Switchgear & Protection

Switch gear: It is a general term covering a wide range of equipment concerned with switching and protection. All equipment's associated with fault clearing process are covered by the term switch gear. Switch gear includes switches, fuses, circuit breakers, isolators, relays, control panels, lightning arrestors, CT, PT and various associated equipment. **Control gear:** It is used for switching and controlling power consuming device.

Circuit breakers (CB): It is one of the equipment in switch gear. This is a switching and current interrupting device.

It has two basic functions:
1) switching during normal operating condition for operation and maintenance.
2) Switching during abnormal condition for interrupting the fault current caused by short circuits.

Switch gear are necessary at every switching point in a power system. Between the generating station and final load point, there are several voltage and fault levels. Hence in various applications, the requirement of switchgear varies depending upon location, rating and local requirements.

Single pole circuit breaker: In this breaker fault current interrupting mechanism is involved with one phase.

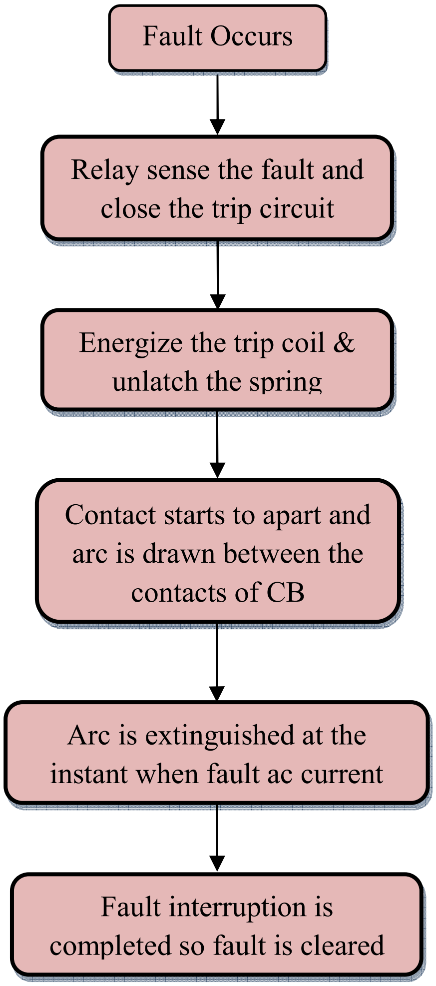
Triple pole circuit breaker: Fault interrupting is involved with three phases in this breaker. Each pole consists of one or more interrupters or arc extinguishing chambers. The interruptions are mounted on support insulators. The interrupters encloses a set of fixed and moving contacts .The moving contact can be drawn apart by means of operating links of operating medium. The operating mechanism provides the necessary energy for opening and closing the contacts of CB.

CB has two states only – close and open.

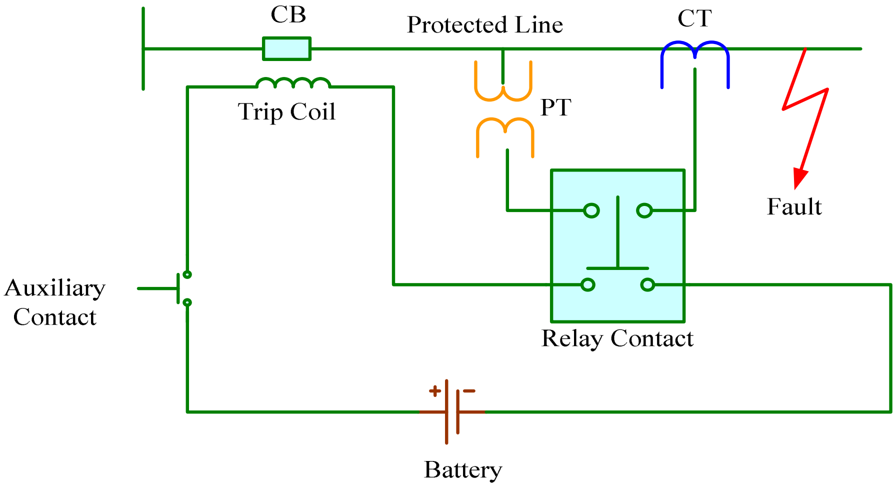
Under normal operating condition its operation can be manual or can be automatic remotely.

During fault condition its operation must be automatic. Operating mechanism is responsible for the automatic operation.

The sequence of operation during abnormal condition:



Trip Circuit:



Trip Circuit

Auxiliary contact can be used for interlocking the CB with other equipment to avoid erroneous operation.

Trip free feature of a CB:

Suppose a CB Suppose a CB has been instructed to close by manual instruction by pushing of push button. The operating mechanism will start operating for closing operation. Meanwhile a fault has taken place and the relay closes the trip circuit of the CB. Then, the mechanism which permits the CB to be tripped by the protective relay ever if it is under the process of closing is called trip free feature.

Classification of CB based on arc quenching medium:

a) Air break CB (miniature CB): up to 600 V, 5-15-35 MVA.
b) Oil CB (tank or bulk oil) : 12 kV , 500 MVA
c) Minimum oil CB : 33 kv-245 kV, 30,000 MVA
d) Air blast CB : 245 kv-400 kV; 3500 MVA
e) Sulphur hexafluoride CB (SF_6 CB) : 245-700 kV , 35000-50000MVA
f) Vacuum CB : 11 kV , 500 MVA

OCB was developed in 1885; oil is used for insulation and arc extinction.

Air blast CB (ABCB) was developed around 1930 and becomes very popular in 1950's. It has a very high rupturing capacity and is very fast.

SF_6 CB --- has good dielectric and arc quenching properties.

Air CB --- arc quenching medium is air at atmospheric pressure.

ABCB -- arc quenching medium is high pressure compressed air (20-30 kg/cm^2)

Bulk oil CB --- contacts are separated in a steel tank filled with dielectric oil.

Minimum oil CB --- contacts are separated in an insulating housing (interrupter) filled with dielectric oil.

SF_6 CB --- contacts are separated in a chamber filled with SF_6 gas having very high arc quenching properties.

Mode of arc extinction:

1) **High resistance interruption:**
   In this process the resistance of arc is increased by lengthening and cooling it to such an extent that the system voltage cannot maintain the arc and thus extinguished. This is used in Air CB and DC CB.

2) **Low resistance or zero point interruption:**
   In this process the arc gets extinguished at the natural current zero of the alternating current zero and is pretended from restriking again by rapid increasing the dielectric strength of the contact space. Used in almost all ac circuit breaker.

Technical particulars of a CB:

1. Type of medium for arc extinction.
2. Rated voltage.
3. Rated breaking current
4. Other rated characteristic (TRV, restriking voltage, make current etc.)
5. Types of construction : indoor metal clad
   Outdoor type
   Metal clad SF_6 gas insulated type
6. Types of operating mechanism: spring opened, spring closed mechanism
   Solenoid closed, spring opened mechanism
   Hydraulic mechanism
   Pneumatic mechanism
7. Total break time : this is (relay+ CB time)
   = (instant of fault to closer of trip circuit) +
   (Closer of trip circuit to final arc extinction time)
8. Structure form : live tank type ,
   Dead tank type

Speed of CB and relay:

Before 1930: CB interrupting time: 15-30 cycles.

Relay time: 6-120 cycles

1930 --- CB time -8 cycles

1935 --- CB time-3 cycles

Present day's relay time becomes as small as 1-3 cycles.

Circuit breaker rating:

In a purely inductor circuit, e=L$\frac{di}{dt}$ $where$ L $= \frac{d\varphi}{di}$, φ is the flux linkage due to i.

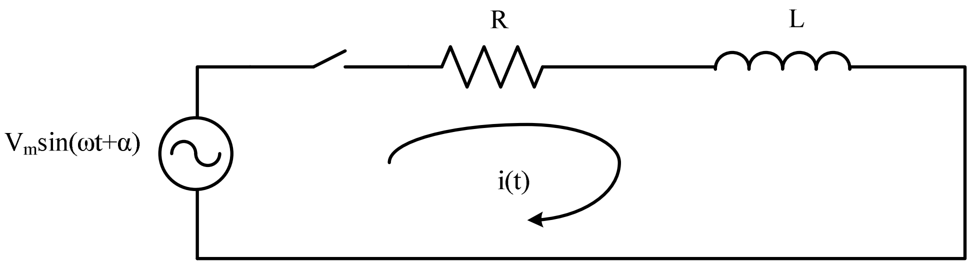
Energy in inductance of L Henry at the instant when the current in it is I amp is given by W_L=1/2 Li^2 joules; 1 joule = 1 watt/sec. In an inductive circuit current cannot change instantaneously. Hence when the e.m.f is applied on inductive circuit at t=0, the current is zero at the instant of closing the switch.

