Problems of Circuit Interruption

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Problems of Circuit Interruption
• The power system contains an appreciable amount of inductance and some capacitance. When a fault occurs, the energy stored in the system can be considerable.

• Interruption of fault current by a circuit breaker will result in most of the stored energy dissipated within the circuit breaker, the remainder being dissipated during oscillatory surges in the system.
The oscillatory surges are undesirable and, therefore, the circuit breaker must be designed to dissipate as much of the stored energy as possible.

The figure above represents equivalent circuit where L is the inductance per phase of the system (including generator, transformer and transmission line) up to the point of fault and C is the capacitance per phase of the system. The resistance of the system is neglected as it is generally small.
(i) Rate of rise of re-striking voltage. It is the rate of increase of re-striking voltage and is abbreviated by R.R.R.V. Usually, the voltage is in kV and time in microseconds so that R.R.R.V. is in kV/µ sec.

Consider the opening of a circuit breaker under fault conditions shown in simplified form in above. Before current interruption, the capacitance C is short-circuited by the fault and the short-circuit current through the breaker is limited by inductance L of the system only. Consequently, the short-circuit current will lag the voltage by 90º as shown in Fig. below, where I represents the short-circuit current and ea represents the arc volt-
age. It may be seen that in this condition, the *entire generator voltage appears across inductance \(L\).

When the contacts are opened and the arc finally extinguishes at some current zero, the generator voltage \(e_{is}\) suddenly applied to the inductance and capacitance in series. This L–C combination forms an oscillatory circuit and produces a transient of frequency:

\[
    f_n = \frac{1}{2\pi \sqrt{LC}}
\]

which appears across the capacitor \(C\) and hence across the contacts of the circuit breaker
This transient voltage, as already noted, is known as re-striking voltage and may reach an instantaneous peak value twice the peak phase-neutral voltage i.e. 2 Em. The system losses cause the oscillations to decay fairly rapidly but the initial overshoot increases the possibility of re-striking the arc.

It is the rate of rise of re-striking voltage (R.R.R.V.) which decides whether the arc will re-strike or not. If R.R.R.V. is greater than the rate of rise of dielectric strength between the contacts, the arc will re-strike. However, the arc will fail to re-strike if R.R.R.V. is less than the rate of increase of dielectric strength between the contacts of the breaker. The value of R.R.R.V. depends upon:

(a) recovery voltage
(b) natural frequency of oscillations

For a short-circuit occurring near the power station bus-bars, C being small, the natural frequency \( f_n \left( = \frac{1}{2} \pi \sqrt{\frac{L}{C}} \right) \) will be high. Consequently, R.R.R.V. will attain a large value.

Thus the worst condition for a circuit breaker would be that when the fault takes place near the bus-bars.
\[ v_R + v_L + v_C = V_s \]

\[ i = C \frac{dv_C}{dt} \]

\[ v_R = iR = RC \frac{dv_C}{dt} \]

\[ v_L = L \frac{di}{dt} = LC \frac{d^2v_C}{dt^2} \]
\[
\frac{d^2 v_c}{dt^2} + \frac{R}{L} \frac{dv_c}{dt} + \frac{1}{LC} v_c = \frac{1}{LC} V_s 
\]

\[
s^2 + \frac{R}{L} s + \frac{1}{LC} = 0 
\]

\[
\alpha = \frac{R}{2L} : \text{ Damping rate} 
\]

\[
\omega_0 = \frac{1}{\sqrt{LC}} : \text{ Natural frequency} 
\]

\[
s_1 = -\alpha + \sqrt{\alpha^2 - \omega_0^2} 
\]

\[
s_2 = -\alpha - \sqrt{\alpha^2 - \omega_0^2} 
\]
\[ vc = Vs + A_1 e^{s_1 t} + A_2 e^{s_2 t} \]

