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Subject:

SF_6 Puffer Type Circuit Breakers for Applications of 15kV Through 38kV

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ABSTRACT:

The use of SF_6 (sulphur hexafluoride) gas as an insulating and interrupting medium is well known. By the selective choice of materials and novel designs, the advantages of SF_6 are now realized at distribution voltage levels. Because of the unique properties of SF_6, the circuit breaker interrupting device, in comparison to other more conventional designs, is simpler in design, smaller in size, less susceptible to adverse environmental conditions, demonstrates superior circuit response characteristics, and may be classified as an "electrically maintenance free" circuit breaker.

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SF_6 PUFFER TYPE CIRCUIT BREAKERS FOR APPLICATIONS AT 15kV THRU 38kV

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SYNOPSIS

The use of SF_6 (sulphur hexafluoride) gas an an insulating and interrupting medium is well known. By the selective choice of materials and novel designs, the advantages of SF_6 are now realized at distribution voltage levels. Because of the unique properties of SF_6, the circuit breaker interrupting device, in comparison to other more conventional designs, is simpler in design, smaller in size, less susceptible to adverse environmental conditions, demonstrates superior circuit response characteristics, and may be classified as an "electrically maintenance free" circuit breaker.

INTRODUCTION

As we deal in the real world of AC high voltage circuit breaker applications at the distribution voltage levels, our choices of interrupting media are:

a. Air
b. Oil
c. Vacuum
d. SF_6

Each device has its own interrupting characteristics, type of construction, and principles of operation. Each carry current by means of metallic conductors but more importantly, the final interruption phenomena occur within a gaseous medium. In the case of an air breaker, those media are principally nitrogen and oxygen. In the case of an oil breaker, hydrogen is the medium, and in a vacuum breaker, metallic vapors are the interrupting media. In the case of SF_6 breakers, the medium is a combination of SF_6 and fluorine, each contributing to the interruption in a unique fashion. Before exploring each of these techniques, the basic principles of circuit interruption will be reviewed.

BASIC PRINCIPLES OF CIRCUIT INTERRUPTION

For the sake of simplicity, we will consider a simple circuit which might consist of a relatively long line supplying a breaker having a short circuit close to its load terminals. We will assume short circuit conditions having relatively low lagging power factors.

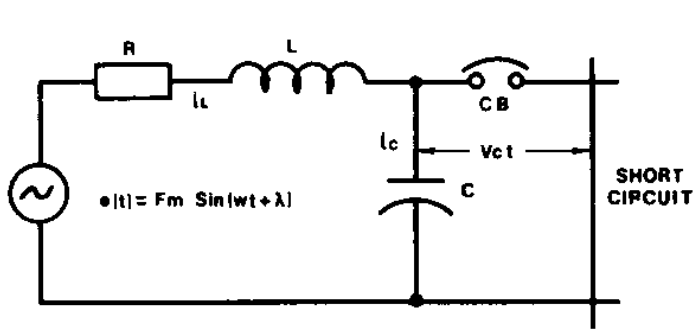

FIG. 1 TYPICAL CIRCUIT

Examination will begin with the circuit breaker closed and proceed until it has completely opened.

CIRCUIT BREAKER IS OPENED.