While interrupting the current flowing through an inductive circuit such as an unloaded transformer or a transformer with inductive load, the circuit breaker should interrupt the arc at natural current zero of the ac current wave. If the arc extinction takes place at the natural current zero, the energy in the inductance is (1/2 Li^2) is zero. If however, the arc is suddenly interrupted before the natural current zero, at the instantaneous value I, the energy 1/2 Li^2 is suddenly interrupts by chopping the current to an artificial zero value. Due to this phenomenon, the interrupting of low magnetizing current of transformer and reactor needs special attention. The CB should be capable of interrupting such current without getting damaged or without giving rise to over voltage above permissible limits.

Transients in RL series circuit:

Selection of CB for a power system depends not only on the normal current but also upon the maximum current it may have to carry momentarily and the current it may have to interrupt at the voltage of the line in which it is placed. In order to approach the problem of calculating the initial current when a synchronous generator is short circuited we consider a RL series circuit.

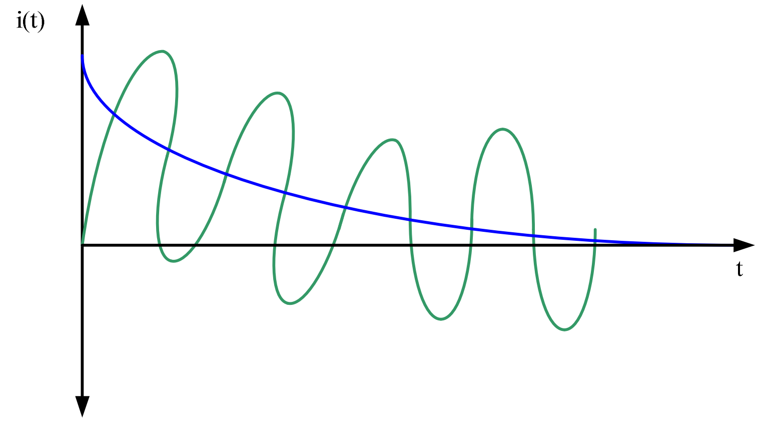
Consider the following RL series circuit:



$v_m \sin(\omega t+\alpha)= Ri+L\frac{di}{dt}$

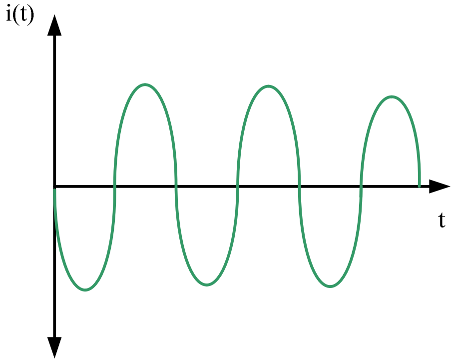
$$i(t)=\underbrace{\frac{v_m}{|z|}\sin(\omega t+\alpha-\theta)}_{\text{AC component}}-\underbrace{\frac{v_m}{|z|}e^{-\frac{R}{L}t}\sin(\alpha-\theta)}_{\text{Dc component}}$$

Where $Z=\sqrt{R^2+(\omega L)^2}$ $\quad and\ \theta=\tan^{-1}\frac{\omega L}{R}$



For α-θ= $-\frac{\pi}{2}$

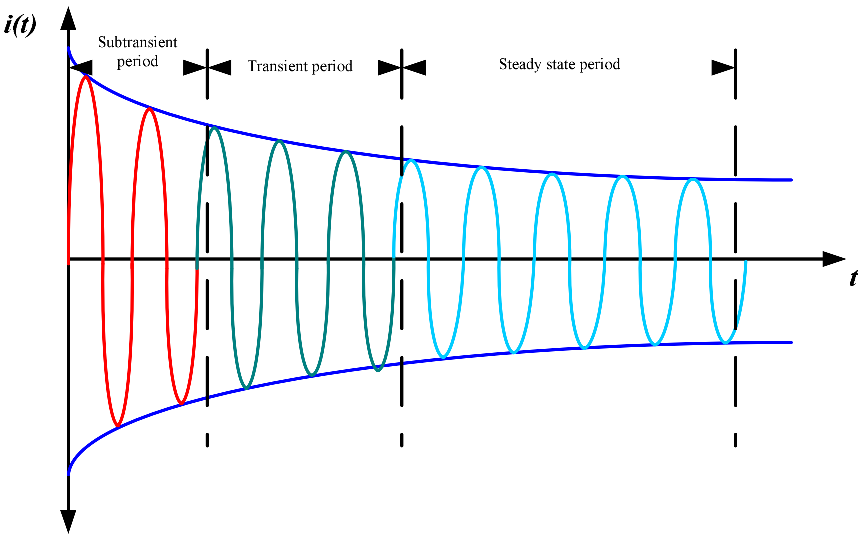
Here maximum dc component



for α-θ=0

no dc component

The case of a short circuit at the terminal of a synchronous generator:



$$I' = \frac{E}{X_d^{'}} , I'' = \frac{E}{X_d^{''}} , I^{'''} = \frac{E}{X_d^{'''}}$$

The fault current attains the peak value at first ½ cycles after the fault inception which is the peak value of the fault current under sub transient period.

Having the fault current been sensed by CT, the operation of the protective relay starts. The CB contact starts to apart after the operation of the protective relay, which generally takes little time. So, the contacts of the CB generally starts to separate when the initial fault current reduces to a lower level in transient period. The r.m.s value of the current at the instant of contact separation is called the breaking current of the CB and is expressed in KA. In other words the breaking current is equal to the r.m.s value of fault current under transient period.

If a CB closes its contact on existing fault, the current would increase to a peak value during the first $\frac{1}{2}$ cycle from the instant of closing the CB on the fault. This peak value of the fault current is called the making current of the CB.

The rated short circuit making current of a CB is the peak value of the first current loop (i.e. at ½ cycles) of the short circuit current which the CB is capable of making at rated voltage.

The expression of instantaneous current of a phase for a three phase solid fault at the terminals of an unloaded generator:

$$\text{i(t)}=\sqrt{2}\text{E} \left[\left(\frac{1}{X''_d} - \frac{1}{X'_d}\right)e^{-t/T''_d} + \left(\frac{1}{X'_d} - \frac{1}{X_d}\right)e^{-t/T'_d} + \frac{1}{X_d}\right]\cos(wt + \alpha - \theta) - \sqrt{2}\text{E} \left(\frac{1}{X''_d}\right) e^{-\frac{t}{T_a}} \cos(\alpha - \theta)$$

$$= \boldsymbol{i_{ac}} + \boldsymbol{i_{dc}}$$

The r.m.s breaking current (symmetrical), $I_{rms} = \frac{\boldsymbol{i_{ac}}^2}{\sqrt{2}}$

r.m.s breaking current (asymmetrical), $I_{rms} = \sqrt{[(\frac{\boldsymbol{i_{ac}}}{\sqrt{2}})^2 + \boldsymbol{i_{dc}}^2]}$

Rated short circuit breaking capacity (rupturing capacity) of a CB = $\sqrt{3} \times KV \times KA$

Normal practice is to use asymmetrical breaking current is calculating the breaking capacity

