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Vacuum Circuit Breaker Technology

Vacuum Interrupters – How They Work

The continuing use of vacuum interrupter technology in the power distribution market as replacements for oil circuit breakers has exposed this technology to people who have not been previously exposed to it. This article covers the features of the vacuum interrupter and how they correspond to the ability of the interrupter to perform according to its ratings.

Vacuum interruption technology has been used for many years and has proven itself to be a reliable means for interrupting fault currents in distribution switchgear. The application of vacuum circuit breakers as replacements for oil circuit breakers offers many advantages to the user in areas such as maintenance, performance, and environmental concerns. From a maintenance point of view, with a vacuum breaker there is no oil handling required with the associated clean up as well as long contact life and lower mechanism operating forces due to the small size and stroke required by a vacuum interrupter. A typical vacuum interrupter as applied in a distribution breaker will easily handle 10,000 operations at rated continuous current and more than 20 full fault operations without the need for contact replacement. Also, as a result of the lower mechanical requirements the mechanisms in today's vacuum breakers are much simpler in design with fewer moving parts and lighter loads being applied.

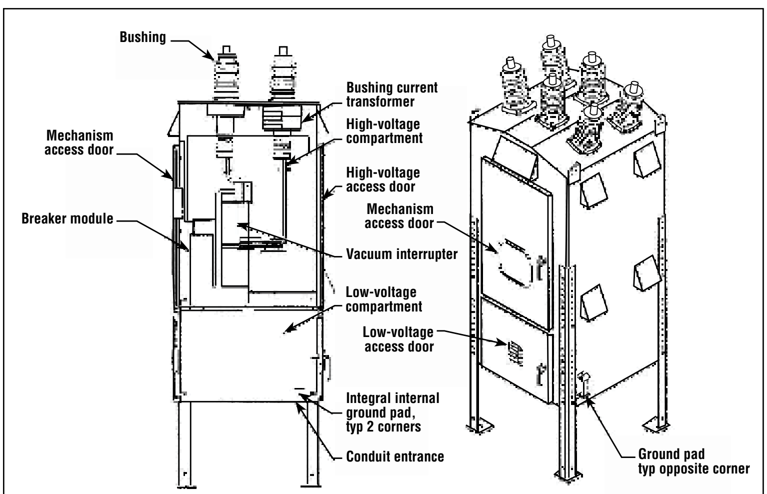

Figure 1 — Structure of an Outdoor VCB (17.5 kV-25 kA)

1. Breaker Overview

The structure of an outdoor vacuum circuit breaker (VCB) is shown in Fig.1. The three-phase ganged interrupter assembly is mounted in a self-contained breaker module containing the operating mechanism, auxiliary switch, mechanical linkage, and vacuum interrupter (VI) mounted in its own support insulator. The mechanical linkage and supporting framework are isolated from the high voltage interrupter by an insulated drive rod and the interrupter support insulators.

2. Features of Vacuum Interrupters

2.1 The Property of Vacuum

The dielectric strength of a vacuum is superior to other dielectric mediums such as air and SF_6 gas as shown in Fig. 2. Due to high dielectric strength of a vacuum environment, it is possible to reduce the arcing time of the interrupter as the dielectric capabilities of a vacuum can better withstand the generated transient recovery voltage (TRV). The net result of this is the

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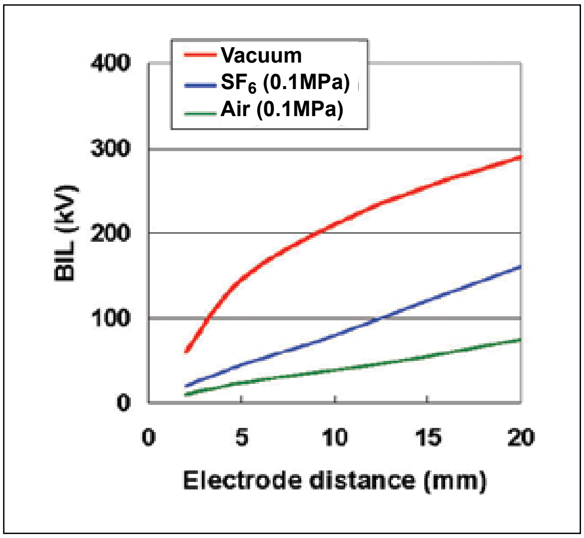

Figure 2 — Dielectric Strength Properties of Vacuum

minimum arcing time of a 15 kV vacuum circuit breaker is approximately 1 to 2 ms. The higher dielectric capability of the vacuum will yield a lower arc voltage and therefore reduce the amount of arc energy to be dissipated across the contacts in comparison with other interrupting mediums. This results in vacuum interrupters being able to break large fault currents with a short interrupting time and with minimal contact erosion. These properties allow vacuum interrupters to have a very compact design.

