Introduction
High voltage circuit breakers (both transmission and distribution types) have, over recent years, seen very significant developments in both their operating function and also in the monitoring aspects of their condition. The distribution voltage circuit breaker application has seen perhaps the greatest development in both of these aspects. The development of SF₆ circuit breakers for distribution level operation and the continued development of vacuum circuit breakers have been the major areas of operational development. Bulk oil circuit breakers, once the mainstay of distribution system short circuit protection are now no longer used, having been replaced by, primarily, vacuum CBs.

In addition, there have also been very significant improvements in the condition monitoring aspects, particularly in the distribution area, with most circuit breakers now providing intrinsic condition monitoring sensors which are able to give data on operational aspects such as contact speed, contact travel (and hence contact wear), gas leakage, contact resistance, gas content etc. The analysis of such data as led to substantial developments using data mining techniques for switchgear condition analysis.
This lecture material will cover all aspects of circuit breakers including operational details and monitoring details. It will cover traditional switchgear types which are still in use and modern types which are now becoming widespread. The means of arc interruption is covered as it is often necessary to use this as a basis for determining condition monitoring requirements.

1 Circuit Breaker Fundamentals

Overcurrent and overvoltage faults in power systems can inflict severe damage upon electrical equipment unless the fault can be isolated quickly. In the general case of faults of the overcurrent type, over-heating of equipment or damage due to electrodynamic forces may occur.

In order to achieve the above aim in protecting electrical equipment it is necessary to have some device or material which is capable of changing its electrical conductivity from that of a good conductor to that of a good insulator in a very short time interval. It is perhaps somewhat ironic that the electric arc, which appeared simply as a considerable obstacle to circuit breaking in early power systems, is the one medium which can best perform the duties outlined above, over the range of voltages and currents needed for system protection. To quote Joseph Slepian, a pioneer of circuit-interrupter development: "...closer scrutiny of the fundamentals involved shows that .... far from being all nuisance, the arc plays a very necessary and useful role in circuit interruption and if the arc did not occur spontaneously it would have been necessary to
invent it or some more expensive and equivalent device to take over its useful functions. Instead of being malicious, nature has really been most kind and beneficent in thrusting upon us the electric arc for use in interrupting high powered circuits".

Since the pioneering work of Slepian in the U.S.A., Wedmore in the U.K. and Kesselring in Germany our understanding of the electric arc and its role in circuit interruption has improved to a stage where it is now possible to predict accurately the performance of some circuit interrupters with the use of theoretical models of the arc. Such detailed knowledge of arc properties and the processes of circuit interruption are necessary if circuit interrupters are to keep pace with increasing voltage and current levels in large power systems and to serve increasingly stringent demands and applications in existing systems.

Although the arc plays a necessary role, the problem is that it will also have some potentially deleterious effects on the further operation of the breaker. For example, the arc will cause substantial heating at the contact surfaces and this may have some negative impact on the contact resistance when they re-close after operation. Any damage to the surface will increase contact resistance and lead to increased contact heating. Thus the damage must be monitored somehow. Further, the mechanical operation of the CB needs to be as fast as possible to limit arcing duration and overall circuit interruption time. The overall circuit interruption time is composed of a circuit breaker unlatching time, spring activation time, contact separation time and arcing time.
During all of this over interruption period the circuit is carrying full current and even before the arc in the CB is generated, considerable damage due to electrodynamic forces and thermal effects may occur in parts of the systems simply carrying through-fault current. Thus the mechanical operation must be as rapid as possible.

If there is some impediment to movement this can have severe ramifications. Thus, contact movement and velocity need to be monitored. In sealed units such as GIS (SF6 gas insulated systems) or in other types of SF6 circuit breakers or in vacuum circuit breakers, there must be some detection of gas leaks (loss of SF6 to the ambient or ingress of air into the vacuum bottle). Loss of (or increase of) pressure may cause loss of interrupting capacity and this can cause severe problems with meltdown due to sustained arcing.

There is thus need for thorough condition monitoring of switchgear and associated items of equipment. To understand the type of monitoring needed we must first look at arc properties.

1.1 The Arc

In essence, the circuit interruption process involves the establishment of an arc discharge followed by controlled extinguishing of the arc, resulting in the formation of a region of high dielectric strength between the terminals of the interrupter. Thus we should consider in turn the way in which an arc can be produced, the properties of the arc generated and, finally, ways in which the arc can be extinguished.
Arc Formation by Contact separation:

This is the method used in circuit breakers (and in all electromechanical switches) and is a simple mechanical separation of the electrical contact between two conductors carrying a current. When separation occurs an arc forms as the result of complex processes occurring during and just after the parting of the contacts. When the contacts are closed during normal CB operation, a mechanical force is applied to the contacts to keep the contact resistance as low as possible and then, during the CB opening process, the force is removed and there is a consequent increase in contact resistance and then springs act to open the contacts quickly.

As a result, before the contacts move, ohmic heating increases; then as the moving contact starts to move, but before actual separation, the resistance increases further as contact area decreases until at the instant just before actual separation the area of electrical contact is so small and resistance so high that the contact material melts because of ohmic heating. The high temperature generated at the contact by contact heating and the voltage across the gap after final separation are then able to generate enough electron emission from the contact metal to ionize the medium between the contacts, thus allowing current to continue via the establishment of a self-sustaining arc between the contacts. The nature of the arc and its properties are dependent on the medium between the opened contacts; the arc may be in air, sulphur hexafluoride ($\text{SF}_6$), vacuum etc., depending on the type of circuit breaker.
The effect of arcing on the contacts can be quite severe and the need to ensure low contact resistance when reclosing occurs after arcing means that considerable attention has to be paid to the contact material and design. The wear of the arcing contacts is a particularly important parameter to measure as part of CB monitoring systems. Similarly the opening and closing actions and their reliability are important, particularly in low voltage (less than 1000 volts) current-limiting circuit breakers.

1.2 Arc Properties

To describe the operation of circuit interrupters it is necessary to understand some of the processes and properties of the arc and the way in which the arc can be manipulated in circuit interruption.

The electric arc is a particular type of electrical discharge and is manifest only in gaseous media. When a gas is sufficiently hot (about 6000 K for air) ionization due to thermal agitation and collisional processes occurs, thus providing free electrons and ions which may then allow the conduction of current if an electric field is applied. Once current starts flowing the electrons and ions gain energy from the electric field and can maintain ionization if the current is high enough: the arc is then a self-sustaining discharge capable of carrying current. Thus air, for example, which is a good insulator at room temperature will become a good conductor when sufficiently hot.
If the heat source is removed, recombination of ions and electrons takes place as the temperature falls without the heat input and the non-conducting state is again attained with no significant damage to the medium.

At this stage it should be explained that oil circuit breakers, which have contacts opening under oil are actually a form of gas circuit breaker in that, when the contacts part, the high temperature generated by the heating causes the oil to decompose into hydrocarbon gas (mainly hydrogen) and the arc thus burns in a gaseous bubble of hydrogen, surrounded by oil.

From the above discussion it can be seen that the heat dissipation processes from the arc are of paramount importance in circuit interruption. Further, as arc interruption depends on the competing processes of arc heating and heat dissipation from the arc, then the best time for circuit interruption would be at the natural current zeros in A.C. arcs when the power input is zero. This is the case for high voltage CBs, but as will be seen it is possible to make current limiting CBs at low voltage, which drive the current to an artificial zero by virtue of the very high impedance of the arc generated in such a current limiting CB. This is a similar result to that that occurs in HRC fuses, which are also current limiting. The generation of the high arc impedance in fuses and LV circuit breakers is by different means, but achieves the same result.
1.3 Heat Dissipation from Arcs

To extinguish the arc, heat must be removed from the arc more quickly than it is being developed by the ohmic heating caused by current passing through the arc resistance.