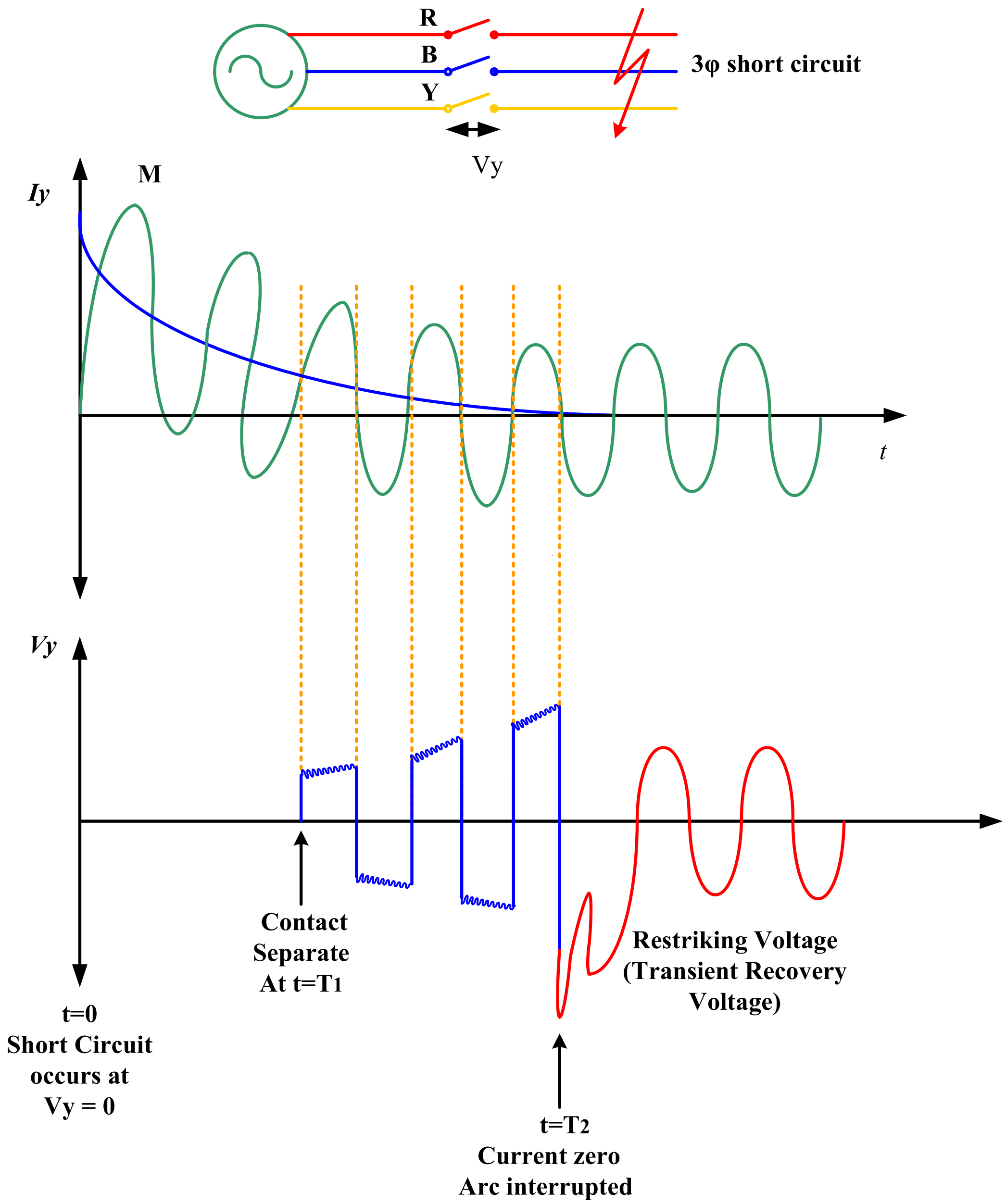
Rated short circuit making current = 1.8 × $\sqrt{2}$×rated short circuit symmetrical breaking current

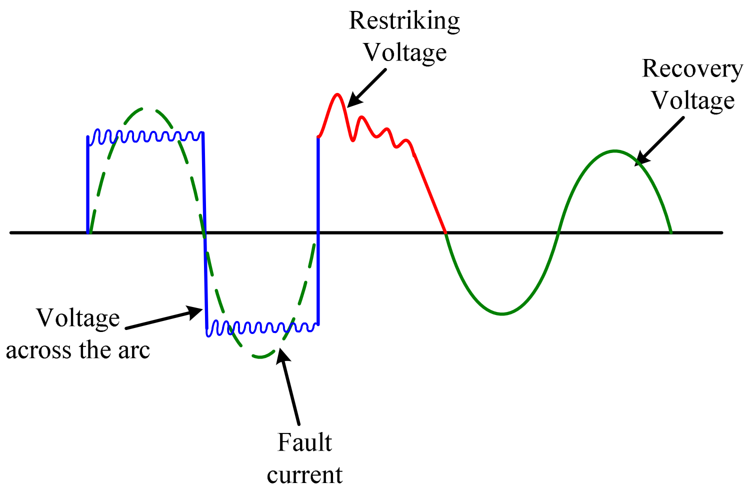
= 2.55× rated symmetrical breaking current

Making capacity = 2.55 × symmetrical breaking capacity.

Current interruption in an AC CB:

Suppose a three phase short circuit is applied on an unloaded alternator at the instant when voltage of phase Y with respect to neutral is zero. In such case the short circuit current in phase Y will have the maximum dc component and the waveform of I_y will be maximum unsymmetrical about normal zero axis as shown:





When the arc gets extinguished at fault current zero, a high frequency transient voltage appears across the contacts of the CB. This transient vanishes within very short time in the order of less than .001 sec. This high frequency transient voltage tries to restrikes the arc. This is called restriking voltage or transient recovery voltage (TRV). The power frequency system voltage appearing between the poles of the CB after arc extinction is called recovery voltage.

Prospective current: the current that would flow in the circuit of the CB were replaced by solid conductor is called prospective current.

For successful arc interruption, the rate of building up of dielectric strength must be higher than the rate of rise of TRV

The rate of rise of TRV depends on:

1. Circuit parameters
2. Type of switching duty involved.

Rate of building up of dielectric strength depends on-

1. Effective design of interrupter
2. CB

Due to switching a capacitive current, a high voltage appearing across the contact can cause reignition of the arc after its final extinction. If the contacts space breaks down within a period of ¼ of a cycle of the initial arc extinction, the phenomenon is called reignition. If the break down occurs after ¼ of a cycle of the initial arc extinction, the phenomena are called restrikes.

TRV has a power frequency component and an oscillatory transient component. The oscillatory transient component is developed due to the presence of inductance and capacitance in the circuit. Power frequency component is due to the system voltage.

The frequency of oscillatory transient component is

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

Where, f_n = frequency of TRV

L= equivalent inductance

C=equivalent capacitance

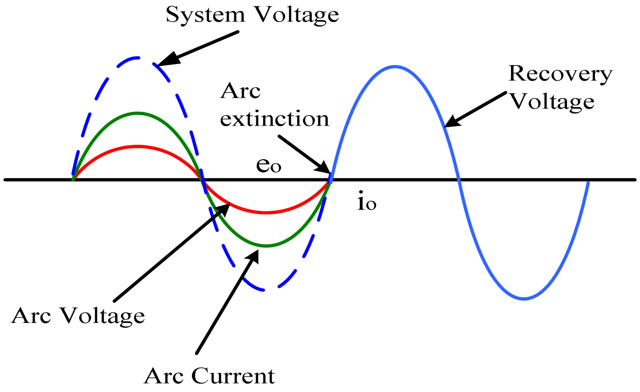
In actual system the wave form of TRV has several component frequencies ranging from a few Hz to several thousand Hz depending upon the circuit parameter.

Effect of natural frequency of TRV:

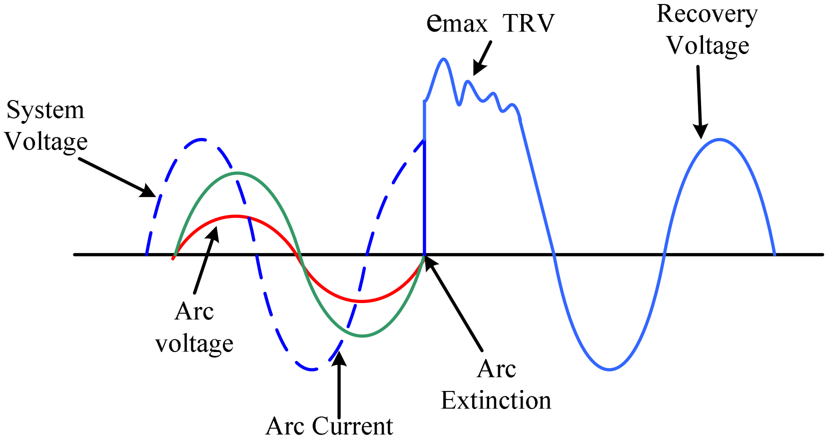
With the increase in the natural frequency of TRV, the rate of rise of TRV increases. The rate of rise of TRV across the breaker pole causes the voltage stress on the contact gap tending to contain the arc. With higher frequency, relatively less time is available to build up the dielectric strength between the contact gaps. Hence higher frequency is associated with greater stress.