2.2 Basic Structure of Vacuum Interrupters

The basic structure of a vacuum interrupter is shown in Fig. 3. The main contacts are installed in a ceramic insulator in which high vacuum approximately 10^{-5} Pa is maintained. The movable terminal is connected to the breaker mechanism through an insulated drive rod which will open and close the interrupter contacts. A stainless steel bellows is used to allow contact travel and still maintain the integrity of the vacuum in the interrupter. The contact material strongly affects the interrupting capability, service life, and reliability of the vacuum interrupter. There are three types of contact designs used in vacuum interrupters, and they are applied based on their application as shown in Table 1. Generally, in applications with fault currents below approximately 20 kA, a flat butt type of contact design is sufficient. In applications where fault currents can exceed 20 kA, the design limitation of the contact will manifest itself as a localized high energy arc which results in large amounts of metal vapor being placed in the contact zone and thereby limiting the fault rating of the interrupter. In order to improve the interrupter's fault capacity either the spiral or axial magnetic field (AMF) contact design can be applied. These contacts are used in higher fault ratings as they are able to utilize the force created by the magnetic fields associated with the fault current. This enables the interrupter to effectively control the generated arc and therefore create a more efficient interrupter design. The spiral contacts will generate a magnetic field caused by the current flow through the contact. Due to the magnetic force generated by the current flow, this will cause the arc to be forced from the point of origin across the spiral petal to the outer diameter of the contact. Once the arc is on the outer edge of the contact, the magnetic force along the outer diameter will cause the arc to rotate around the outside diameter of the contact until it is extinguished. The AMF contact structure will generate an axial magnetic field caused by the current flow through the contacts which in turn will create a diffuse arc (low energy arc) over the entire contact area dispersing the arc energy over the contact surface area. The diameter of spiral contacts can be smaller than that of the AMF contact structure for the same fault current rating due to its ability to rapidly move and control the arc energy. In comparison the AMF contacts are superior for applications which require long arcing times and require a high number of full fault interruptions.

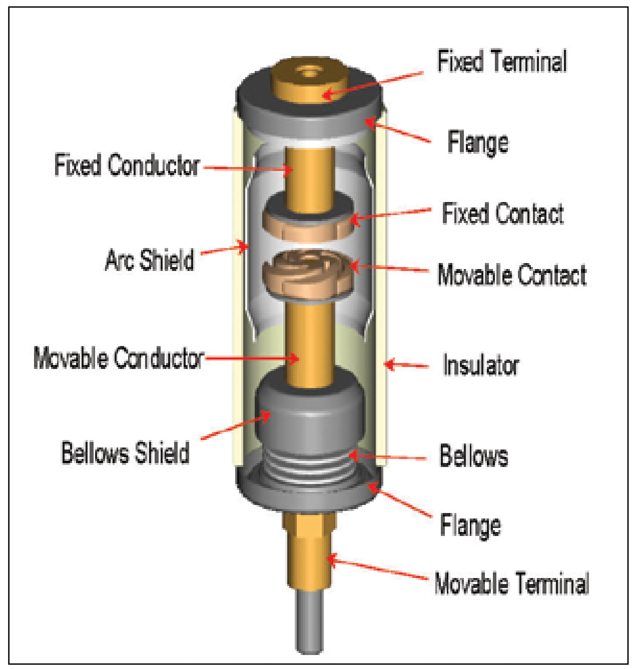

Figure 3 — Basic Structure of a Vacuum Interrupter

Table 1

Typical Contact Structures

Contact Structure	Flat Contact	Spiral Contact	Axial Magnetic Field Contact
Figure			
Application	VCB (General) LBS Contactor	VCB (Large capactiry)	VCB (More interruption) VCB (Low surge)
Materials	Cu-Cr alloy Ag-WC alloy Cu-W alloy	Cu-Cr alloy	Cu-Cr alloy Ag-WC alloy