In its normal free state the arc loses energy by conduction, convection and radiation and when it is in a stable state the rate of heat loss from the arc equals the ohmic heating power input. Because the interruption process occurs at a natural current zero (apart from current-limiting and D.C. devices), the heat capacity of the arc is also important in that, for a given dissipation rate, the heat capacity determines the time required to remove heat from the arc. Because of the inherent thermal capacity of the arc the thermal state lags behind the power input and consequently at current zero the arc column is still at a relatively high temperature, with ionization and dissociated molecules present. Unless the heat can be removed from the arc very quickly the rising voltage across the arc after the current zero will then cause restrike of the arc for another half cycle or longer.

Thus the temperature must be reduced as quickly as possible before voltage builds up sufficiently to re-strike the arc. This particular problem is exacerbated by the fact that a high transient recovery voltage (TRV) will appear across the contacts after a current zero and this has a very high rate of rise of recovery voltage [RRRV] (typically some kilovolts per microsecond in high voltage circuit breakers).
Because of its very high temperature the arc is almost impermeable to external gas flow and to enhance heat dissipation from the arc we are limited to the arc boundary layer if we want to use gas flow around the arc to cool it by forced heat convection and similar means of heat removal from the arc surface. This heat removal will cool the arc surface, steepen the radial temperature gradient over the arc column and thus increase the internal dissipation rate due to thermal conduction.

In terms of the speed of cooling it is possible to enhance the heat dissipation rate by various means such as gas blast around the arc or by pushing the arc into contact with cool metal (deion splitter) plates or insulating (arc extension) plates. Alternatively it is possible to select an arcing medium which has inherently high natural dissipation rates. Two such material media are hydrogen and sulphur hexafluoride which are utilized in the oil and SF$_6$ circuit breakers respectively. SF$_6$ is a particularly useful medium in that, in addition to its unique thermal dissipation processes, it also has a very high dielectric strength. Hydrogen has a very high thermal capacity (and thermal diffusivity).

Another example of adaptation of the medium is the vacuum arc breaker. In this case the arc generated is supported in material evaporated from the electrodes by the heating as the contacts separate and the vapour density of the vacuum arc is many orders of magnitude less than in an air arc at atmospheric pressure. As a result the vacuum arc has a very low thermal capacity and hence a very low heat content from arcing. It is thus relatively easy to interrupt.
2 Recovery of circuit breaker isolation level

Successful interruption of current is achieved by extinguishing the arc between the contacts at the current zero. The arc extinction is dependent on the arc properties and these, in turn, are dependent on the interrupter design. However, arc extinction must be achieved against the recovery voltage which then appears across the gap. This voltage includes the normal power frequency 50 Hz voltage together with a circuit-dependent decaying transient voltage generated by discharge of energy stored in leakage capacitance.

Successful current interruption involves the arc recovery to an insulating state while being able to withstand the voltage across the gap threatening to cause gap breakdown. This has been described, in simplistic terms, as a 'race' between the increasing dielectric strength of the gap and the increasing voltage across the gap after interruption. In this simple picture, if the voltage across the gap is always less than the gap dielectric strength (measured in volts), then interruption is successful. If, on the other hand, the gap voltage is greater than the dielectric strength at any time, re-strike of the gap occurs.

In fact the recovery process is much more complex than a simple race analogy. In particular, we can define two distinct categories of gap re-strike, these being dielectric breakdown and thermal re-ignition.
2.1 Dielectric Breakdown.

This breakdown mechanism is essentially of the spark breakdown type, whereby voltage is applied across an insulating gap, with no apparent free charges being present, until at some stage a free electron passes into the gap, causes some ionization and dielectric breakdown then ensues. Such breakdown tends to occur relatively long periods after the current zero (up to hundreds of microseconds) when the voltage has reached relatively high levels across the gap and is thus able to accelerate the free electron and give it enough energy to cause ionization by collision with other molecules or atoms.

2.2 Thermal Re-ignition

Immediately after interruption the gap still contains high temperature remnants of the arc, with some free charges present. As a result, when the recovery (restriking) voltage is imposed across the recovering gap, there may result some small post-arc current flow through the finite conductivity and this will inject additional thermal energy into the gap. If the cooling action is sufficiently powerful to remove heat and extinguish this post-arc current, then current interruption will be successful. If it is not, the thermal content of the gap will build up and re-strike of the arc will occur by thermal re-ignition. Thermal re-ignition occurs very soon after extinction (few microseconds).
2.3 Interruption of small inductive currents

When circuit breakers are used to switch small inductive currents such as transformer magnetising currents, or large motors at no load, the interruption action of the arc extinguishing may be sufficiently strong to cause “current chopping” to occur. In this event, the current is interrupted before a natural zero with the result that the stored energy in the inductance \( \frac{1}{2} LI^2 \) at the non-zero current is dissipated in a high amplitude LC voltage oscillation \( (C \text{ is any shunt capacitance across the gap})\). The amplitude of the voltage is determined by the surge impedance of the equipment supplied by the circuit breaker.

\[
V_c = I_c \sqrt{\frac{L}{C}}
\]

I\(_c\) is the chopped current, \( \sqrt{L/C} \) is the surge impedance of the load. For transformers or motors, the surge impedance can be very high and the voltage arising from such chopping action will be correspondingly high. In fact the voltages from current chopping can be higher than those occurring during normal interruption.

Somewhat similar forms of overvoltage can be generated by current limiting interrupters which ramp current rapidly down to zero and, in effect, cause a controlled form of current chopping. This was a problem with early designs of fuses but with some attention to the fuse element design (e.g. notching) the overvoltage can be reduced significantly.
Variation of CB arc voltage with time

Note that the arc is a resistive circuit element

The full interruption process

Note that the peak of the recovery (restriking) voltage is greater than the peak of power frequency voltage (maximum of two times).
TRV occurring at natural current zero

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

TRV with current chopping causing an abnormal current zero.
3 Circuit Breaker Types

3.1 Air-break Circuit Breakers
As the name implies, air-break circuit breakers use air as the arcing medium. They operate at atmospheric pressure and are usually vented to the ambient. Their mode of operation is essentially aimed at forcing the arc into a state such that the necessary re-ignition voltage after a current zero is unable to be supplied (ie it is too high) from the power source. This requires that the arc be controlled so that the arc voltage is increased by some means during the interruption process. This can be done by increasing the arc length, by increasing the electric field required by the arc column to be maintained (by increasing rate of heat loss) or by increasing the total electrode voltage drop contribution of the arc.

![Variation of arc voltage with arc length](image-url)
The figure above shows the typical voltage variation along the length of an arc. Note that there are three major components: the anode voltage \(V_a\), the column voltage \(V_{\text{column}}\) and the cathode voltage \(V_c\). The sum of \(V_a + V_c\) is about 30 volts for most arcs and materials in common use as CB electrodes. The column voltage is linear with length with an approximately constant electric field. Whereas \(V_a + V_c\) is constant and independent of arc length, the column voltage will vary depending on the electric field required by the arc column thermal processes and the length of the column. Simply increasing the arc length will thus increase the arc voltage requirements. But the \(V_a + V_c\) will not change if there is only one arc.