<table>
<thead>
<tr>
<th>Series</th>
<th>Parallel</th>
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<tbody>
<tr>
<td>( \omega_o )</td>
<td>( \omega_o = \frac{1}{\sqrt{LC}} )</td>
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<tr>
<td>( \alpha )</td>
<td>( \alpha = \frac{R}{2L} )</td>
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Critically Damped
\[ \alpha = \omega_o \]

Response: \( A_1 t e^{-\alpha t} + A_2 e^{-\alpha t} \)

Under Damped
\[ \alpha < \omega_o \]

Response: \( e^{-\alpha t} \left( \frac{K_1 \cos \omega_d t + K_2 \sin \omega_d t}{\omega_d^2} \right) \)

Where \( \omega_d = \sqrt{\omega_o^2 - \alpha^2} \)

Over Damped
\[ \alpha > \omega_o \]

Response: \( A_1 e^{s_1 t} + A_2 e^{s_2 t} \)

Where \( s_1, 2 = -\alpha \pm \sqrt{\alpha^2 - \omega_o^2} \)
(ii) Current chopping. It is the phenomenon of current interruption before the natural current zero is reached.

Current chopping **mainly occurs in air-blast circuit breakers because they retain the same extinguishing power irrespective of the magnitude of the current to be interrupted. When breaking low currents (e.g., transformer magnetising current) with such breakers, the powerful de-ionising effect of air-blast causes the current to fall abruptly to zero well before the natural current zero is reached. This phenomenon is known as current chopping and results in the production of high voltage transient across the contacts of the circuit breaker as discussed below:

\[
\frac{1}{2} L i^2 = \frac{C e^2}{2}
\]

\[ e = i \sqrt{ \frac{L}{C} } \text{ volts} \]

For example, if \( L \) and \( C \) are 4mH and 0.001 \( \mu \)F respectively, a current chop of magnitude 50 A would induce a voltage of

\[ e = i \sqrt{ \frac{L}{C} } = 50 \sqrt{ \frac{4 \times 10^{-3}}{0.001 \times 10^{-6}} } = 100 \times 10^3 \text{ volts} = 100 \text{ kV} \]
(iii) Capacitive current breaking. Another cause of excessive voltage surges in the circuit breakers is the interruption of capacitive currents. Examples of such instances are opening of an unloaded long transmission line, disconnecting a capacitor bank used for power factor improvement etc.
Resistance Switching

- It has been discussed above that current chopping, capacitive current breaking etc. give rise to severe voltage oscillations. These excessive voltage surges during circuit interruption can be prevented by the use of shunt resistance $R_{\text{connected}}$ across the circuit breaker contacts as shown in the equivalent circuit in Fig. below.

This is known as resistance switching.

$$f_n = \frac{1}{2\pi} \sqrt{\frac{1}{LC} - \frac{1}{4 R^2 C^2}}$$
$R$ is so chosen that the circuit is critically damped. The value of $R$ required for critical damping is $0.5\sqrt{L/C}$. Fig. 19.23 shows the oscillatory growth and exponential growth when the circuit is critically damped.

To sum up, resistors across breaker contacts may be used to perform one or more of the following functions:

(i) To reduce the rate of rise of re-striking voltage and the peak value of re-striking voltage.

(ii) To reduce the voltage surges due to current chopping and capacitive current breaking.

(iii) To ensure even sharing of re-striking voltage transient across the various breaks in multibreak circuit breakers. It may be noted that value of resistance required to perform each function is usually different. However, it is often necessary to compromise and make one resistor do more than one of these functions.
Circuit Breaker Ratings

- A circuit breaker may be called upon to operate under all conditions. However, major duties are imposed on the circuit breaker when there is a fault on the system in which it is connected. Under fault conditions, a circuit breaker is required to perform the following three duties:
  - (i) It must be capable of opening the faulty circuit and breaking the fault current.
  - (ii) It must be capable of being closed on to a fault.
  - (iii) It must be capable of carrying fault current for a short time while another circuit breaker (in series) is clearing the fault.
- Corresponding to the above mentioned duties, the circuit breakers have three ratings viz.
  - (i) breaking capacity.
  - (ii) making capacity
  - and (iii) short-time capacity.
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\[
\text{Breaking capacity} = \sqrt{3} \times V \times I \times 10^{-6} \text{ MVA}
\]

(ii) Making capacity.