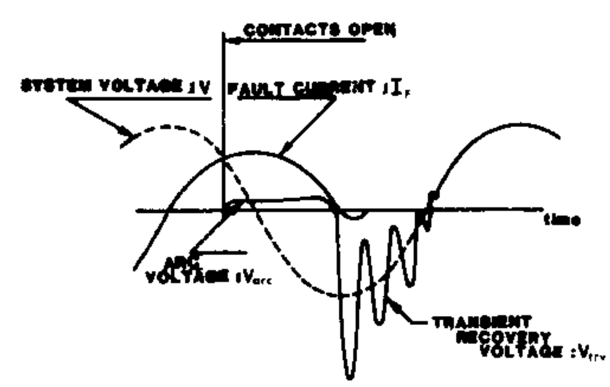

FIGURE 2 – TYPICAL CIRCUIT RESPONSE

As the metallic contacts separate, an arc is established between the intended electrodes. The establishment of the arc is best explained by the existence of extremely high electric field intensities created by the separating electrodes. Depending upon the nature of the gas and the geometry of the arcing electrodes, an arcing voltage in phase with the current will appear across the electrodes. This represents a transfer of energy into the arcing medium necessary to disassociate atoms and molecules. The gas molecules thus produce a source of free electrons to carry the imposed current. As can be seen by Figure 2, if the contacts are opened at a point indicated, an increasing amount of energy is imparted to the disassociating gas, tending to guarantee conduction to at least the first current zero. In the case of interruption at the current zero, energy ceases to be imparted to the gas medium and further disassociations cease due to the lack of energy. Prior to current zero, recombination is beginning to take place due to attractive ionic forces.

The success of the interruption depends upon the rate at which recombination occurs vs. the ionization produced by the electric field intensity established between the electrodes.

Recombination is a function of temperature, collision cross section, and time, which is influenced by the characteristics of the gas medium and the heat transfer of the system.

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The field intensity is influenced by the transient response of the system and the di/dt which is influenced by the interrupting medium. If we consider the voltage appearing across the terminals of an ideal circuit breaker having no arcing, the transient recovery voltage would be expressed as:

$$V_c(t)=\frac{E_m}{\omega CZ}\Big[-\cos(\omega t+\lambda-\theta)+e^{-\frac{Rt}{2L}}\Big\{\cos(\lambda-\theta)\cos\omega' t$$

$$\Big(\frac{\omega Z}{\omega' Z_1}\sin(\lambda-\theta_1)-\frac{\omega}{\omega'}\sin(\lambda-\theta)+\frac{R}{\omega' L}\cos(\lambda-\theta)\Big)\sin\omega' t\Big\}\Big] \quad \text{3a}$$

$\lambda =$ Source Phase Angle

$Z_1=\sqrt{R^2-\omega_1^2 L^2}$ Impedance prior to the interruption

$\theta_1=\tan^{-1}(\omega L/R)$ Phase angle prior to the interruption

$\omega=120\pi$ The line 60 Hz frequency

$Z=\sqrt{R^2+(\omega L-\frac{1}{\omega C})^2}$ Impedance after the interruption

$\theta=\tan^{-1}\left[\frac{\omega L-\frac{1}{\omega C}}{R}\right]$ Phase angle after the interruption

$\omega'=\sqrt{\frac{1}{LC}-\frac{R^2}{4L^2}}$ Angular frequency of the transient recovery voltage

With the initial condition

$$i_L(0^-)=i_L(0^+)=\frac{E_m}{Z_1}\sin(\lambda-\theta_1)$$

Note: The derivation may be supplied upon request.

Angle λ represents the angle at which the contacts of the ideal circuit breaker separate in relation to the applied voltage. If the value of λ is chosen to be θ_1, then the circuit breaker is opened at a point where the current is zero. The transient recovery voltage is then expressed as:

$$V_c(t)=\frac{E_m}{\omega CZ}\Big[-\cos(\omega t+\theta_1-\theta)+e^{-\frac{Rt}{2L}}\Big\{\cos(\theta_1-\theta)\cos\omega' t$$

$$\Big(\frac{R}{\omega' L}\cos(\theta_1-\theta)-\frac{\omega}{\omega'}\sin(\theta_1-\theta)\Big)\sin\omega' t\Big\}\Big] \quad \text{3b}$$

Further, if we consider no damping (R=0) we find that the frequency of the transient portion of the recovery voltage to be:

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

The peak value of the first voltage crest is equal to twice the peak of the supply voltage.

Therefore, if the rate of dielectric recovery exceeds the rate of rise of the transient recovery voltage, then the interruption is successful.

It is interesting to note from the original transient response formula, when the angle λ is other than θ_1, the transient recovery voltage takes on an entirely different characteristic. In this case, the frequency of the transient recovery voltage remains the same, however, the phase is shifted. As this phase angle is shifted, the initial voltage crest becomes very large. This crest can be many times the rated BIL of the system.