2.3 Arc Control During Interruption

By using a high-speed video camera and a specially adapted vacuum chamber, the motion of the arc movement can be observed. Fig. 4 shows the movement of the arc for a spiral contact configuration during fault current interruption. At contact part plus 1.5 ms, the arc has been established between the contacts. At contact part plus 2 ms the arc is beginning to rotate around the outer edge of the contacts as a result of the magnetic forces that are being generated from the flow of the fault current through the contacts. This movement of the arc around the outer diameter of the contact surface provides the greatest amount of surface for the arc to travel over thus providing a larger area to distribute the heat generated from the arc. The net result of this movement of the arc is less localized overheating of the contact surfaces and therefore less metal vapor being introduced into the area between the contact surfaces. This greatly improves the interrupting capability of the interrupter and also results in less erosion of the contact surfaces, improving the life of the interrupter.

Fig. 5 shows the arcing that takes place in an AMF contact configuration during fault interruption. At contact part plus 1 ms, the arc is beginning to be dispersed as a result of the axial magnetic fields generated by the contact geometry. This dispersal will generate numerous low energy arcs (macroscopically one diffused arc) which will spread out across the entire contact surface by contact part plus 3 ms. As the contacts continue to separate, the density of the diffuse arc will continue to decrease so that at contact part plus 5 ms interruption will occur when the next current zero is encountered. By dispersing the arc energy into numerous low energy arcs spread across the entire contact surface, the amount of contact erosion and thus metal vapor in the contact area can be controlled. This will result in greater interrupting ratings for the contacts and longer contact life.