It is a relatively simple matter to increase the overall length of an arc: the usual method is to lengthen the arc by making it interact with a transverse magnetic field (generated by the arc current). This forces the arc to move away from the contacts. To achieve a large increase in length within a relatively small volume, insulating 'splitter' plates can be used as shown in Fig.1(a).

Further improvement in interruption efficiency is obtained if the plates have good thermal conductivity for then they cool the arc. Because of the high temperature of the arc the splitter plate material must be able to withstand considerable thermal shock and high temperature. Thus a refractory material is necessary, usually alumina.
If, instead of being electrically insulating, the plates are conducting, then the arc will divide into a number of arcs in series [as in Fig. 1(b)] with each (isolated) plate acting as a cathode on one side and an anode on the other. There is no significant increase in arc length but for $N$ arcs in series there are $N$ cathodes and $N$ anodes and thus $V_c + V_a$ is increased to $N(V_c + V_a)$ for $N$ arcs. As $V_c + V_a$ is about 30 volts, only four or five arc splitter plates would give a significant increase in total $V$ for 415/240V applications. The added metal plates also aid in cooling the arc.

At very high voltages it is impractical to use air-break breakers because of the very long arcs needed or the large number of conducting splitter plates necessary. 11kV is about the usual limit, but is not used much at these voltages. This type of circuit breaker is no longer used for higher voltages: it
has been superseded by rotating arc SF$_6$ breakers and vacuum breakers.

The metal grid or de-ion type breaker is almost exclusively used for voltages below 1000 volts where, for a small number of grids and a simple design, it is an extremely efficient circuit breaker, capable of breaking very large fault currents. The design has changed very little since its original conception by Slepian in the 1930s. This technique is used for all modern LV air-break circuit breakers, including miniature breakers (up to about 32 A) and moulded case breakers, up to a 1000 A or more.

There are a number of parameters of importance to the air circuit breaker operation which must be monitored. These include contact wear, plate damage (both metal and insulating) and deposition of metal on insulating splitter plates.

### 3.2 Medium and high voltage circuit breakers

#### 3.2.1 Oil Circuit Breakers

The arc in an oil circuit breaker burns in a bubble of gas (mainly hydrogen) formed from the chemical decomposition of the oil by the heat of the contact arcing. The oil, apart from providing the gas bubble, plays little part in the interruption process which is entirely determined by the interaction of the arc with the gas bubble that it forms.
The arc is generated in a confined chamber with the result that the gas bubble generates an overpressure in the arcing chamber and forces gas to flow out of a side vent. The effect of the arc-gas interaction is to cool the arc. The gas flow set up by the arcing chamber (explosion pot) design causes convective dissipation of heat from the outer regions of the arc.

Oil circuit breakers fall into two main classes: either bulk-oil or small-oil-volume. The bulk-oil (or dead-tank) circuit breaker uses oil both to provide the gas bubble and to give basic insulation of live conductors from earth. The bulk oil breaker although still in use is not generally manufactured these days, having been supplanted by the small oil volume
(minimum oil, live tank) breaker. This form uses a small volume of oil only to provide the gas for the extinguishing process. Insulators provide isolation to earth.

Oil circuit breakers suffer from oil deterioration due to the arcing process and the oil quality is thus an important factor in the monitoring and assessment of oil CB condition. Contamination of the oil (e.g. moisture) is thus an important monitoring requirement.
3.2.2 Gas blast circuit breakers

The gas blast circuit breaker is the logical extension of the oil circuit breaker interruption principle. The gas blast circuit breaker uses a blast of gas flow to cool the arc periphery by forced convective dissipation. The extinguishing action is then dependent on the gas properties, its pressure and flow velocity relative to the arc.

Initially air was used, but during the 1950's, sulphur hexafluoride gas (SF\(_6\)) was found to have unique thermal and electrical properties which make it a far superior arc quenching medium than air. An air arc has high thermal capacity and low heat dissipation rate, while an SF\(_6\) arc has a low thermal capacity and a high thermal dissipation rate. Thus, an SF\(_6\) arc has a much lower thermal time constant than an air arc and this is the major reason for its superior arc quenching ability.

The first SF\(_6\) breaker design was adapted from dual pressure air-blast systems. However the modern SF\(_6\) high voltage breaker is much simple and has an interrupting action which is determined by the current level. This type of breaker, the SF\(_6\) 'puffer' does not have a high-pressure tank; instead the SF\(_6\) blast is generated by a piston action incorporated in the operating mechanism. The compression of SF\(_6\) by the piston, plus the pressure increase due to the heat of the arc generate a high gas flow relative to the arc.
Air blast principle with four breaks per phase. Current flow in red.

Detail of the mechanisms of two breaks in an air blast breaker. Note the resistors for control of TRV level and capacitors for voltage grading over the breaks.
3.2.3 Rotating arc circuit breakers

In gas blast circuit breakers the arc is essentially stationary after the contacts open and the relative motion between arc and gas, which provides the cooling action, is obtained by forcing the moving gas to move past the stationary arc. It is possible to achieve the same cooling effect by forcing the arc to move relative to a static gas environment. This latter approach has been used in the SF6 rotating arc breaker which provides an extremely efficient circuit breaker within the general distribution voltage regime.

The basic operation is very simple, requiring less moving parts than gas-blast breakers, and thus mechanical problems are reduced. The principle of operation is shown in Fig.2. The arc current is subjected to a magnetic field with the result that the arc moves. The magnetic field is the arc current. The arc current and magnetic field produce an azimuthal force which rotates the arc around a circular or cylindrical
electrode structure. This causes the relative motion between arc and gas which aids in arc cooling.

Fig. 2: Rotating Arc Mechanism.
The rotating arc has a number of advantages, in addition to its simple mechanical construction. The arc velocity is current-dependent (because the driving force scales as $I^2$) and thus the extinguishing action is also current dependent. This aspect is particularly useful in breaking small inductive currents without producing current chopping. Because the arc and its roots are always moving, contact wear is much reduced by comparison with the stationary arc type breaker. These features, together with the simple robust construction, make the rotating arc breaker attractive both from a maintenance and a reliability viewpoint.

In terms of maintenance and monitoring requirements the SF$_6$ breakers need to have checks on gas leakage, both for operational requirements and for greenhouse concerns, on the various chemical products produced by the arcing, and on the wear of contacts.

### 3.2.4 Vacuum Circuit Breakers

The vacuum circuit breaker represents almost the ideal interrupter in that it has an extremely simple construction (Fig.3a) comprising two butt contacts, one of which is moveable, in a vacuum bottle with a pressure of about $10^{-3}$ N/m$^2$. The arc formed during interruption is very diffuse and burns in evaporated electrode material. It consists of a large number of independent arcs burning in parallel, each carrying about 100A and moving freely and non-collectively about the electrode surfaces. The motion of the individual arcs over the electrode ensures that surface heating and thus evaporation of the electrode is minimised. With the
minimal evaporation and the low arc particle density the arc extinguishes itself with no external aid at a current zero. Thus, in this mode, the vacuum breaker is almost the ideal interrupter, being extremely simple in construction and operation and possessing an extremely low arc thermal time constant.

**Fig. 3:** Vacuum circuit breakers.
(a) 15kV vacuum bottle (b) Segmented electrode design (c) Axial field design
However, at high currents (about 10kA for simple electrode designs) the electro-dynamic action of the multiple parallel arcs causes 'pinching' and collective concentration of the arc. The result is a single intense constricted arc which is anchored to the electrodes and remains static. Because of this, electrode heating and evaporation intensify to such an extent that the vacuum arc in its constricted form has almost no interrupting ability: this places upper limits on interrupting capacity and operating voltages.