A similar result is produced when the interruption process occurs before current zero and the di/dt becomes higher than normal. The selection of gasses and interruption media is important. In the case of metallic ion interrupters, the medium tends to become unstable at particularly low levels of current, resulting in higher than normal transient recovery voltages. This phenomenon is known as current chopping.

The success of an interrupter is judged by its ability to recover corresponding to the rate of recovery voltage and along with its ability to carry current to near the natural zero without chopping.

COMPARISON OF VARIOUS BREAKERS

Air Breakers - The principal arcing media are nitrogen and oxygen. The arc length is long, thus the total energy released into the medium is high. Because of the long arc length,it must be moved and controlled. This is usually accomplished by large refractory lined arc chutes,resulting in equipment that is relatively large and often subject to damage during handling.

Oil Breakers - The principal arcing medium is hydrogen liberated during interruption from the decomposition of the oil. Due to the head of the oil or other techniques, the dynamic pressure imposed on the hydrogen creates a favorable medium for interruption. If the hydrogen bubble mixes with air, an explosive mixture is possible, creating an undesirable condition. Maintenance is high due to the liberation of free carbon as a result of the decomposition of the oil during the production of hydrogen.

Air Blast - Air blast breakers have been quite successful. Recombination is enhanced by high number density. Their dependency on the availability of dry, high pressure air has made them less attractive economically to competitive devices.

Vacuum - The interruption medium is metallic vapor and their operation depends upon the maintenance of a good vacuum level. As such, we find their characteristics quite different from other gas type interrupters. Their success has depended upon a critical combination of different metals within the arcing contacts. Metals with low work functions are added in an attempt to prevent high transient recovery voltages. At the same time these same materials tend to limit maximum current interruption capabilities. Among their characteristics is the fact that they are capable of withstanding extremely high recovery voltage rate of rises. Under certain conditions, this tends to stress the system by producing high values of electric field. Of concern is the ability of the envelope to retain a vacuum since even a small pressure change results in a dramatic change in performance. The degree of vacuum required for the successful operation of a vacuum circuit breaker is associated with the mean electron free path λ_e. λ_e must be maintained to be equal or greater than the inter-electrode spacing. Other media of interruption are less critical in this respect.

SF_6 (Sulphur Hexafluoride Gas) - The interrupting medium is sulphur hexafluoride gas. There are various types of SF_6 interrupters. Some operate at relatively high pressures while others operate at 1.5 to 3 times atmospheric pressure. Some move the arc magnetically through the gas while others, principally the puffer type, move the gas through a nozzle system across the arc. SF_6 gas is a heavy gas, having a mass approximately five times greater than air at normal pressures. Because of the difference in density, the gas is more easily handled and system purity easily assured. The interrupting properties of this gas are so efficient that the design of devices is simple, small, and displays many of the properties of an ideal circuit breaker.

PROPERTIES OF SF_6 GAS

At room temperatures, SF_6 gas is colorless and odorless. The molecular weight is 148 as compared to 28 for nitrogen and 32 for oxygen. The dielectric strength of SF_6 as well as other fluorinated gasses is several times greater than that of other known media. The dielectric strength is attributed to the large collision cross section of its molecule and the many inelastic collision mechanisms which allow an efficient, slowing down of free electrons.

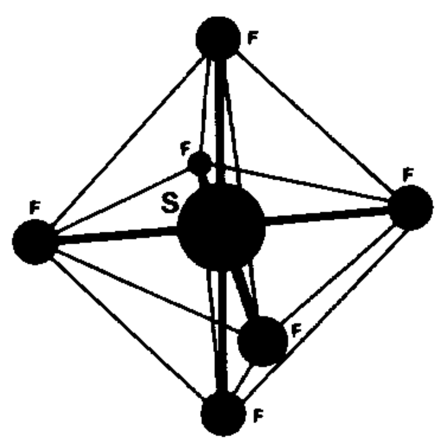


FIG. 3 THE SF6 MOLECULE

The sulphur-atom (at the center) has a valence of +6. Electrons are shared with six fluorine atoms symmetrically arranged. This structure, with its chemical bonds saturated, is chemically inert and is highly stable. Its energy of formation is 262 K cal per mole.