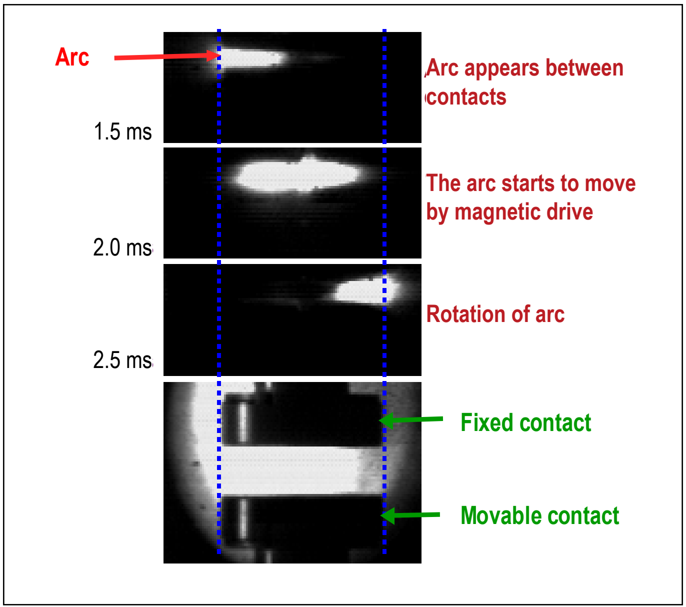

Figure 4 — The Arc Motion of Spiral Contacts

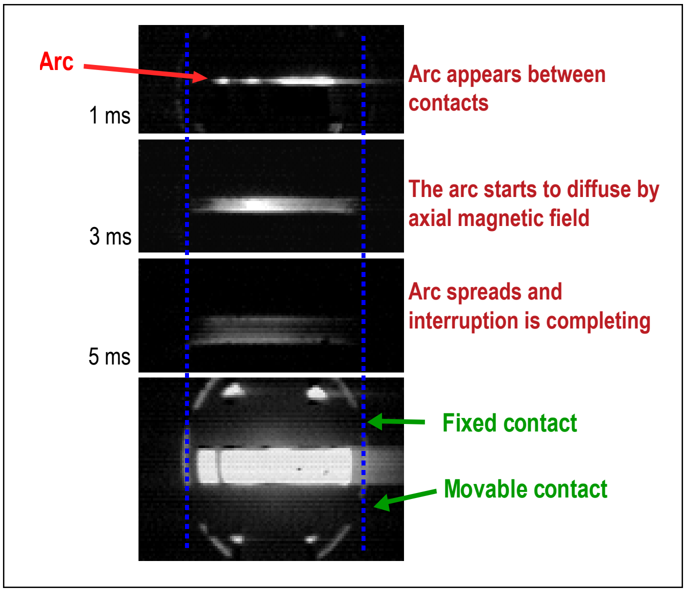

Figure 5 — The Arc Motion of AMF Contacts

2.4 Short Circuit Fault Interruption

Fig. 6 shows a typical oscillograph during short-circuit current interruption. When the contacts separate during fault interruption an arc appears between the contacts and is maintained until the next current zero crossing is encountered. At the same time, an arc voltage is present across the contacts. Once the current flow is interrupted a TRV will appear across the contacts. If at the time the TRV appears, the dielectric withstand of the contact gap is greater than the TRV value, the current will be successfully interrupted. If the TRV is greater than the dielectric withstand of the contact gap, the arc will reappear and will be successfully interrupted at the next current zero crossing. This condition will occur when the time to the first zero crossing event is less than the designed minimum arcing time of the interrupter.

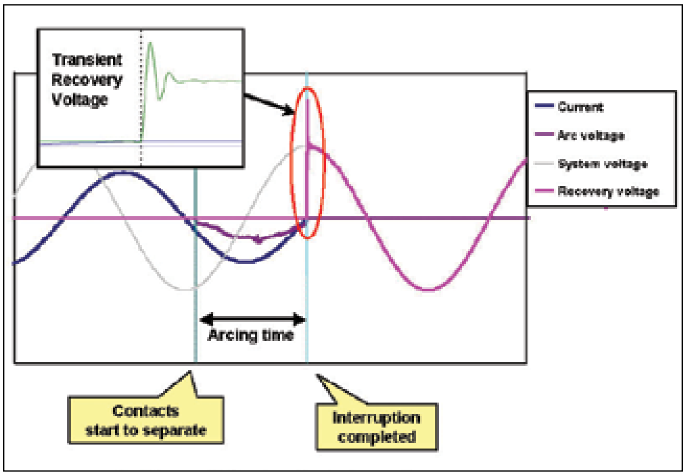

Figure 6 — Oscillograph During the Interruption

3. Design Test

The capability of a medium-voltage circuit breaker is verified by design tests specified in the IEEE/ANSI standards, C37 series. In the design tests, a series of capabilities (dielectric, current carrying, short-circuit current interruption, and other current switching) are tested to meet the required ratings. The following items, based on the design test requirements, need to be taken into consideration when demonstrating the circuit breaker's capability and application.

3.1 Asymmetrical Short-Circuit Current Interruption and the Effect of Various X/R Ratios

3.1.1 The rated interrupting time of a circuit breaker is defined as the maximum permissible time interval between the energization of the trip circuit (at rated control voltage), and the interruption of the current in the main circuit in all three phases. The standards allow for ½ cycle of relay time prior to the trip circuit energizing. This ½ cycle of relaying time is not allowed to be counted as part of the interrupting time of the circuit breaker. A circuit breaker rated for three cycles must completely interrupt all current flowing in the main circuit by the time three cycles of 60 Hz current has passed (50 ms) after the trip circuit is energized. If the current continues to flow beyond the 50 ms, the breaker cannot be rated as a three-cycle breaker. A five-cycle breaker is one that interrupts the current between three and five cycles (50-83 ms) after the trip circuit is energized. If there is any current flow after 83 ms, the breaker cannot be rated as a five-cycle breaker. The interrupter must be able to interrupt current flow on the first or second current zero after contact part. See Fig. 7.