The problem can be alleviated by forcing the arc to move over the surface of the electrode thereby reducing evaporation. This is achieved by electrode design to generate an electro-dynamic driving force on the arc (Fig.3b). The electrode design provides an axial magnetic field which drives the arc. This disperses the arc column uniformly over the electrode, thus avoiding constriction (Fig.3c).

Early vacuum circuit breakers were prone to current chopping but careful choice of electrode materials has controlled this, by keeping a controlled evaporation of electrode material almost down to current zero.

The major problem with vacuum circuit breakers relate to the level of the vacuum and so leak testing and/or bottle pressure are important requirements. This is however not easy to do: it requires very sophisticated equipment to measure very low level leakage currents due to electron emission. Wear of the arcing contacts is also an important consideration and the erosion of the contacts must be monitored.
4 Failure of circuit breakers and interrupters

Fault protection switchgear, including circuit breakers, fuses and surge arresters, are items of considerable importance in electrical systems. Their reliable operation is a pre-requisite for a reliable electrical supply system. However there are a number of factors involved in their operation which may act to reduce their effectiveness and thus cause some potential problems when they are called on to operate. These problems relate to both the intrinsic operational characteristics and behaviour of such devices and also to the ensuing effects of their operation (both normal and abnormal) on other equipment and components in the power supply system. More specifically, the operation of switchgear can cause problems with safety of personnel, with quality of supply, with damage to other equipment and also some potential deleterious effect on the environment.

With this in mind the operational characteristics of switchgear and their potential hazards must be examined in order to allow some evaluation of the risk associated with their operation. The potential mal-operation of such equipment also requires some attention to the condition monitoring of switchgear.

Fault protection equipment is somewhat different to other items of equipment in that it is required to operate at very infrequent periods and this lack of regular operation can lead to some problems, particularly with circuit breakers which have some substantial mechanical operation involved in their
activation. In such equipment it is the mechanical operation that most often causes problems.

In this discussion it is proposed to examine the operation and maintenance requirements of circuit breakers and the potential for risk in their use in the electrical power system.

4.1 Circuit Breaker Types

4.1.1 Transmission voltage levels:

The main types of circuit breaker are:

- Air blast,
- SF$_6$ (single and dual pressure)
- oil (bulk and SOV or minimum oil) and
- vacuum.

Small oil volume and SF$_6$ are the most common types in general use, although air-blast and bulk-oil are still in use in many older installations. Transmission level vacuum circuit breakers are very rarely found.

Of the above types, SF$_6$ is almost the only type currently manufactured for transmission voltage levels, although some of the others are still available at the lower voltage levels. Apart from SF$_6$ gas insulated switchgear (GIS) all of the above are essentially outdoor type circuit breakers at this voltage level.
4.1.2 Distribution voltage level:
The main distribution types are:

- Oil (bulk),
- SF$_6$, (self extinguishing and rotating arc)
- vacuum,
- air (magnetic) break.

Bulk oil circuit breakers, particularly at 11 kV are very extensively used in distribution and high voltage utilisation systems in industry. High voltage air break circuit breakers are still in use at these voltage levels up to 11 kV, but their size is a major limitation.

Most current manufacturing is concentrated on vacuum and SF$_6$ units. The above units are mostly for indoor applications.
4.1.3 Low and Medium voltage level (up to 1000 V)
There is only one LV type in general use:

- Air-break (moulded case) circuit breakers

These are almost universally of the air-break type, using the de-ion plate interruption arrangement developed by Westinghouse in 1926-30 and effectively unchanged since.
4.2 Circuit Breaker Faults

As dynamic rather than static electrical devices, circuit breakers are subject to general wear and other problems associated with their mechanical operation. There are also potential problems with electrical contacts and contamination and these are additional to any dielectric problems with the various insulation materials used in circuit breakers.

In addition to the specifically equipment-related problems, circuit breakers can also generate system problems when they operate: these are normally related to the various switching overvoltage transients generated by the breaker.

A typical distribution of fault categories in distribution circuit breakers is as follows:

- Mechanical 55%
- Electrical (Interrupting Circuit) 15%
- Electrical (Ancillary circuits) 15%
- Gas loss 10%
- Dielectric problems 5%

4.2.1 Mechanical Problems

It has been a long-standing tenet that the majority of circuit breaker faults are mechanical in origin (perhaps up to 90%) and while there is some truth in this for older breakers it is not necessarily true for new types of breakers. A feature of modern circuit breakers is the reduction of the complexity of
the mechanical operation. There has been some criticism of this policy as it is claimed that it renders circuit breakers less “robust”. However the reduced mechanical complexity has led to significant improvement in the mechanical fault rate.

The old dual pressure gas-blast circuit breakers (air and SF$_6$) have a myriad of mechanical levers, arms, valves, contacts etc (see a previous figure) which were (and are) prone to failure and it was this type that gave rise to the claims of a 90% failure rate. Other types such as the bulk oil and small (minimum) oil volume (SOV) type were less complex mechanically and had fewer problems. The very superior arcing and dielectric properties of SF$_6$ gas gave rise to the “puffer” or single pressure gas-blast circuit breaker, as detailed in a previous figure, and this has allowed the significant improvement in reliability that is typical of modern circuit breakers.

The sublime simplicity of the vacuum circuit breaker also means less mechanical problems and the newly developed rotating arc SF$_6$ breakers are almost as simple and reliable in mechanical operation as vacuum breakers.

The major problem with the mechanical operation is that the circuit breakers are only operated at relatively infrequent intervals and this means that the mechanical operation can suffer from seizing problems when the mechanical parts freeze up and do not move. The main problem which occurs in circuit breakers is that the circuit breaker does not open or close when activation signals are sent. The cure for this is regular operation and maintenance of existing breakers and
use of circuit breakers with minimal mechanical operation for any new installations or replacements.

In the distribution area, there is some attempt to move away from the use of withdrawable switchgear in rack-mounted systems. It is claimed that the development of such systems was the result of the need for regular maintenance of oil and high voltage air circuit breakers. Contacts needed regular attention, arc chutes needed to be cleaned and oil had to be sampled and changed. However the development of vacuum breakers and of SF₆ rotating arc technology, which have reduced maintenance requirements has led to some support for use of cheaper fixed switchgear rather than the withdrawable types.

### 4.2.2 Electrical and Insulation Problems

The electrical (dielectric) problems of circuit breakers relate to the deterioration of the insulation materials used in the circuit breakers. The dielectric materials used cover a wide range for the various types of breakers in use and include gases (air, SF₆ and hydrogen [in oil breakers]), liquids (oil) and solids (thermoplastics, epoxies, porcelain, polymers composites and laminated wood).

The potential electrical failure mechanisms which can occur include deterioration of the insulation by a variety of means, including pollution (particularly moisture ingress), chemical change and also the application of overvoltages to the various components of the CB.
Pollution is a problem particularly in those circuit breakers that are exposed to contamination from the atmosphere. This will include pollution of porcelain insulators which can lead to flashover or electrical surface tracking then leading to dielectric failure.

Dielectric problems can also occur in oil where contamination (particularly moisture) may affect the dielectric strength by chemical change and in SF$_6$ where pollution such as metal particles (mainly in GIS) may cause failure. In both of these cases, the pollution may result in electrical tracking of surfaces that can eventually cause full dielectric failure.

