(s) = E/s$$

$$LCV_c(s)\left[s^2 + 1/RC\,s + 1/LC\right] = E/s$$

$$V_c(s) = \frac{E}{sLC\,(s^2 + 1/RC\,s + 1/LC)}$$

For no transient oscillation, all the roots of the equation should be real. One root is zero (ie) s=0 which is real. For the other two roots to be real, the roots of the quadratic equation in the denominator should be real. For this, the following condition should be satisfied.

$$\left[\left(\frac{1}{2RC}\right)^2 - \frac{1}{LC}\right] \geq 0$$

$$\frac{1}{4R^2C^2} \geq \frac{1}{LC}$$

$$\frac{4}{LC} \leq \frac{1}{R^2C^2}$$

$$R^2 \leq \frac{LC}{4C^2}$$

$$R \leq 1/2\,\sqrt{L/C}$$

* In order to decrease the arcing, Rf should be increased, but with this the value of Rf the arc extinction voltage will increase.

* To summarize it is clear that the function of the circuit breaker is to modify the arc characteristic sufficiently to avoid its stability which is achieved by reducing the arcing time, but it will cause higher arc extinction voltages. Generally a compromise is made between the arcing time & the arc extinction voltage.

Fuses:-

Fuse:-

A fuse is a protective device used for protecting cables & electrical equipment against overloads or/& short circuits. It breaks the circuit by fusing (melting) the fuse element (fuse wire) when the current flowing in the circuit exceeds a certain predetermined value.

Fuse element (Fuse wire):-

Fuse element is that part of fuse which melts when the current flowing in the circuit exceeds a certain predetermined value & thus breaks the circuit.

Materials commonly used are copper, Aluminium, tin, lead, zinc, silver etc.

A fuse being a thermal device, possesses inverse time characteristic i.e. the breaking time decreases as the fault current increases.

Rated current:-

The rated current of a fuse is the current that it can carry indefinitely without fusing.

Minimum fusing current:-

It is the minimum current (rms value) at which the fuse element will melt. It depends on various factors like material, length, shape, area of cross-section of the fuse element, size & location of the terminals, the type of enclosure employed & number of strands in the standard fuse wire.

$$I = kd^{3/2}$$

d - diameter

k - constant depending upon the material of the fuse wire.

Fusing factor:-

$$\text{Fusing factor} = \frac{\text{Minimum fusing current}}{\text{Rated current}}$$

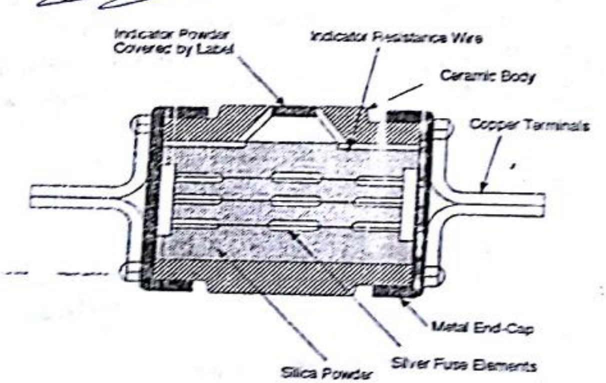
This factor is always more than unity.

* It is either pure ... The fuse element has 2 or more sections joined
* Normally the fuse element has 2 or more sections joined together by means of a tin joint.
* The fuse element in the form of a long cylindrical wire is not used, because after melting it will form a string of droplets & an arc will be struck between each of the droplets. Later on, these droplets will also evaporate & a long arc will be struck.
* The purpose of the tin joint is to prevent the formation of a long arc. As the melting point of tin is much lower than that of silver, tin will melt first under fault condition & the melting of tin will prevent silver from attaining a high temperature. The shape of the fuse element depends upon the characteristic desired.

Working:-

* When the fuse carries normal rated current, the heat energy generated is not sufficient to melt the fuse element. But when a fault occurs, the fuse element melts before the fault current reaches its first peak.
* As the element melts, it vaporizes & disperses.
* During the arcing period, the chemical reaction between the metal vapour & quartz powder forms a high resistance substance which helps in quenching the arc. Thus the current is interrupted.

HRC Fuse with Indicator:-



* This HRC fuse is developed by General Electric company.
* The cylindrical body made of ceramic material is closed by metal end caps which carry the copper terminals tags.
* The brass end caps & the copper terminal tags are electro-tinned.
* The fuse element made of pure silver is surrounded by silica as the arc quenching medium.

* In order to increase the breaking capacity of the fuse, two or more silver fuse elements are used in parallel.
* The breaking capacity is increased due to greater surface area of the fuse element in contact with the silica filler.
* An indicating device consisting of a fine resistance wire connected in parallel with the fuse elements & led through a small quantity of mild explosive housed in a pocket in the side of the fuse & covered by a label is also provided.
* It indicates whether the fuse has blown out or not.
* When the fuse operates on occurrence of a fault, the fine wire is automatically fused resulting in the combustion of the explosive material. The combustion of the explosive material chars the label & thus indicates that the fuse has blown out.

Advantages of HRC Fuses:-

1. Capability of clearing high values of fault currents.
2. Fast operation.
3. Non-deterioration for long periods.
4. No maintenance needed.
5. Reliable discrimination.
6. Consistent in performance.
7. Cheaper than other circuit interrupting devices.
8. Current limitation by cut-off action.
9. Inverse time-current characteristic.

Disadvantages of HRC Fuses:-

1. It requires replacement after each operation.
2. Interlocking is not possible.
3. It produces overheating of the adjacent contacts.

Applications of HRC Fuses:-

1. Protection of low voltage distribution systems against overloads & short circuits.
2. Protection of cables.
3. Protection of busbars.
4. Protection of motors.
5. Protection of semiconductor devices.
6. Back up protection to circuit breakers.

Selection of Fuses:-

1. It should be able to withstand momentary over current due to starting a motor & transient current surges due to switching on transformers, capacitors & flourescent lighting etc.
2. It's operation must be ensured when sustained overload or short circuit occurs.
3. It should provide proper discrimination with the other protective devices.
4. It's selection depends upon the load circuits.
   1. steady load circuits.
   2. Fluctuating load circuits.

Discrimination:-

When two or more protective devices (e.g) two or more fuses, a fuse & a circuit breaker etc are used for the protection of the same circuit, there needs a proper discrimination.

The condition is the prearcing time of the major fuse (nearer to the source) must exceed the total operating time of minor fuse (Far from source).

If a fuse & circuit breaker are used,

circuit breakers operate for the breaking capacity of circuit breaker & the fuse operates for faults of larger current.

1. A circuit breaker interrupts the magnetising current of a 100MVA transformer at 220kV. The magnetising current of the transformer is 5% of the full load current. Determine the maximum voltage which may appear across the gap of the breaker when the magnetising current is interrupted at 53% of its peak value. The stray capacitance is 2500 μF. The inductance is 30H.

Soln:

Full load current of the transformer $= \frac{100 \times 10^6}{\sqrt{3} \times 220 \times 10^3} = 262.44A$

Magnetising current $= \frac{5}{100} \times 262.44 = 13.12A$

Current chopping occurs at $0.53 \times 34.44 \sqrt{2} = 9.83A$

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

$$\frac{1}{2} \times 30 \times (25.33)^2 = \frac{1}{2} \times 2500 \times 10^{-6} V^2$$

$V = 1077V$

$V = 1.077kV$