The breaking capacity of a CB is related with the rate of rise of TRV and therefore with natural frequency of TRV, the breaking capacity is reduced with the increase in natural frequency.

Effect of power factor on TRV:



Unity power factor e_o at i_o (Resistive)



Zero power factor emax at io (Inductive)

The voltage appearing across the CB pole at the instant of final current zero is influenced by the power factor of the current.

The instantaneous value of the voltage developed across the pole at the instant of current zero (when the arc is extinguished) depends on the phase angle between voltage and current. i.e. power factor for unity power factor load, both current and voltage are in phase and both are zero at the instant of current zero. For zero power factors at current zero the peak of the voltage e_{max} is imposed across the pole.

Such sudden application of voltage gives rise to severe transient and has a high rate of rise of TRV. Hence interrupting current of low p.f. is a difficult switching duty.

Rate of rise and peak value of TRV depends upon several aspects such as:

1) Network configuration
2) Type of fault
3) Type of neutral earthing

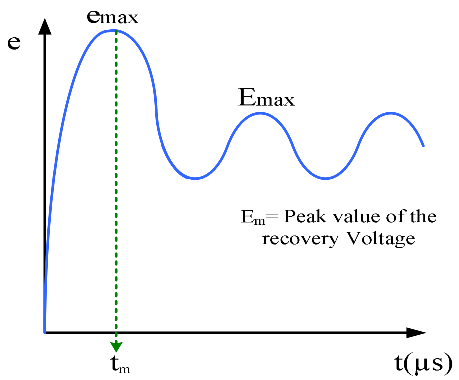
<u>Rate of rise of TRV:</u> Rate of rise of restriking voltage or TRV is usually abbreviated by RRRV and is expressed in volts/ μsec. Rate of rise of TRV and natural frequency of TRV are closely associated .RRRV depends on the system parameters. The CB should be capable of interrupting its rated breaking current under the specified condition of TRV.

The following characteristics of TRV are significant:

1) Peak value of TRV, time to reach the peak, hence the rate of rise.
2) Frequency of TRV.
3) Initial rate of rise.

If e is the restriking voltage, then RRRV = $\frac{de}{dt}$ volts/µSec.

Peak restriking voltage is defined as the maximum instantaneous value attained by the restriking voltage (e_m)



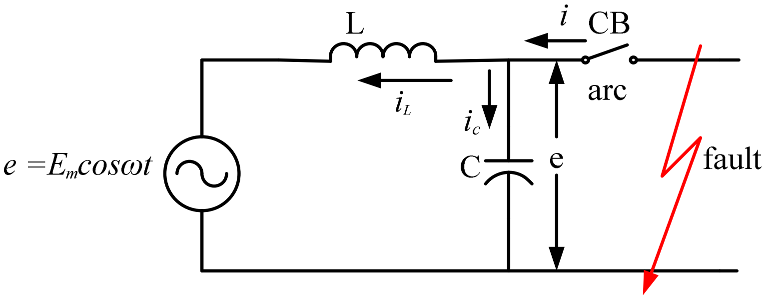
RRRV = $\frac{e_m}{t_m}$ V/ µSec; Amplitude factor = $\frac{e_m}{E_m}$

e_m = Peak value of restriking voltage ; E_m = Peak value of recovery voltage.

Natural frequency = $\frac{10^3}{2t_m}$ kilocycle / sec

Since f = $\frac{1}{t}$ $=$ $\frac{1}{2t_m}$ for any sinusoidal wave form.

Derivation of Restriking Voltage



Consider the above circuit , when current reaches zero at final arc extinction , a voltage e is suddenly impressed across capacitor and therefore , across the CB contacts.

The current i which would flow to the fault is now injected in the capacitor and inductance . Thus

$$i = i_L + i_c = \frac{1}{L}\int e\,dt + c\,\frac{de}{dt} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

$$\therefore \frac{di}{dt} = \frac{e}{L} + c\,\frac{d^2e}{dt^2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (2)$$

System voltage, $e = E_m \, Cos\ \omega t$

$I = \frac{E_m}{\omega L} Sin\ \omega t$ [since the current lags the voltage by 90 degree before opening of CB]

$$\frac{di}{dt} = \frac{E_m}{\omega L}\omega Cos\omega t \ldots\ldots\ldots\ldots\ldots.. \quad (3)$$

At t=0, $$\left|\frac{di}{dt}\right| = \frac{E_m}{L} \ldots\ldots\ldots\ldots\ldots\ldots.. \quad (4)$$

Putting (4) in equation (2) we get,

$$\frac{Em}{L} = \frac{e}{L} + c\,\frac{d^2e}{dt^2}$$

Solving this equation for e, we get

$$e = E_m\left(1 - Cos\frac{t}{\sqrt{LC}}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

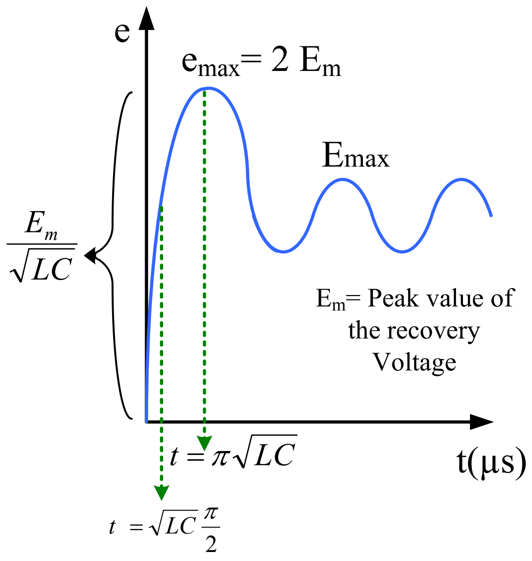
E_m = Peak value of recovery voltage, phase to neutral

t = time in sec

L = inductance in Henry

e = restriking voltage in volts

C = Capacitance in farad



$$RRRV = \frac{de}{dt} = \frac{d}{dt}\left[Em\left(1 - \cos\frac{t}{\sqrt{LC}}\right)\right]$$

$$= \frac{Em}{\sqrt{LC}}\sin\frac{t}{\sqrt{LC}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

RRRV is maximum when its derivative is zero

$\therefore \quad \frac{d}{dt}\left(\frac{de}{dt}\right) = 0 \qquad$ or, $\quad \frac{d}{dt}\left(\frac{Em}{\sqrt{LC}} \sin\frac{t}{\sqrt{LC}}\right) = 0$

or, $\frac{Em}{LC} \cos\frac{t}{\sqrt{LC}} = 0$

$\therefore \quad \frac{t}{\sqrt{LC}} = \frac{\pi}{2}$ or, $t = \sqrt{LC}\,.\frac{\pi}{2}$ …… …… …… …… …… …… …… …… …… …… ….(7)

The maximum RRRV is the value of $\frac{de}{dt}$ at $t = \sqrt{LC}\,.\frac{\pi}{2}$

Putting equation (7) in equation (6)

$$(RRRV)_{max} = \frac{Em}{\sqrt{LC}} \sin\frac{\sqrt{LC}\,.\frac{\pi}{2}}{\sqrt{LC}} = \frac{Em}{\sqrt{LC}} \sin\frac{\pi}{2} = \frac{Em}{\sqrt{LC}}$$

Further, peak restriking voltage occurs when e is maximum i,e.