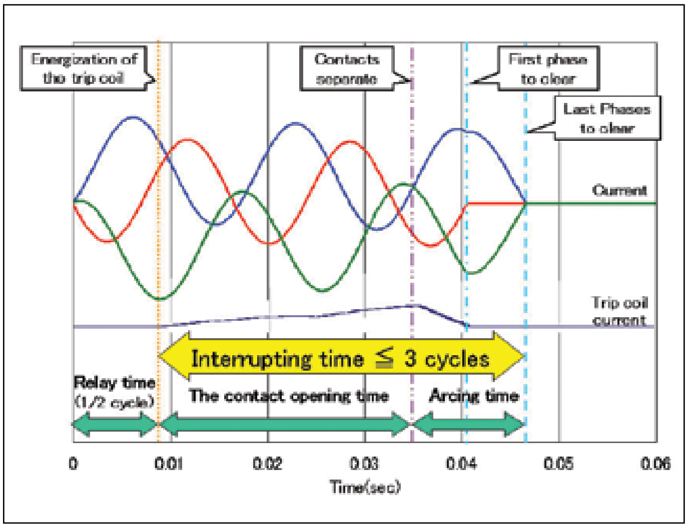

Figure 7 —Three-Phase Current Interruption for Three-Cycle CB

3.1.2. A typical short-circuit asymmetrical wave is shown in Fig. 8. For a three-cycle circuit breaker, it is necessary to complete the interruption where the interrupting time is equal to or less than three cycles. Moreover, the test procedure in the IEEE standards requires demonstrating that an interrupter can reliably interrupt current under the most severe switching conditions with the maximum arcing energy (longest arcing time and a major loop of asymmetrical current). Symmetrical interruptions must be performed to meet the ANSI/IEEE standards. The test duties included in Table 1 of IEEE C37.09-1999 demonstrate the interrupter's capability to interrupt current flow, both symmetrical and asymmetrical.

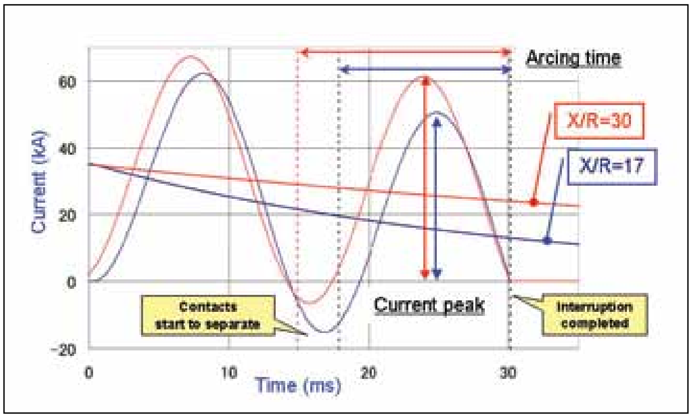

Figure 8 — Short Circuit Asymmetric Current (for 25 kA)

3.1.3 The current peak value and major loop duration are controlled by the value of X/R. The X/R ratio is the ratio of the main circuit's inductance divided by the resistance. The higher the ratio is, the slower the decay of the dc component of the asymmetrical fault current. Fig. 8 shows the decay characteristic of an asymmetrical current. Notice the peak current decreasing with time. A standard value of X/R is given as 17 at 60 Hz in IEEE Std C37.09-1999. However, the purchaser of the breaker needs to evaluate his system and verify that the X/R of the system is less than 17. When the circuit has an inherently high X/R, the interrupting time must still meet the interruption rating of the breaker (three or five cycles); however, the arcing time will increase due to a larger major current loop. The major loops will not only have an increased time between current zeros, it will also have a higher peak current due to a higher X/R ratio. Very high X/R ratios may not even have a current zero for the first couple of cycles. For example, if you compared an X/R=30 with an X/R=17 (see Fig. 8), the arcing time increases by a factor of 1.1, and the current peak value increases by a factor of 1.4.

3.1.4 Symmetrical current interruptions must also be performed according to IEEE C37.09-1999, Table 1. The symmetrical interruptions are required for design testing and to verify that the contact serviceability as stated in IEEE C37.04-1999 section 5.8.2.5 is achieved. The standards require a minimum of 800 percent of the required asymmetrical interrupting capability of the circuit breaker be accumulated on a single interrupter. Contact serviceability is the amount of contact erosion that the interrupter must be able to withstand and still be able to perform a successful interruption.

3.1.5 There are several design features that cause a vacuum interrupter to be superior to other types of interrupters for this application. The AMF style of contact inside the interrupter allows for a longer arcing time due to the low current density of the diffused arc. This reduced energy will keep the surface of the contacts from overheating and thus reduce the possibility of restrikes. The reduction of restrikes is due to reduced hot spots and reduced metal vapor in the contact gap.