As an interrupting medium, SF_6 has three outstanding properties which make it a remarkable material. First are its thermal characteristics, secondly, the chemical characteristics, and third, its electrical properties.

First are its thermal properties. SF_6 becomes hyperconductive at relatively low temperatures. A comparison of SF_6 to nitrogen is shown in Figure 4.

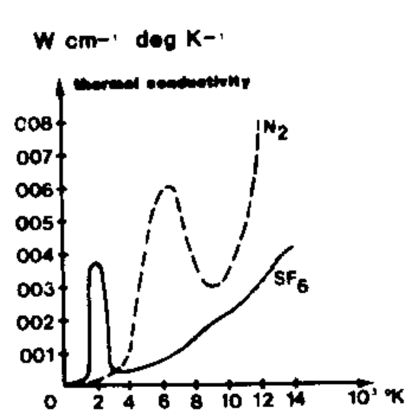


FIG. 4 - THERMAL CONDUCTIVITIES OF SF6 AND NITROGEN.

The hyperconductivity is associated with the energy exchange required for molecular disassociation. The temperature of disassociation and hyperconductivity for SF_6 is $2100^{o}K$. Below $2100^{o}K$ the medium is SF_6 gas and just above this temperature, mostly disassociated sulphur and fluorine atoms.

During arcing in any gas, the majority of the current is carried in a well defined arc core. If the temperature of the medium is measured at locations perpendicular to the flow of current, an abrupt temperature rise is encountered as the arc core is traversed with significantly lower plateaus of temperature measured on either side of the arc core as shown in Figure 5.

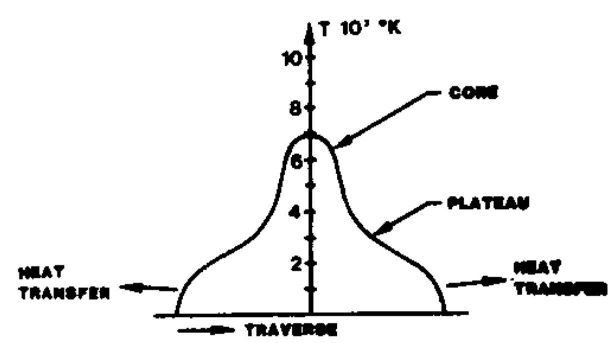


FIGURE 5

At relatively high currents, a pronounced arc core develops.

Gasses within the arc core are more completely disassociated, providing a source of free electrons which carry the current. As the current increases, the temperature of the core increases, and conversely, as the current decreases, the core temperature decreases and merges into the plateau region.

As noted by Figure 4, SF_6 gas becomes hyperconductive at a relatively low temperature. This characteristic tends to concentrate the arc core into a smaller region, leaving the majority of the medium to act as a heat sink. If nitrogen (air) was explored, its temperature characteristics would be as shown in Figure 6 in comparison with SF_6.

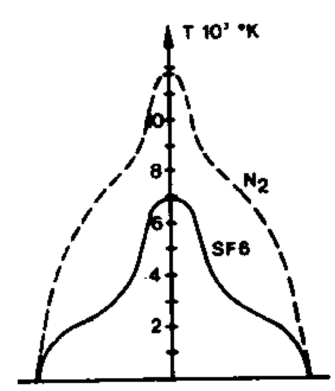


FIGURE 6

If the temperature of the plateau is high, as it is for most diatomic gasses (N_2 & O_2), the gas would still be strongly ionized after the disappearance of the arc core. With further decrease in current, the temperature decreases much more slowly. The plateau temperature of SF_6 is much lower, in the order of $2100^{o}K$. At this temperature, the population of free electrons is low and for all practical purposes, the gas has become an insulator. Therefore, as the arc core reduces in temperature due to the reduction in current, the SF_6 ceases to conduct current. The fact that the arc core is well defined, with the majority of the media in a state of hyperconductivity, the evacuation of energy from the arc core is very efficient. As the current is reduced, the thermal energy within the arc core is quickly transferred to the hyperconductive medium and to the surrounding heat sink regions. For this reason, the design of efficient SF_6 interrupters causes the arc core to be confined within a rather small diameter metallic tube so arranged as to quickly evacuate the thermal energy transferred by the hyper-conductive characteristics.