When $\frac{de}{dt} = 0$

i,e, $\frac{de}{dt} = \frac{Em}{\sqrt{LC}} \sin\frac{t}{\sqrt{LC}} = 0 = \sin\pi$

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

So, Peak restriking voltage is equal to [from eq (5)]

$$e_{peak} = E_m \left(1 - \cos\frac{\pi\sqrt{LC}}{\sqrt{LC}}\right) = 2\,E_m$$

Summary

$e = E_m (1 - \mathrm{Cos}\frac{t}{\sqrt{LC}})$

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

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

$(RRRV)_{max} = \frac{Em}{\sqrt{LC}} \quad (\text{at} \quad t = \frac{\pi}{2}\sqrt{LC})$

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

so, $(RRRV)_{max} = 2\pi f_n \times E_m$

or, $(RRRV)_{max} \infty f_n$

The maximum value of rise of restriking voltage is proportional to the natural frequency of the circuit.

Example:

A 50Hz , 3ϕ alternator with grounded neutral has inductance of 1.6 mH per phase and is connected to bus bar through a CB. The capacitance to earth between the alternator and the CB is 0.003μF per phase . The CB opens when r.m.s value of current is 7500A.

Determine:

a) Frequency of oscillation.

b) The expression of TRV.

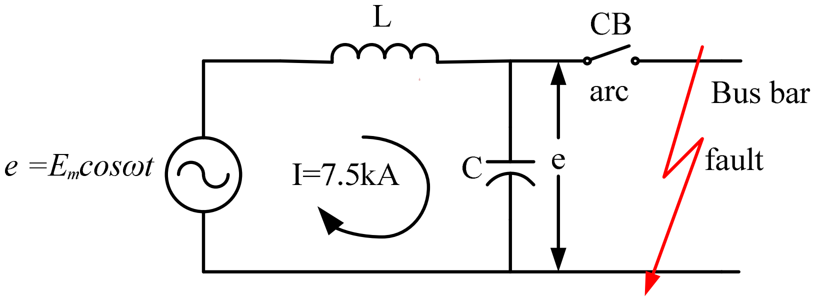
c) Maximum RRRV.

d) Time for maximum RRRV.

e) Maximum voltage across the contacts of the CB after the instant when arc extinction takes place

f) Average rate of rise of voltage up to the first peak of the oscillation.

Solution:



a) $f_n = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{1.6\times10^{-3}\times0.003\times10^{-6}}}$ Hz ≅ $72644\ Hz$

b) I = 7500A ωL = 2πfL = 2πf× 1.6×10^{-3}

E = IωL = 7500× 314 × 1.6×10^{-3} = 3768 volts (rms)

$E_m = \sqrt{2}E = \sqrt{2}\times3768 = 5328$ volts.

Restriking Voltage, $e = E_m\,(1-\cos\frac{t}{\sqrt{LC}}) = 5328\,(1-\cos\frac{t}{\sqrt{1.6\times10^{-3}\times0.003\times10^{-6}}})$

$= 5328\,(1-\cos\frac{t}{2.2\times10^{-6}})$

c) $(RRRV)_{max} = \frac{Em}{\sqrt{LC}} = \frac{5328}{2.2\times10^{-6}}$ = 2422 volts/μSec

d) Time for max $(RRRV)_{max}$, $t = \frac{\pi}{2}\sqrt{LC} = 2.2\times10^{-6}\times\frac{3.14159}{2}$ = 3.45 μSec.

e) $e_{max} = e_{peak} = 2E_m = 2 \times 5328 = 10.656$ kV

f) Average rate of rise $= \frac{e_m}{t_m}$, t_m is the time to reach e_{peak}

$$= \frac{\text{e peak}}{\pi\sqrt{LC}} = \frac{10.656}{3.14\times2.2} \text{ KV/µSec}$$

Problem:

A 50 Hz, 66 kV, 3 phase generator has an earthed neutral. The inductance and capacitance per phase of the system are 7.5mH and 0.015 µF respectively . In a short circuit test the p.f. of the fault current was 0.25A and the fault current was symmetrical and the recovery voltage was observed as 90% of the full line voltage. Calculate the rate of rise of restriking voltage (phase of neutral value assume that fault is isolated from the ground).

Solution :

L-L voltage = 66 kV

∴ Phase voltage $= \frac{66}{\sqrt{3}}$ kV (rms)

Peak value of the recovery voltage, $E_m = \frac{66}{\sqrt{3}} \times \sqrt{2} = 54$ kV

Active recovery voltage, $Em = k_1k_2k_3E \sin\varphi$

Where k_1 = demagnetizing factor $= \frac{recovary\ voltage}{system\ voltage} = 0.9$

k_2 = condition factor

= 1 (when the symmetrical fault is grounded) or,

= 1.5 (when the symmetrical fault is not grounded)

K_3 = 1 (if active recovery voltage between phase & neutral is required)

or, $\sqrt{3}$ (if active recovery voltage between the two lines is required)

In this case $E_m = 0.9\times1.5\times1\times \sin[\cos^{-1} 0.25] \times E_m = 70.58$ kV

Max. Restriking Voltage, $e_{peak} = 2E_m = 2\times 70.58 = 141.16$ kV

Time to reach the peak restriking voltage, $tm = \pi\sqrt{LC} = 3.14\sqrt{7.5\times10^{-3}\times0.015\times10^{-6}}$

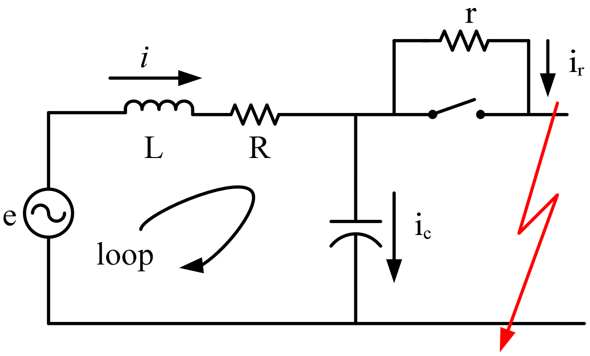
$$= 33.3\mu Sec$$

∴ Rate of rise $= \frac{e_{peak}}{33.3} = \frac{141.16}{33.3}$ kV/μSec.

Resistance Switching, Damping of TRV, Opening resistors:

A deliberate connection of resistance in parallel with contact space (arc) is called resistance switching. Resistance switching is used in CB having high post zero resistance of contact space (Air blast CB).

Let us see the effect of such a resistance on the frequency of restriking voltage transient (TRV)



Considering the current loop, we get

$$e = Ri + L\frac{di}{dt} + \frac{1}{C}\int i_c\,dt \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.(1)$$

$i_r.\,r = \frac{1}{C}\int i_c\,dt$ or, $r\,\frac{di_r}{dt} = \frac{i_c}{C}$ or, $i_c = r.c\,\frac{di_r}{dt}$ or, $\frac{di_c}{dt} = r.c\,\frac{d^2 i_r}{dt^2}$

Again, $i = i_r + i_c$

From equation (1), $e = Ri + L\frac{di}{dt} + i_r.\,r$

or, $e = R(i_r + i_c) + L\frac{d}{dx}(i_r + i_c) + i_r.\,r$

or, $i_r\,(R + r) + L\frac{di_r}{dt} + L\frac{di_c}{dt} + Ri_c = e$

or, $i_r\,(R + r) + L\frac{di_r}{dt} + L\,r\,c\frac{d^2 i_r}{dt^2} + R\,r\,c\frac{di_r}{dt} = e$

or, $L\,r\,c\frac{d^2 i_r}{dt^2} + (R\,r\,c + L)\frac{di_r}{dt} + (R + r)\,i_r = e$

we want to see the transient response of this 2nd order differential equation, so we need form the homogeneous equation . we can do it by setting the forcing function equal to zero(i.e: e=0)

So ∴ The Above equation becomes

$$\mathrm{L\,r\,c}\,\frac{d^2 i_r}{dt^2} + (\mathrm{R\,r\,c} + \mathrm{L})\,\frac{di_r}{dt} + (\mathrm{R} + \mathrm{r})\, i_r = 0$$

$$\mathrm{b_2} \qquad\qquad \mathrm{b_1} \qquad\qquad \mathrm{b_0}$$

The characteristic equation becomes

$$\mathrm{r\,L\,c}\; m^2 + (\mathrm{R\,r\,c} + \mathrm{L})\,\mathrm{m} + (\mathrm{R} + \mathrm{r}) = 0 \qquad (\text{ where } \mathrm{m} = \frac{d}{dt})$$