In the case of bulk oil circuit breakers the gases generated by oil breakdown caused by the tracking discharge can generate substantial internal pressure and the failure may involve explosion and fire effects. With such a large volume of flammable material oil fires caused by oil circuit breaker failures are a major potential problem.

Partial discharge monitoring is able to be used for such insulation tests, and these days on-line PD testing is possible. Other monitoring means include DDF monitoring for insulation determination, thermal monitoring with thermo-vision equipment for temperature rise due to bad contacts. With oil CBs, dissolved gas analysis methods are also sometimes used to detect electrical discharging.
4.2.3 Contact Problems

One of the major sources of problems with circuit breakers is that caused by the deterioration of the main switching electrical contacts. The contacts in switchgear are required to provide two main functions that are mutually incompatible. On the one hand the switching contacts have to provide a low resistance electrical joint with negligible heating during normal closed operation - this requires use of relatively soft and malleable materials such as silver or copper which give good (low) contact resistance but have very poor resistance to arcing damage. On the other hand, when the contacts open to interrupt fault current they are subject to severe damage from the high temperature arcing which occurs - ideally this task requires use of hard refractory metals such as tungsten or molybdenum which have good arcing resistance but very poor (high) electrical contact resistance. Some compromise is obviously necessary and various solutions include sintered mixtures of, for example, tungsten and copper, or the use of two separate contact systems, one for arcing and one for normal closed contact operation, with transfer of the current flow occurring during opening.

Chemical contamination is also often present in contacts, particularly in oil circuit breakers and those air circuit breakers where the contacts are exposed to atmospheric air. In the case of the oil circuit breakers the contamination may arise from the chemical decomposition products of the arcing, including carbon deposits and chemical films, such as oxides, on the contacts. The effect of these contaminants is to increase the contact resistance and this can eventually lead to
thermal runaway and arcing and melting in the contacts. This is a relatively common problem with oil switchgear, particularly the rack-mounted type.

In the air break type of circuit breaker, atmospheric contamination such as in industrial situations can also cause contact films to build up and lead to high contact resistance. Sulphide layers are particularly a problem in such situations and can also lead to thermal runaway. Sulphides are commonly encountered in some industrial sites, eg from H2S, Sox etc.

**Contact welding** can occur in situations where the fault currents are very high and where DC offset transients occur as these will generate substantial electro-dynamic forces on the contacts. This occurs because of the constriction of current streamlines which occurs at contacts and particularly at switching contacts. The constriction results in an electro-dynamic force which tends to separate the two contact faces. If the retaining spring is not strong enough, then separation may occur before the unlatching mechanism operates. Then, as the contacts separate momentarily the arcing melts the surfaces and then after the first half cycle of current the force decreases and the contacts close on to molten surfaces and weld together. Then when the unlatching process does occur a little later the contacts will not open.

Vacuum circuit breakers have a particular contact feature that makes their operation very sensitive to the contact material composition. Whereas all other circuit breakers generate arcs which burn in ambient gases (such as air or SF₆) or in gases
generated by the arcing such as the hydrogen produced by the arcing decomposition of the oil in oil breakers, the arc in a vacuum circuit breaker actually burns in a gas vapour which is the evaporated contact material and thus the arc and its interrupting properties are very sensitive to the contact material.

This dependence is such that in the initial version of vacuum breakers the contact material used caused overvoltage generation by current chopping in that the interrupting action was often premature and occurred before the natural current zero. This then leaves considerable inductive energy storage that is dissipated as an overvoltage transient which is potentially much higher than the normal TRV of the circuit breaker which interrupts at a natural current zero. Contemporary vacuum breakers now have very carefully chosen contact materials that allow current flow to continue until the true current zero.

4.3 Safety Risks Associated with Circuit Breakers

Failure of circuit breakers to perform their given duty can lead to a number of hazards, and even in the case of normal operation there are hazards that must be taken into account.

4.3.1 Risk to personnel

There are significant risks to personnel who operate switchgear, particularly in the case of high voltage indoor switchboard type systems. Many such switchboards are well-sealed and any arcing inside such systems will generate very
high pressures which can cause explosive failure of the enclosure, usually rupturing at doors or panels etc. Exposure of personnel to the high gas temperatures and arc radiation can cause very traumatic injuries to workers, including very severe third degree burns and/or electric shock.

Figure 4 shows some examples of pressure rise curves in switchgear rooms and housings during arcing faults. Prevention of such faults requires attention to:

- Conductor shrouding and effects of moisture
- Appropriate choice of insulation material for the environment
- Prevention, by design, of partial discharges or tracking
- Choice of interrupter type or regular condition monitoring
- Quality control of materials and assembly of the switchgear and housing

If the fault is of the high impedance arcing type it may be difficult to detect and this is a major problem which is not only confined to personnel safety but can also cause very substantial equipment and property loss. (The issue of high impedance faults will be examined in more detail later).

In the outdoor circuit breaker situation the personnel safety problem is not so great. However, particularly with the old dual-pressure systems explosions can occur which can create a personnel and property hazard. As an example, moisture entry into the compressed air system of air-blast circuit breakers can result in internal flashover of the ceramic
support insulators, causing explosive fracture of the porcelain which then produces high velocity missiles in the substation area.

**Fig. 4**: Examples of pressure rise in switchgear housings and enclosures.

There are also some potential hazards resulting from the decomposition products of arcing or discharges occurring in SF$_6$. While SF$_6$ is a quite inert and benign gas in its pure (and only dangerous by asphyxiation effects) some of the decomposition products which are generated by electrical discharge in SF$_6$ are toxic and some care must be exercised in maintenance and repair procedures which involve opening the SF$_6$ chambers. Maintenance procedures for preventing contact with such materials are well developed.
4.3.2 Fires arising from circuit breaker problems

Oil circuit breakers are a particular problem because of the large concentration of flammable material contained in them. Such circuit breakers are extensively used in utility distribution systems and in industrial situations and while they have proved to be very reliable, their large number and their advancing age makes them a significant risk in terms of fire. Such breakers have been in use since about the 1920s or 1930 in some cases and they represent an increasing problem of maintenance and ageing. In many cases they require some manual operation and this then creates the hazard to the operator as well as to the property in the surrounding area if they fail.

One of the major problems in such situations is the addition of extra circuits without any additional interrupting capacity of the circuit breaker. Ref (1) in the bibliography is a good review of problems with ageing oil circuit breakers and methods of failure prevention.

Other circuit breakers do not have the same bountiful source of flammable material available and are thus less likely to cause problems with fire.

4.3.3 Equipment damage caused by circuit breaker faults

There is an increasing awareness of the potential of switching transients to cause damage to electrical and electronic equipment. This is because of the consumer’s increasing
concern with power supply quality and also because of the increasing susceptibility of modern microelectronic equipment to overvoltages. Modern computers and computer controlled equipment have a much lower damage threshold than older equipment and thus circuit breaker overvoltage switching transients are often seen as a major hazard for electronic equipment.

In addition to electronics the use of switchgear for control of large motors can also present problems because of the very high surge impedance of such motors and the non-uniform voltage distribution which arises because of the leakage capacitance to earth in the windings of such items. The problem may also be exacerbated by the surge voltage build-up caused by multiple reflections in short lengths of cable connections.

Many of such problems may in fact be due to the increasing use of adjustable speed motor drives which use IGBTs as the switching elements and these devices produce many more overvoltages than circuit breaker switching and they are subject to the same build-up in cables. However the stigma of the current chopping by the old-style vacuum circuit breaker designs remains and they are often blamed for any damage to computer-controlled equipment in industry for example.