3.2 Transient Recovery Voltage

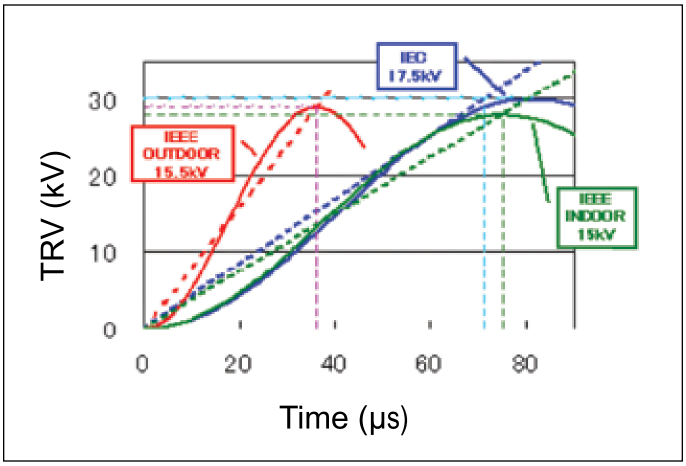

Figure 9 — TRV Waveform for 15-17.5 kV Breaker

The TRV characteristics depend on the system in which a circuit breaker is installed. The TRV is controlled mainly by the amount of inductance and/or capacitance on each side of the breaker. However, to provide a general application guide, the TRV values under most system circuit conditions are specified in the following standards.

Table 2

Rating of TRV for 15-17.5 kV Breaker

	IEEE Outdoor 15.5 kV	IEEE Indoor 15 kV	IEC 17.5 kV
Peak (kV)	29	28	30
Rise (kV/μs)	0.81	0.37	0.42

For circuit breakers rated below 100 kV, in IEEE Std C37.04-1999, the rated TRV is represented by a 1-cosine wave, while on the other hand, in IEC 62271-100, 2003 the TRV is represented by an exponential-cosine wave as shown in Table 2 and Fig. 9. These ratings are for short-circuit tests, duty 4 and duty 5 in IEEE C37.09 and for terminal fault test, duty T100a, in IEC. It is worth noting that in the IEEE standards the TRV specifications are different for outdoor and indoor applications. The outdoor specification is more severe than the indoor. Breakers tested and rated for indoor use, may not be suitable for outdoor applications. Also, the differences between the IEC and the IEEE TRV requirements are significant enough that breakers tested to the IEC standard may not pass testing for IEEE. The steeper slope of the recovery voltage will change the requirements of the contact design to achieve a greater rate of dielectric recovery inside the interrupter. The capability of the interrupter to successfully interrupt this high rate of rise of recovery voltages (RRRV) is dependent upon the internal geometry of the interrupter. The type of contact and the surrounding dielectric fields produced by the internal shield all have a large impact on the capability of the interrupter. The AMF style of contact is well suited for this purpose due to reduced hot spots and metal vapor in the contact gap. The smooth contact surface allows for a very rapid dielectric recovery of the gap which allows the vacuum interrupter to withstand the TRV better than other types of medium. The rapid recovery allows for small contact gaps, which translates to a very short stroke of the interrupter and operating mechanisms.

3.3 Continuous Current Carrying Capability of Vacuum Interrupters

3.3.1 The rated continuous current of a breaker is determined by the current carrying capability without exceeding the temperature limitations as listed in Table 2 of IEEE C37.04-1999. This temperature limit takes into consideration the types of materials, plating, and atmosphere that surround the point where the temperature is being measured.

Table 3

Example of the Limits of Total Temperature and Temperature Rise

Nature of the part and material		Total temperature (°C)	Temperature rsie at ambient ª40°C)
Contact	Silver-coated - in air	105	65
Connections, bolted or the equivalent		115	75

Table 4

Example of Typical Measurement Points and the Temperature Limitation (°C)

Measurement point	Incoming Bus	Top of Bushing	Upper Bus	Top of VI	Moving Stem of VI	Lower Bus
Temperature rise limit	± 5° from top of busing temp during testing	65° Tin coated	75° Silver coated	75° Silver coated	75° Silver coated	75° Silver coated

The most common spot in a VCB where temperature rise is a concern is the moving stem of the vacuum interrupter. It is necessary to monitor the temperature very closely at this critical connection point where the current path must allow for the motion of conductors. A typical temperature rise graph is shown in Fig. 10. In a medium-voltage VCB, the thermal time constant is usually small. If a VCB is required to carry overload current for several hours, the temperature rise on a VCB will approach the saturation values. This temperature may be over the thermal limits of materials. Whether or not the breaker will exceed any critical temperature limits will need to be evaluated carefully. The IEEE standards cover standard overload requirements; refer to IEEE C37.10-1999 section 5.4.4. If the breaker will be required to exceed these limits, the purchaser and manufacturer will need to review the continuous current test data to verify the breaker's capability for higher overload ratings.