Critical Damping, $b_1^{'} = 2\sqrt{b_2 . b_0} = 2\sqrt{rLc\,(R+r)}$

Actual Damping, $b_1 = (\mathrm{Rrc} + \mathrm{L})$

Damping ratio, $\zeta = \frac{b_1}{b_1^{'}} = \frac{\mathrm{R\,r\,c} + \mathrm{L}}{2\sqrt{rLc\,(R+r)}}$

Undamped natural frequency of oscillation of RRV

$$\omega_n = \sqrt{\frac{b_0}{b_2}} = \sqrt{\frac{R+r}{rLc}}$$

The damped natural frequency of oscillations

$$\omega_d = \omega_n \sqrt{1-\zeta^2}$$

$$= \sqrt{\frac{R+r}{rLc}} \cdot \sqrt{1 - \frac{(Rrc+L)^2}{4rLc\,(R+r)}}$$

$$= \sqrt{\frac{1}{Lc} + \frac{R}{rLc} - \frac{1}{4}\,\frac{(Rrc+L)^2}{(rLc)^2}}$$

$$= \sqrt{\frac{1}{Lc} - \frac{1}{4}\left(\frac{R}{L} - \frac{1}{rc}\right)^2}$$

Damped natural frequency, $f_d = \frac{1}{2\pi}\sqrt{\frac{1}{Lc} - \frac{1}{4}\left(\frac{R}{L} - \frac{1}{rc}\right)^2}$

The attenuation $\sigma = -\frac{b_1}{2b_2}$ (which is the real part of the complex root)

$$= -\frac{Rrc + L}{2(rLc)} = -\frac{1}{2}\left(\frac{R}{L} + \frac{1}{rc}\right)$$

If R≤ L, then, $f_d = \frac{1}{2\pi}\sqrt{\frac{1}{Lc} - \left(\frac{1}{2rc}\right)^2}$

From the above equation it is clean that if parallel resistance r across the contact is $r = \frac{1}{2}\sqrt{\frac{L}{C}}$, then , The, $f_d = \frac{1}{2\pi}\sqrt{\frac{1}{Lc} - \left(\frac{1}{2\times\frac{1}{2}\times\sqrt{\frac{L}{c}}\times c}\right)^2} = \frac{1}{2\pi}\sqrt{\frac{1}{Lc} - \frac{1}{Lc}} = 0$

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 CB for opening operation is called opening resistor R.

When the post zero resistance of contact space is low, no resistance switching is necessary as in the case of plain oil CB. Resistance switching assists the CB in interrupting low magnetizing current and capacitive currents. The post zero resistance of Air blast CB is high. This may result in sever voltage transients due to current chopping. Then resistance switching is adopted.

The magnitude of opening resistance for resistance switching is given by, $r = \frac{1}{2}\sqrt{\frac{L}{c}}$

The fault current, $I_{sc} = \frac{E}{\omega L}$ $\therefore L = \frac{E}{\omega . I_{sc}}$

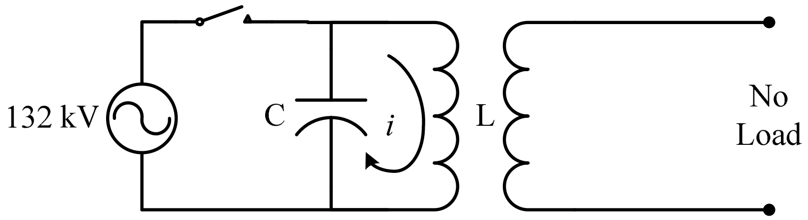
$$\therefore r = \frac{1}{2}\sqrt{\frac{E}{\omega . I_{sc} . C}} = \frac{1}{2}\sqrt{\frac{E}{\omega C I_{sc}}} = k\sqrt{\frac{1}{I_{sc}}}$$

Hence, the magnitude of resistance depends on the fault current.

Example:

In a system of 132 kV , the phase to ground capacitance is 0.01 μF , the inductance is 6.0 H. Calculate the voltage appearing across the pole of a CB , if a magnetizing current of 10A (instantaneous) is interrupted. Calculate the value of the resistance to be used across the contact gap to eliminate the restriking voltage transients.

Solution:



$1/2Li^2=1/2Cv^2$

L = 6 H; C = 0.01 μF

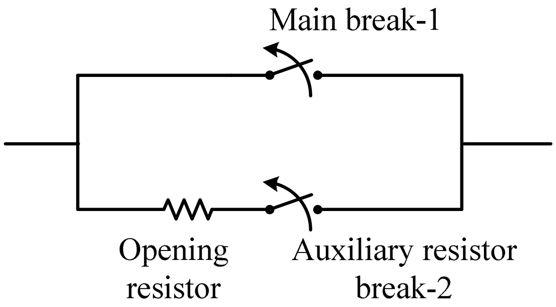
$$\frac{1}{2} L\, i^2 = \frac{1}{2} C\, v^2$$

$$v = i\sqrt{\frac{L}{C}} \quad = \quad 10\sqrt{\frac{6}{0.01\times10^{-6}}} \quad = 254 \text{ kV}$$

The magnitude of r for which no TRV is produced,

$$r = \frac{1}{2}\sqrt{\frac{L}{C}} \quad = \frac{1}{2}\sqrt{\frac{6}{0.01\times10^{-6}}} = 0.5 \times 2.45 \times 10^{4}\,\Omega \quad = 12.25\ \text{K}\Omega$$

<u>Use of opening resistor / switching resistor</u>



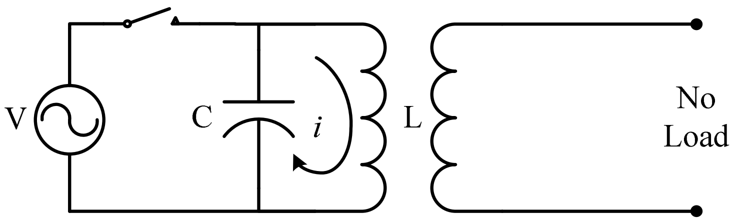
Opening resistors , also called switching resistor, are fitted in parallel with main break in series with a resistance switch. The opening resistor comes into the circuit prior to the opening of the main break-1 by closing the resistor switch-2.

During arc interruption process in the main break , the resistor switch-2 remains closed. The resistor switch-2 open with a certain delay after the opening of the main break.

<u>Interruption of low magnetic current, current chopping:</u>

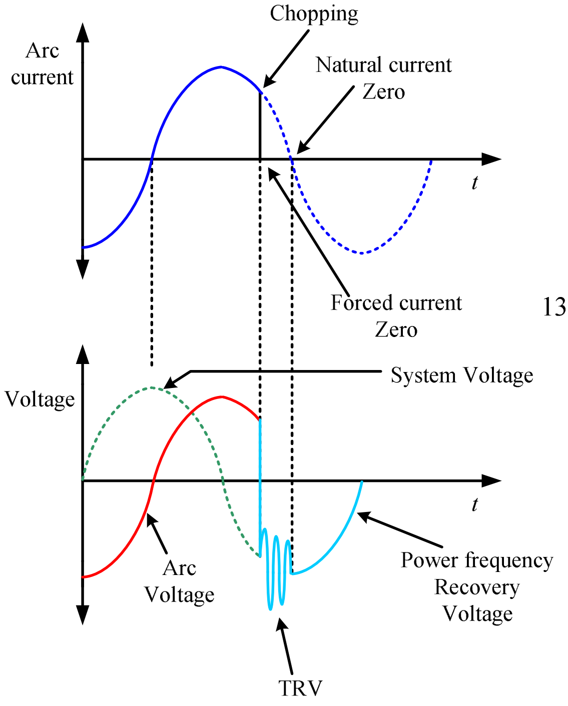
The necessity of interrupting small inductive currents arises while disconnecting transformers on no load. No load current of transformer i.e. magnetizing current are almost zero p.f lag. The current is much smaller than normal current rating of the CB. The breaking of such a low current presents a severe duty on the breaker.

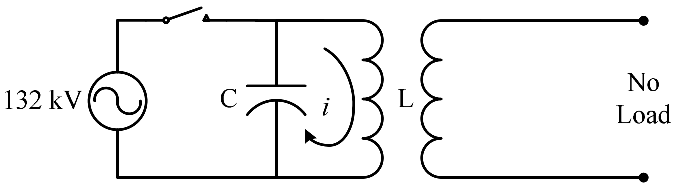
The following circuit diagram illustrate low inductive current,



$$1/2Li^2 = 1/2Cv^2$$

When interrupting low inductive current such as magnetizing current of transformer, shunt reactor, the rapid deionization of contact space and blast effect may cause the current to be interrupted before its normal zero. This is called current chopping.