Given the risk of damage to equipment as described above, adequate overvoltage protection of such equipment is a necessary requirement for industry these days. Thus surge arresters may be needed in some locations.
4.3.4 High Impedance Arcing faults

Although they are only an indirect effect of circuit breaker operation (or lack thereof) the problem of high impedance arcing is perhaps the major problem which faces the power engineer in industry. It is difficult to detect and its effects can be devastating.

They occur because the effect of the impedance of an arcing fault which is inserted into the fault circuit. This high impedance can reduce the fault current level to a value which delays significantly the operation of the circuit breaker or fuse because of its specific current-time fault characteristic. In some cases the fault current reduction may mean that the fault is not detected by the circuit breaker’s overcurrent fault detection system because it has been reduced below the protection tripping current.

Such faults occur in both high voltage transmission and distribution lines and also in industrial supply situations. Typical forms of such faults commonly encountered include:

a Trees in contact with overhead lines, leading to potential fires caused by ignition of the moisture laden wood: the current is too low to activate normal protection and even earth leakage protection may have difficulty in detecting the fault.

b Clashing of overhead line conductors where the duration of arcing is too short to operate the overcurrent protection and in most cases the clashing fault will not be to earth, but
instead will be phase to phase and so will not be able to be protected against by earth leakage devices. This is a regular cause of bushfires in rural areas because of the emission of molten particles from the clashing arc.

c Fallen and grounded conductors: in this case the fault is obviously an earth type but the high resistance of the line-earth contact will mean that the fault current is extremely low. The arcing which occurs is able to cause fires if there is flammable material available.

d Medium voltage busbar systems where arcing is initiated by contaminated insulation are a common source of high impedance arcing faults and often are undetected and cause much damage and potential fires. In such situations arcing may occur for tens of minutes without detection. The IEEE Red Book gives guidance of allowance for such arcing in protection design. It gives multiplying factors to use when calculating fault currents. For example at 120 V, it recommends multiplying the bolted short circuit current from the fault calculation by about 0.15 to get the likely level of arc fault current.

e High impedance arcing faults can also produce substantial overvoltages because of the often high values of \( LdI/dt \) which can occur in arcs which change their length very suddenly (also common in arc furnaces): they are sufficiently damaging to have had the Petersen coil developed to attempt to eliminate them. The Petersen coil utilizes an inductance that combines with arc earth capacitance when arc faults occur and gives easy interruption of the fault current.
4.3.5 Hazards of SF₆ usage

There are two areas where the significant use of SF₆ for circuit breakers can possibly cause hazards in electrical systems. These are:

- The toxicity of (some) of the arcing or discharge products of SF₆
- The potential greenhouse effects of SF₆ in the atmosphere

A problem with gas leakage can arise in such systems with the result that there may be a substantial leakage of SF₆ gas into the atmosphere during normal power system operation. In other situations where repairs or maintenance are being performed on SF₆ equipment, the urgency of repair and any unfamiliarity of utility personnel with proper gas handling and filtering techniques often results in SF₆ being exhausted to the atmosphere rather than being retained, filtered and used again. Thus such leakage can impinge on both of the above potential hazards.

There is a potential hazard to maintenance personnel from some of the by-products produced from SF₆ when an electrical discharge occurs in the gas. Some by-products such as S₂F₁₀ and SOF₂ are toxic and thus some care is needed in handling the gases during maintenance. There have been many papers written on the toxicity of SF₆ by-products and specific maintenance procedures have been devised to prevent hazards to personnel. These procedures and provision
of adequate ventilation in buildings is necessary for the protection of personnel so that they do not inhale SF$_6$ gas which has been contaminated by the arc and corona decomposition by-products.

The other problem arising from SF$_6$ in the atmosphere relates to the potential of SF$_6$ to act as a greenhouse gas. Lack of care in maintenance procedures in the early years of SF$_6$ use has caused the levels of SF$_6$ in the atmosphere to increase significantly over recent years. Although the levels are still extremely low, there is concern that unrestricted exhaust of SF$_6$ to the atmosphere will cause greenhouse problems. These potential problems arise because SF$_6$ is an extremely efficient greenhouse gas, much more so than CO2 and on a par with the CFCs in its potential radiative forcing effects. Fortunately SF6 it is not an ozone deplete in the way that many chlorofluorocarbons are.

While these problems are relatively insignificant at the moment, there is a long-term problem that may arise in the event of unrestrained exhaust of SF$_6$ to the atmosphere. This arises because the SF$_6$ molecule is extremely stable and thus accumulates inexorably in the atmosphere. There have been some calls to ban the use of SF$_6$ and this would be a significant problem in the light of a complete lack of viable alternatives to SF$_6$. However improvements in reducing leak rates and the development of an SF$_6$ re-cycling and destruction plant have thus far managed to stave off further calls for the banning of SF$_6$. 
5 Specified Tests for Circuit Breakers

Current Standards provide only details of off-line tests and there is as yet no specification for general condition monitoring tests or for on-line condition monitoring. The relevant Australian Standard are AS2650-2000 and AS2006-1986. AS2650 gives general requirements for switchgear while AS2006 gives specific requirements. AS2650 is essentially taken from IEC60694-1996.

Because of their mechanical operation complexity, many of the tests are specifically aimed at determining the speed of contact separation and the efficiency of mechanical operation.

The common type and routine tests specified by AS2650 are detailed below.

5.1 Type Tests

- Dielectric tests
- Radio interference voltage (132 kV and above)
- Current path resistance
- Temperature rise
- Current withstand tests
- Make and Break tests
- IP tests
- Mechanical tests
- Gas tightness tests
- Environmental tests
The dielectric tests cover the widest range of type tests and include the following:

- Power frequency voltage
- Lightning impulse voltage
- Switching impulse
- Partial discharge
- Pollution (creepage discharges)

The current path resistance tests will include contact resistance effects as will the temperature rise test (in part). The specified mechanical tests include basically impact tests. The gas test will include gas pressure, liquid sealing and vacuum tests. The environmental tests specified for general purposes are only EMC and EMI tests.

5.2 Routine Tests

The routine tests specified for common requirements include the following which are done as on-site tests:

- Dielectric test on main circuit
- Dielectric test on the control and auxiliary circuits
- Main circuit resistance test
- Tightness test
- Design and visual tests

These tests are essentially those which have been used over many years to prove the operational characteristics of switchgear. They are essentially installation tests on new or refurbished items. There is no detail of any tests for condition assessment and particularly for on-line monitoring tests. These have to be developed and applied by the operators.
6 Condition monitoring of circuit breakers

In the new age of asset management, the major means of failure prevention of switchgear is detailed condition monitoring and there has been significant development in this area of asset management in recent years.

There has always been condition monitoring of circuit breakers, of course, but previously it has mainly occurred during periodic outages for maintenance procedures. Such typical maintenance tests used in older methods have included:

- Insulation resistance tests
- DC or AC high potential tests
- Dielectric dissipation factor tests
- Contact resistance measurement
- Contact time-travel analysis tests
- Dissolved gas analysis tests (for oil CBs)
- Partial Discharge measurement
- Vibration Tests

Many of these tests are still carried out on older switchgear. But the problems with such tests are that they require disconnection of the breakers to perform, whereas modern asset management requires tests to be done on-line, either as routine tests or, in some cases, as continuous monitoring. To achieve this requirement, there must be a new approach to testing and indeed many modern circuit breakers now have integral condition monitoring equipment incorporated. This operates on-line and provides continual data on CB condition.
Some of the typical monitoring parameters incorporated include:

- Vibration analysis of mechanical operation
- Contact wear
- Contact operating time-travel and velocity
- Gas pressure (including vacuum)

All of these characteristics can be monitored by sensors installed within the breakers. For example, contact position, detection and speed can be achieved by magnetic sensors installed in the housing. Density monitoring can be achieved by pressure and temperature sensors: either the semiconductor type or the fibre-optic type. Vibration analysis can be achieved by accelerometers mounted on the casings.