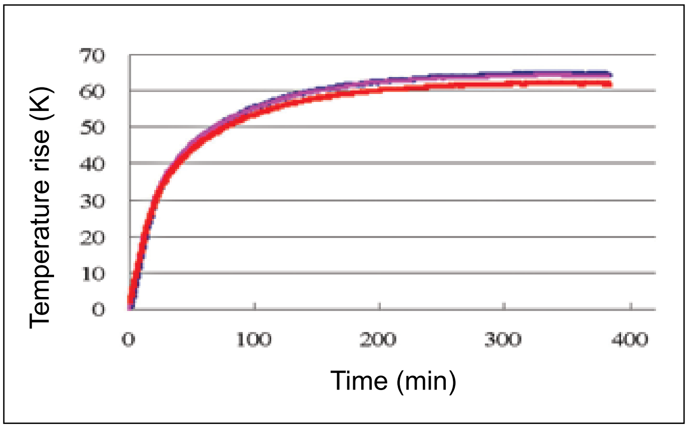

Figure 10 — Example of Temperature Rise Time Charts

3.3.2 The size and design of the main contacts and conductors contribute to the continuous current rating of the interrupter. The larger the contact diameter, the better the current carrying capability. The contact design and material also play a part in the continuous current rating. The different contact materials may have different resistance values. A higher resistance value may limit the amount of current due to the temperature rise associated with the higher resistance. The spiral or butt type contact is generally better suited for high continuous currents than the AMF style of contact. Consideration must also be given to the location where the circuit breaker will be installed. If the installation site has an ambient temperature rating of 50°C, as compared to the 40°C used in the IEEE standards, then the total temperature rise must be decreased accordingly (by 10°C in this case). The overall performance of the interrupter needs to be considered to determine the best contact design, material, and size for any given application. To ensure proper application of the circuit breaker, the purchaser and manufacturer should review the test reports.

3.4 Dielectric Capabilities of Vacuum Interrupters.

3.4.1 Vacuum interrupters are well suited to withstand voltage surges due to the rapid recovery of the dielectric strength of the contact gap caused by the high level vacuum. Other types of interrupter medium take much longer to recover due to the need to remove hot gas (in SF_6 for example) from the gap. The smooth contact surfaces and surrounding geometry (primarily the internal shield), as well as the high level of vacuum, all contribute to the interrupter's voltage withstand capability.

3.4.2 Lightning Impulse Withstand Voltage (BIL)

Vacuum is very reliable during lightning impulse withstand voltage. This is demonstrated by testing performed per section 4.4. of IEEE C37.09-1999. The flat design of contacts and the voltage profiling of the surrounding components (for example, the internal shield, bellows, moving contact stem, etc.) make this a very impulse friendly interrupter. Another factor that allows the small contact gap to withstand voltage surges is the high level of vacuum inside the interrupter. A high level vacuum eliminates all foreign particles within the interrupter. This results in having no impurities and a very low molecular count across the contact gap. The absence of foreign particles and molecules will not allow the voltage to jump across the internal gap.

There are several ways of improving the external dielectric capabilities of a vacuum interrupter. Many manufacturers will use various types of minor modifications to improve the dielectric capabilities, or margins, within a particular interrupter design. Some examples are the use of an externally contoured, or shedded, porcelain body to increase the creepage distance. The increase in creepage distance allows for more margin in a high contamination environment.

Another example would be to use a heat shrink material on the ends to increase creep and strike. The use a potting material to completely cover the outside of the interrupter to increase the dielectric strength has also been used for increased margins or capabilities of a given interrupter design.

Vacuum interrupters are ideal for use in low-, medium-, and even the lower end of high-voltage applications. Vacuum will eventually be used in high-voltage applications as technology keeps improving the capability of vacuum interrupters. The internal design of the vacuum interrupter, especially the main contacts, greatly impacts the capability of the interrupter. There are different types of contact designs that will utilize different materials to achieve different ratings and capabilities. The internal design of the interrupter will depend on the rating of the circuit breaker where the interrupter will be installed. Some of the items to consider on the internal design are not only the contact shape but also the internal shield shape, the moving stem shape, blending radii, and even the mounting configuration of the vacuum interrupter. Whether the breaker will be primarily used for capacitor switching duty, transformer magnetizing, or just fault interruptions, will affect the design. It is the responsibility of the end user of the circuit breaker to verify that the breaker (ultimately the interrupter) is suited to meet the specific needs of the system. The ability of the circuit breaker to function properly on a given system will ultimately come down to the review of the test data to ensure that the breaker has been tested and verified to function correctly under the duties in which it will be asked to perform.

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