There is always a possibility of closing or making the circuit under shortcircuit conditions. The capacity of a breaker to “make” current depends upon its ability to withstand and close successfully against the effects of electromagnetic forces. These forces are proportional to the square of maximum instantaneous current on closing. Therefore, making capacity is stated in terms of a peak value of current instead of r.m.s. value. The peak value of current (including d.c. component) during the first cycle of current wave after the closure of circuit breaker is known as making capacity.
Making capacity $= 2.55 \times \text{Symmetrical breaking capacity}$

(iii) Short-time rating.

It is the period for which the circuit breaker is able to carry fault current while remaining closed. Sometimes a fault on the system is of very temporary nature and persists for 1 or 2 seconds after which the fault is automatically cleared. In the interest of continuity of supply, the breaker should not trip in such situations. This means that circuit breakers should be able to carry high current safely for some specified period while remaining closed.

(iv) Normal current rating. It is the r.m.s. value of current which the circuit breaker is capable of carrying continuously at its rated frequency under specified conditions. The only limitation in this case is the temperature rise of current-carrying parts.
Example 19.1. A circuit breaker is rated as 1500 A, 1000 MVA, 33 kV, 3-second, 3-phase oil circuit breaker. Find (i) rated normal current (ii) breaking capacity (iii) rated symmetrical breaking current (iv) rated making current (v) short-time rating (vi) rated service voltage.

Solution.

(i) Rated normal current = 1500 A

(ii) Breaking capacity = 1000 MVA

(iii) Rated symmetrical breaking current = \( \frac{1000 \times 10^6}{\sqrt{3} \times 33 \times 10^3} \) = 17496 A (r.m.s.)

(iv) Rated making current = 2.55 \times 17496 = 44614 A (peak)

(v) Short-time rating = 17496A for 3 seconds

(vi) Rated service voltage = 33 kV (r.m.s.)
Example 19.2. A 50 Hz, 11 kV, 3-phase alternator with earthed neutral has a reactance of 5 ohms per phase and is connected to a bus-bar through a circuit breaker. The distributed capacitance upto circuit breaker between phase and neutral in 0.01 μF. Determine

(i) peak re-striking voltage across the contacts of the breaker
(ii) frequency of oscillations
(iii) the average rate of rise of re-striking voltage upto the first peak

Solution.

Inductance per phase, \[ L = \frac{X_L}{2\pi f} = \frac{5}{2\pi \times 50} = 0.0159 \text{ H} \]

Capacitance per phase, \[ C = 0.01 \mu \text{F} = 10^{-8} \text{ F} \]

(i) Maximum value of recovery voltage (phase to neutral)
\[ E_{max} = \sqrt{2} \times \frac{11}{\sqrt{3}} = 8.98 \text{ kV} \]

\[ \therefore \text{ Peak re-striking voltage } = 2E_{max} = 2 \times 8.98 = 17.96 \text{ kV} \]

(ii) Frequency of oscillations is
\[ f_n = \frac{1}{2 \pi \sqrt{LC}} = \frac{1}{2\pi \sqrt{0.0159 \times 10^{-8}}} = 12,628 \text{ Hz} \]

(iii) Peak re-striking voltage occurs at a time \( t \) given by;
\[ t = \frac{1}{2f_n} = \pi \sqrt{LC} = \pi \sqrt{0.0159 \times 10^{-8}} = 39.6 \times 10^{-6} \text{ sec} = 39.6 \mu \text{ sec} \]

\[ \therefore \text{ Average rate of rise of re-striking voltage} = \frac{\text{Peak re-striking voltage}}{\text{Time upto first peak}} = \frac{17.96 \text{ kV}}{39.6 \mu \text{ sec}} = 453 \times 10^3 \text{ kV/sec} \]