Fibre-optic sensors are particularly useful because of their dielectric strength and immunity to electromagnetic interference. Their development as a multi-parameter sensor has led to a very substantial improvement in circuit breaker monitoring capabilities.

Contact wear can be monitored by measuring the contact temperature during normal operation and after fault and normal load current interruption. Tests have shown that contact operating temperature is a good indicator of contact wear and a temperature probe has been developed using a micro-silicon sensor and an interferometer illuminated by a fibre-optic system. The technique of chromatic modulation is used to obtain temperature.
Interrupter travel can be accurately monitored by a fibre-optic sensor installed in the arc chamber, again using chromatic modulation to eliminate problems with optical noise from the arc discharge. Accuracies of about 1mm have been achieved with such a system.

Fibre-optic sensors can also be used to detect low level corona discharge in switchgear or in switchgear enclosures. The fibre-optic sensor simply monitors light levels, particularly in the blue and violet end of the visible spectrum, which is typical of the light emitted by corona or tracking discharges. When the level exceeds a particular threshold, an alarm can be obtained. Use of narrow band optical filters means that it is possible to use such detectors in areas with high levels of ambient light background.

In addition it is now possible to perform on-line partial discharge detection in circuit breakers. For example, with the system developed by EA Technology using multi-element electromagnetic sensors being able to achieve PD location in oil metal-clad systems. This is symptomatic of a move to the use of VHF or UHF partial discharge sensors for monitoring of PDs in circuit breakers and switchgear housings.

The UHF technique was originally developed for PD detection in GIS busbar systems, where the busbars act as quite efficient transmission lines for carrying PD signals to the VHF/UHF sensors which may be either simple metal plates for capacitive coupling to the electric field or simple aerials for coupling of both E and B fields of propagating electromagnetic radiation.
7 Example of a comprehensive diagnostic system for distribution circuit breakers

The Dutch testing organization KEMA have developed a complete monitoring system that is able to provide a complete analysis of CB condition. It includes the following features:

<table>
<thead>
<tr>
<th>Technique</th>
<th>CB component tested</th>
<th>Measured quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact travel</td>
<td>Mechanical</td>
<td>Contact dist.-time, vel.-time [on opening &amp; closing]</td>
</tr>
<tr>
<td>Vibration</td>
<td>Mechanical wear</td>
<td>Vibration signature</td>
</tr>
<tr>
<td>Total timing</td>
<td>Mechanical / electrical</td>
<td>Operating time-all phases</td>
</tr>
<tr>
<td>Trip coil current</td>
<td>Magnetic circuit / mechanical wear</td>
<td>Magnetising current</td>
</tr>
<tr>
<td>Partial discharge</td>
<td>Dielectric efficacy</td>
<td>PD magnitude, PD rate and PD pattern</td>
</tr>
<tr>
<td>DGA</td>
<td>Oil dielectric integrity</td>
<td>Moisture, gases, Breakdown voltage</td>
</tr>
<tr>
<td>Gas density / vacuum integrity</td>
<td>Leakage of SF₆ or vacuum</td>
<td>Gas pressure/flow visualization</td>
</tr>
</tbody>
</table>

The advantages of such a comprehensive scheme are that it includes techniques which are able to be used to provide trending analysis of the circuit breaker condition. The contact travel, vibration, trip coil and partial discharge test
diagnostics will all provide instantaneous records of current condition and these can be used for comparison with similar tests at later dates to show up any change in function or operation characteristics. The data obtained from these monitors is also an ideal source for developing data mining applications which use sophisticated techniques of mapping etc to exhibit features of the data set which are not easily identifiable using normal standard analysis techniques. (See attached paper).

Modern distribution circuit breakers are either SF6 or vacuum, with the simplest and most economical mechanical operating mechanisms, and with interrupting actions which are attuned to the level of current to be interrupted. Thus there is minimal electrode wear, there is little or no deterioration of the dielectric and as a result the maintenance requirements of modern breakers are much reduced.

8 Future Developments

There is considerable on-going development of condition monitoring techniques for CBs as well as for other major plant assets. The trend is towards the integration of monitoring sensors within the circuit breakers at the time of manufacture and this trend will continue. There is still much scope for improvement in partial discharge monitoring, particularly using VHF/UHF sensors. The other major areas of monitoring include the development of gas loss sensors for SF6 and vacuum breakers.
Switching overvoltages in all levels of power systems are a relatively common occurrence. Even the switching of a standard ballasted fluorescent light will generate an overvoltage because of the inductance in the ballast. However the main problems occur with circuit breaker operation in high voltage systems. The problem that they represent to the power system is that their voltage amplitude can be much higher than the power frequency value and this may exceed the insulation strength of the power system components, such as transformers and large rotating machines in particular. If this happens then dielectric (insulation) failure can occur. In this section we will look just at the ways in such switching transients are generated. Protection against such transients will not be covered here.

The general term “overvoltages” includes a range of different voltage events, including simple increase in the power frequency voltage level, perhaps sustained for times ranging from seconds to minutes or hours. The magnitude of such “steady state” overvoltages are typically less than about 1.2 per unit of rated voltage. These are generally not a matter of much concern to the power system equipment.

The overvoltages that are of most concern are the short duration transient overvoltages. Such transient impulses can have voltage amplitudes that can be many times the peak value of the rated power frequency voltage. They also have very high frequencies and, in general, electrical insulation is
more susceptible, in terms of potential breakdown, to high frequency transient overvoltages.

In most respects the impulse voltage withstand requirement is the most important insulation test and specification for any power system. The power frequency overvoltage test is only of secondary importance in most cases. For this reason the impulse voltage withstand requirement is normally called the BIL or Basic Insulation Level (sometimes the Basic Impulse Level) of a power system.

The most obvious source of such overvoltages are lightning generated transients, but for very high voltage systems it is the internally generated or switching transients that are of most concern, because they last longer (some milliseconds as opposed to a fraction of a millisecond) and stress the system for longer.

9.1 Transient Recovery (restriking) Voltage (TRV) of switchgear

This is generated by the operation of a circuit breakers during current interruption for fault clearance or even just load current breaking. The following circuit model can be used to analyse the circuit breaker operation during such circuit interruption operation.

L represents the system inductance between the fault and source and C is the total distributed capacitance of the system in that same section.
The typical circuit breaker voltage and current waveforms prior to circuit interruption are shown below, with the voltage over the arc in the circuit breaker having the characteristic square wave shape of an AC electric arc voltage. After the circuit interruption at the natural current zero the voltage at terminal A has to recover to the power frequency voltage: however the exact way in which it achieves this recovery is not immediately clear (the circled area). It this initial recovery voltage (pessimists say restriking voltage) that we need to determine because this voltage is applied across the terminals of the CB immediately after arc extinction has occurred between the terminals.