$1/2Li^2=1/2Cv^2$

The energy stored in inductance for value of current i, is diverted to the capacitance at the time of current interruption i.e.

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

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

Due this current chopping transient voltage having high RRRV appears across the contacts unless they arc restrikes. If it restrikes further chop may occur or several chops may be occur before the current is finally interrupted. CB may fail to clear the fault. If restrike does not occur, a severe voltage appears across the CB contact and on the system. Resistance Switching is adopted to overcome the effect of over voltage due to the current chopping.

Example of rating of the 145KV CB:

Rated voltage - 145 KV;

Rated frequency - 50 Hz;

Rated insulation level- 1min, Power frequency withstands - 275 KV;

Impulse withstand - 650 KV (Peak);

Rated normal current - 1600 A (r.m.s);

Rated short circuit breaking current - 25 KA;

Rated duration of short circuit - 1 sec;

Rated short circuit making current - 62.5 KA (Peak);

Total break time (max) - 3cycle;

Low resistance or zero point instruction:

This method is employed in AC arc interruption. Actually the alternating current passes through zero 100 times per second in 50 cycle's current wave. At every current zero the arc is vanished for a brief moment. However the arc appears again with the rising current wave. In AC CB the arc is interrupted at current zero. At current zero, the space between the contacts is deionized quickly by introducing fresh unionized medium such as oil or blast of fresh air or SF_6 gas between the contacts .The dielectric strength between the contact space increases to such an extent that the arc does not continue after current zero. A high voltage may appear across the contacts. This voltage may re establish the arc if the dielectric strength of the gas is less than the restriking voltage. In this case the arc continues for another half cycle and may get extinguished at next current zero.

In various types of CB design, the provision is to remove the hot gases from the contact space immediately after the arc extinction so as to fill the contact space by fresh dielectric medium of high dielectric strength.

Merits of AB CB:

1. Air which is free of cost can be used at high pressure.
2. Reliable operation due to external source of extinguishing energy.
3. Air is free from decomposition.
4. Air is clean and non inflammable.
5. Free availability of air anywhere.
6. Fresh medium is used every time. Hence the breaker can be repeatedly operated if designed for such duty.

7. Due to high pressure a small contact travel is enough.
8. The same air serves the purpose of moving the contact and arc extinction.
9. High speed operation.
10. It is easy to incorporate the rapid auto releasing facility.
11. Less maintenance is required compared to OCB.
12. Better stability for repeated operation.

Disadvantages of ABCB:

1. To maintain a compressed air.
2. Leakage from the compressed air system.
3. Current chopping.
4. Very noisy.

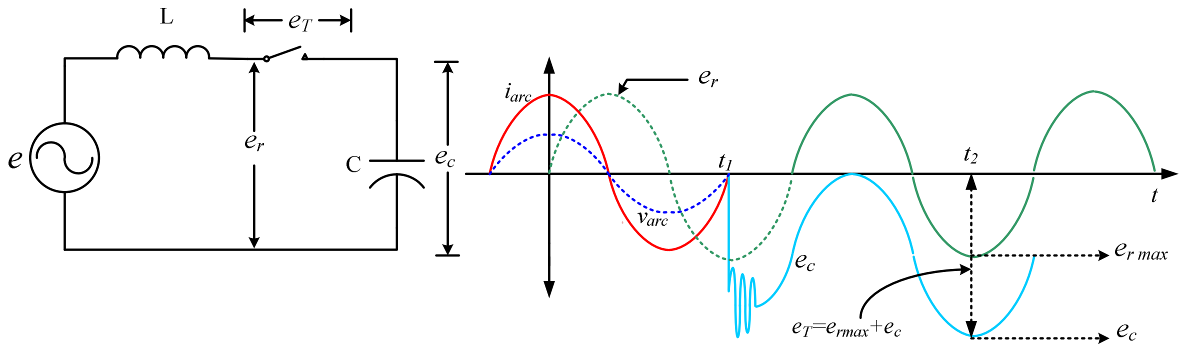
Merits of SF_6 CB:

1. Dielectric strength of SF_6 gas being higher than any other medium like oil, air, the clearance necessary for insulation is small. This why the size of SF_6 metal clad switch gear is smaller than that of conventional outdoor switchgear of same rating. Hence SF_6 gas insulated switchgear is preferred in urban areas.
2. SF_6 Gas is non inflammable and chemically stable. The decomposed products are not explosive. Hence there is no danger of fire and explosion.
3. Same gas is re circulated in the circuit. Hence refilling of gas is not required in the long run.
4. Ample overhead margin. For the same size of conductors current carrying ability of SF_6 CB is 1.5 times than that of air blast CB because of superior heat transfer capability of SF_6 gas.
5. Operation of SF_6 CB is silent unlike ABCB.
6. Sealed construction avoids the contamination by moisture, dust, sand, etc.
7. Maintenance requirement is minimum.
8. Ability to intercept low and high fault currents, magnetizing current, capacitive current without creation of excessive over voltage.
9. Excellent insulating, arc extinguishing, physical and chemical properties of SF_6 gas is greatest advantage of this CB.
10. No contact replacement is required.
11. No over voltage problem, because the arc is extinguished at natural current zero without current chopping and associated over voltage originating in CB.

Demerits of SF_6 CB:

1. Scaling problem arises due to the type of construction used.
2. Imperfect joints lead to leakage of gas.
3. Presence of moisture in the gas is very dangerous to SF_6 gas CB.
4. Double pressure SF_6 CBs are relatively costly due to the type of construction and complex gas system.
5. Single pressure SF_6 CBs are generally slower than ABCB.
6. Special facilities are needed for transporting the gas, transferring the gas and maintaining the quality of the gas. The deterioration of the quality of the gas affects the reliability of SF_6 CB.

Switching of a Capacitor Bank:



During opening a capacitor bank, the reignition and restriking can occur in an interrupter. The current drawn or supplied to the capacitor is generally of small order and CB can interrupt such small current invariably at first current zero. Due to 90^0 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 till t_2. After another cycle t_2, the recovery voltage of approximate magnitude $e_{r\,max}$ appears across the CB and the total voltage across the contact gap is sum of the two voltages i.e.

$$e_T = e_{r\,max} + e_c$$

[Voltage across CB=Maximum power frequency recovery voltage + voltage across the Capacitor]

Thus the transient recovery voltage of the order of $2E_{max}$ might appear across the CB of the instant of t_2, after one cycle from current zero. Therefore, restrikes may occur and this can cause damage to the interrupter.

Switching of unloaded transmission line:

When charging current of line is to be interrupted, the current gets interrupted while the trapped voltage on the line remains leaking away slowly. The same thing happens here as in the case of capacitor bank i.e. after one cycle from the arc interruption when the voltage from the supply side has reached positive peak, the voltage across the current of the breaker twice the normal value. If the insulation of the breaker gap is insufficient, restrikes occur. The whole energy $\frac{1}{2}CV^2$is discharged through the arc. This may shatter the arc control devices in the interrupting chamber. The over voltages are relatively less in earthed neutral system. Overvoltage of 3.5 times the normal voltage can be developed on a cable system.