We need to analyse the circuit model to determine quantitatively how this transition from arc voltage to power frequency voltage occurs. It is this initial natural transient that is termed the Transient recovery voltage (TRV) associated with the circuit breaker operation.
At arc extinction at the natural current zero, the capacitance $C$ has stored energy

$$W_c = \frac{1}{2} C V_{arc}^2$$

When the breaker contacts AB open and current flow ceases and the gap AB becomes non-conducting, this capacitance then discharges its stored energy back through the inductance $L$ with the result being an LC oscillation:

$$\frac{1}{2} C V^2 \longleftrightarrow \frac{1}{2} LI^2$$

The frequency of the oscillation is

$$f_o = \frac{1}{2\pi\sqrt{LC}} = \frac{\omega_o}{2\pi}$$

This voltage oscillation is then superimposed on the power frequency voltage on terminal A of the circuit breaker. The resulting voltage waveform imposed across the circuit breaker gap contacts after interruption is that shown below schematically.
The problem that occurs for the circuit breaker (and the power system insulation) is the fact that the CB voltage can rise to about twice the peak of the power system voltage waveform very quickly after the interruption of the current.

After interruption: \[ V_{AB}(t) = V_m (\cos \omega t - \cos \omega_0 t) \]

or, because there will always be some resistance present in the circuit to dampen the transient voltage:

\[ V_{AB}(t) = V_m (\cos \omega t - e^{-Rt/L} \cos \omega_0 t) \]

The second term is the transient recovery voltage. When combined with the power frequency voltage the peak of the TRV, \( V_{\text{max}} \), may reach almost \( 2V_m \) and the rate of rise of the TRV, \( V_{AB} \), in the first half cycle of the TRV oscillation may be very rapid if the TRV frequency \( f_0 \) is high.

Typically, the frequency may be about 1-5 kHz depending on the system and the fault location.

In high voltage circuit breakers, the initial rate of rise of the recovery voltage (RRRV) may reach magnitudes of 4-5 kV/\( \mu \text{sec} \). Because this recovery voltage transient is applied across the gap immediately after the arc has been extinguished, this represents a very severe stress for the circuit breaker to maintain the open gap in a non-conducting condition against such a rapidly rising voltage.
For the above circuit after interruption, Kirchoff’s voltage equation is:

\[
L \frac{di}{dt} + V_c = V_m \cos \omega t
\]

\[
I = C \frac{dV_c}{dt}
\]

\[
\frac{d^2V_c}{dt^2} + \frac{V_c}{LC} = \frac{V_m}{LC} \cos \omega t
\]

Hence

\[
v_c(t) = \frac{\omega_o^2}{\omega_o^2 - \omega^2} \cdot V_m \left[ \cos \omega t - \cos \omega_o t \right]
\]

In general, the TRV frequency is much greater than the power frequency, so that we have \( \omega_o \gg \omega \) and thus we can approximate the equation to:

\[
v_c(t) = V_m \left[ \cos \omega t - \cos \omega_o t \right]
\]
As the part of the TRV of most interest is the initial increase of voltage immediately after interruption, only the first cycle of the high frequency component is of real interest and this is of very short duration in terms of a single 50 Hz cycle. Thus we can write, with reasonable accuracy:

\[ v_c(t) = V_m[1 - \cos\omega_o t] \]

In general there will always be some damping resistance in the circuit to modulate the second term to \( e^{-\frac{Rt}{L}} \cos\omega_o t \).

\[ v_c(t) = V_m[1 - e^{-\frac{Rt}{L}} \cos\omega_o t] \]

In fact some circuit breakers will have resistors built into their design to provide such damping of the TRV to allow the circuit breaker recovery to be successful. (Air blast CBs in particular are prone to very high RRRV). Switching resistors are used with auxiliary contacts to perform the damping, usually arranged to give close to critical damping.

The peak of the TRV has magnitude \( V_{c(peak)} = 2V_m \) and the initial rate of rise of recovery voltage is:

\[
RRRV = \left( \frac{dv_c(t)}{dt} \right)_{\text{aver}} = \frac{2V_m}{0.5T_o} = \frac{2V_m\omega_o}{\pi} \text{ Volts / sec}
\]
Double frequency TRV
The fault situation assumed above is a short circuit at the terminal B of the circuit breaker and this is the TRV in the case of a terminal fault. If the fault does not at the terminal then there will also be some inductance and capacitance in the fault circuit on the load side of the circuit breaker, with some voltage across the capacitance on that terminal of the breaker (B) at interruption. When the CB gap clears and becomes non-conducting there will thus be two isolated LC circuits each generating an LC voltage oscillation on the isolated terminals. The TRV across the breaker will then be the difference of these two oscillations. Thus the TRV will then have a double frequency variation. In general the voltage contribution on the load side terminal B will be the lower level, but the frequency of the oscillation on the load side will generally be much higher because L will be much lower there. Thus means that although the peak voltage will not be affected the initial rate of rise will be rather greater and this may be a problem.

9.2 Current chopping

This event can occur when circuit breakers are interrupting small inductive currents such as transformer magnetizing current or when high rupturing capacity (HRC) fuses of low rating interrupt very high fault currents with consequent substantial current limitation. The result that can occur is that the current can be interrupted before a natural current zero and as a result the inductance still contains substantial stored energy (which is zero at a natural current zero) and the dissipation of this energy will cause an
enhanced and additional voltage transient at the breaker terminals.

The chopping effect and an effective equivalent circuit are shown below:

![Equivalent Circuit Diagram](image)

The load may be a motor, a transformer or other such item with significant inductance $L_m$ in addition to the supply inductance $L_1$. There will also be some load side capacitance $C_1$ in addition to the source capacitance $C$. We have neglected $L_1$ in the diagram as being very small compared to $L_m$.

Current chopping will occur when the current interruption occurs before the natural current zero as shown in the diagram below.
The stored inductive energy $\frac{1}{2} L_1 i^2$ must be dissipated and again this occurs in an LC oscillation with $C_1$ on the terminal $B$ of the circuit breaker. The difference is now that, in contrast to the normal TRV on terminal $A$ due to an LC oscillation, the transient voltage due to current chopping is not limited to a peak of $2V_m$: it can potentially be much higher.

$$\frac{1}{2} L_1 i^2 + \frac{1}{2} C v_L^2 = \frac{1}{2} C v_{c(max)}^2$$

$$V_{c(max)} = \sqrt{V_m^2 + i_o^2 \left( \frac{L}{C} \right)}$$
\[ v_c(t) = i_o \sqrt{\frac{L}{C}} \sin \omega_o t + V_m \cos \omega_o t \]

Chopping voltage    Normal TRV

\[ v_{AB}(t) = v_C(t) - V_m \cos \omega t \]

\[ = V_m (\cos \omega_o t - \cos \omega t) + i_o \sqrt{\frac{L}{C}} \sin \omega_o t \]

where \[ \omega = 2\pi \times 50 = 314 \] (power frequency term)

\[ \omega_o = \frac{1}{\sqrt{LC}} \] (in the TRV term)

\[ Z_0 = \sqrt{\frac{L}{C}} \] is the surge impedance of the load: for items such as transformers or motors, the surge impedance can be very high (eg 4,000 – 20,000 ohms) with a correspondingly high voltage transient generated \( i_o Z_0 \) due to chopping.

Other sources of switching surge voltages

(a) Capacitor switching (eg PF banks or unloaded lines)
(b) Overvoltages due to arc movement in arc furnaces.
(c) Ferro-resonance due to arc faults and circuit L and C
(d) Arcing earth faults
(e) Switch operation (open and close) under normal load

The problem for the power system is that any overvoltage can be propagated over the lines and may cause damage to distant electrical components.
10 References

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11 Bibliography