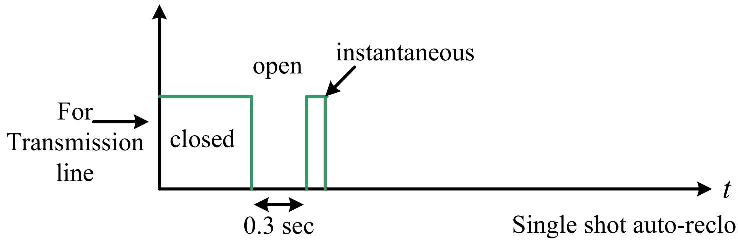
Remedies:

1. Earth neutral.
2. Uses of lightning arrestor.
3. Uses of switching resistor.

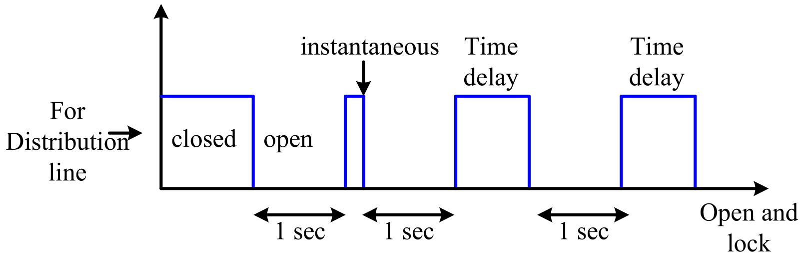
Auto reclosure:

It is the special type of CB in which a mechanism is provided so that the contact of CB will be opened due to a fault on the system. Then the contacts of the CB will be automatically closed after a short delay. If the fault is removed within this delay time, the contact will remain closed; otherwise it will be opened. In this way The CB will try to close its contact three times. If the fault still exists, then the CB will remain opened.

Dead time of auto reclosure: minimum 0.2 sec must be allowed to enable the contact space to become deionized completely. Hence a dead time of 0.3 sec can be taken as a safe re closure time.

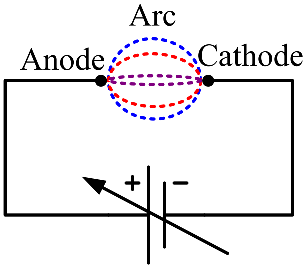


Single shot auto-reclosure



Electric arc:

The electric arc is a self sustained discharge of electricity between electrodes in gas or vapor, when the voltage is applied between the electrodes of the order of minimum ionizing or minimum existing potential of the gas or vapor.



If the supply voltage is increased, the space between the electrodes is ionized by electric field emission and a current start to flow through gas in the contact space. This phenomenon is called discharge gas. The arc has a brightly burning core of high temperature ranging from 6000°k to 25000°k. If the arc is cooled, the temperature increases. The cooling reduces its diameter and there by current density increases resulting in high temperature. The current density of arc core is several thousand ampere/cm^2. The central core is surrounded by a column of hot gases of temperature of about 1000°k down to a low temperature.

Volt ampere characteristic of a steady arc is given by

$$V_{arc} = A + Bd + \frac{C+Dd}{i_{arc}} \qquad \ldots\ldots\ldots\ldots (1)$$

Where, V_{arc}=Voltage across the arc;

i_{arc}=current in the arc;

d=length of the arc;

A, B, C, D=constants;

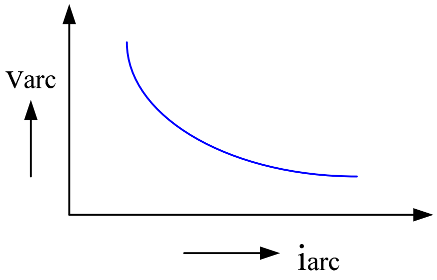
A+$\frac{C}{i_{arc}}$ is the cathode plus anode voltage;

(B+$\frac{D}{i_{arc}}$)d is the component of voltage across the length of the arc;

For small length of arc the second component should be neglected and then the V_{arc} becomes

$$V_{arc} = A + \frac{C}{i_{arc}} \qquad \ldots\ldots\ldots\ldots (2)$$

Hence from equation 1 & 2 it is seen that the voltage across the arc is reduced as the arc current is increased as shown below,



Energy dissipated in the steady arc in the form of heat is

$E_{arc} = V_{arc} \times i_{arc}$ .... (3)

Where, E_{arc}= Energy in joules;

V_{arc}=arc voltage (volts);

i_{arc}=arc current (amp);

t=duration of arc in sec.

Let, $i=i_m sin\omega t$;

v (arc voltage) $=i \times r$; [where r is the arc resistance]

Assuming the resistance of arc is constant during the brief period of arcing.

The energy dissipated in the arc is

$$E_{arc} = \int_0^t vidt$$

$$=\int_0^t vi_m sin\omega tdt$$

$$=\int_0^t iri_m sin\omega tdt$$

$$=\int_0^t ri_m sin\omega ti_m sin\omega tdt$$

$$=\int_0^t ri_m^2 sin^2\omega tdt$$

Mode of arc extinction:

1. High resistance arc extinction,

2. Low resistance arc extinction,

High resistance arc extinction:

This can be achieved by increasing the resistance of the arc

$$r_{arc} = \frac{v_{arc}}{i_{arc}}$$

Assuming i_{arc} constant, r_{arc} can be increased by increasing the length of the arc.

The voltage of the arc is increased till it is more than the system voltage across the contacts. At this point the arc gets extinguished .This method is used in the dc CB and low & medium voltage air circuit breaker (ACB).

The arc resistance can be increased by the following methods

1. Lengthening the arc by means of arc runners,
2. Splitting of the arc,
3. Cooling of the arc.

Advantage of multi breaks CB:

By the use of large number of breaks in series per pole, it is possible to increase the aggregate arc length of a more rapid rate than would be feasible with only two breaks per pole. Furthermore, even on the basis on equal rates of increase of total arc length, an increase in series is advantageous possibly because of the cooling effect of the added electrodes.

Tests of CB:

Development test -	Test individual component of CB during the development of CB.
Normal routine test-	Done at manufacturer's premises; this test confirms the proper functioning of CB.
Reliability test -	This test can be conducted at specially built laborites or at actual field where addition stress arises such as ambient temperature, humidity, dust, repeated operation, vibration etc.
Dielectric test -	1.2/50 μ sec lighting impulse withstand. 1 minute power frequency voltage withstands.

Commissioning test - This test is done after installation to verify the operational readiness and proper functioning.

Short circuit test - Stress on CB during short circuit test:

Thermal stress, in turn stress on insulation.

Electrodynamics force.

Making test

Breaking test

Fuse:

Fuse is essentially a small piece of metal connected in between two terminals mounted on insulated base which forms a series part of the circuit.

The duty of a fuse wire is to carry the normal working current safely without heating but when normal working current is exceeded it should rapidly heat up to the melting point and eventually the circuit is opened.

Metal used for fuse: - tin, lead, zinc, silver, antimony, copper, aluminum.

Minimum fusing current: - It is minimum current at which the fuse melts.

Current rating of fusing element: - It is the current at which the fuse wire can carry continuously without melting

$$\textbf{Fusing factor} = \frac{Minimun\ fuse\ current}{Current\ \ rating\ of\ the\ fuse}$$

Fuse is the simplest current interrupting device for protection for excessive current. It can be used for overload and/or short circuit protection in medium voltage up to 11 kV even 66 kV and low voltage up to 400 V installations.

Modern high rupturing capacity (HRC) fuse provides a reliable discrimination and accurate characteristics. In some respects HRC fuse is superior to CB.

Types of devices with fuse:

1. Semi enclosed or rewire able type;
2. Totally enclosed or cartridge type;
3. Current limiting fuse link - A fuse link which limits current to a considerable lower value than prospective peak.
4. Drop out fuse - A fuse link in which the fuse carrier drops out after the operation of the fuse thereby providing isolation between the terminals.
5. Explosive fuse - arc occurring during blowing of fuse is extinguished by explosion of gases produced by them.
6. HRC - Breaking capacity is above 11 KA for medium voltage cartridge fuse.
7. Striker fuse - It is a device which incorporates a fuse and a mechanical device. Its operation releases the striker with certain pressure and displacement. Striker is used for signaling /tripper indicates.
8. Switch fuse- It is a combined unit comprising fuse and switch.

Advantages of HRC fuse:

1. Capable of clearing high as well as low current.
2. Do not deteriorate with high speed.
3. Consistence in performance.
4. Comparatively cheap.
5. No maintenance is required.
6. It has inverse characteristics.
7. Quite reliable and can be selected for proper discrimination.

Disadvantages:

1. Must be replaced after each operation.
2. No interlocking facility can be incorporated.
3. Produce high heating of adjacent contacts.

How arc is formed in alternating current CB?

The separation of contacts of CB leads to the high local temperature on the contact surface. The electrons are emitted from the contact surface by thermal and field emission. The gas between the contact spaces are ionized by thermal and field collision. Because of these aspects, the space between the contacts is in the state of plasma. Therefore, arc discharge takes place between the contacts as the current carrying contacts separate.