Considering the chemical characteristics, we note first the manner in which SF_6 decomposes with increasing temperatures and then recombines as the temperature decreases.

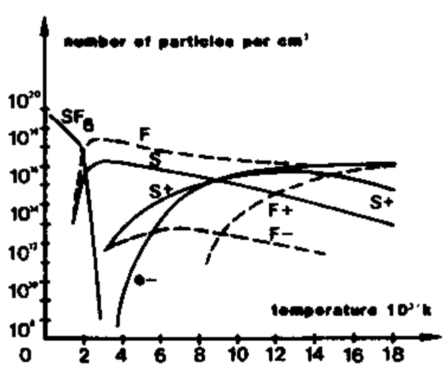


FIG. 7 – CURVES OF SF6 DECOMPOSITION

As the temperature increases, SF_6 molecules first disassociate into sulphur and fluorine atoms. This occurs at about 2100°K. As temperature is further elevated, the sulphur gradually ionizes to positive sulphur ions (S+), giving up electrons. These electrons are quickly captured by fluorine atoms producing negative fluorine ions (F-). The F- ions are heavy and move with a speed 185 times slower than free electrons. Thus, at temperatures between 2100°K and 4000°K, the media remains a fairly good insulator. As the temperature is increased to 4000°K, the energy level is sufficiently high to cause stripping of extra electrons bonded to the fluorine atom and the medium becomes more conductive. At about 6000°K, the medium develops into a conductor by virtue of the abundance of free electrons stripped from the fluorine and sulphur atoms.

Conversely, as the temperature in the arc core decreases with decreasing current, the population of free electrons likewise decreases. At above 6000°K the decrease is slow, however, below 6000°K the flourine atom begins to capture free electrons. At 3000°K, nearly all of the free electrons are captured by the fluorine atoms producing F- ions. Since the F- ions are 185 times slower than free electrons, each electron captured reduces the current by 1/185 of its original value. As all electrons are captured, the current is reduced to zero.

High ionization potential, large electron collision cross section, and high electro-negativity properties contribute towards its outstanding electrical properties.

THE PUFFER TYPE SF_6 INTERRUPTER

Along with an efficient interrupting medium, it is also important to arrange a device to efficiently contain the medium, control the arc, transfer heat and dispose of product of interruption. By understanding of the characteristics of the gas and electro-mechanical concepts, a skillful technique of arc control has been devised. The current carrying and arcing electrodes consist of metallic tubes arranged in a butt contact configuration. A piston and cylinder are arranged such that during the initial motion to open the contacts, SF_6 gas is compressed on the outside of the contact tubes. This creates a higher gas pressure on the outside of the contact tubes in comparison to the inside.

Upon separation of the contacts, the arc core is established in a circular configuration about the entire circumference of the tube edges.

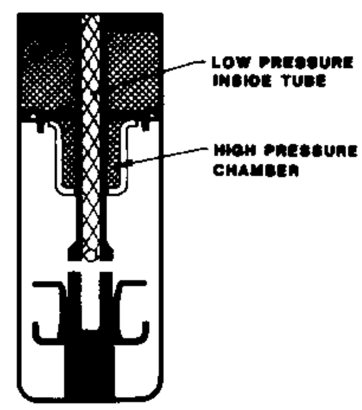
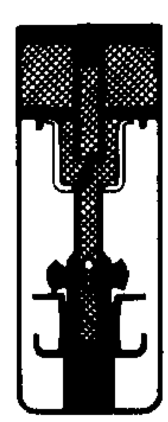


FIGURE 8

Puffer Type SF_6 Interrupter. Shown at point of contact separation.

At high currents, the interruption process is delayed by what is known as the "corking effect". Due to the thermodynamic properties of the arc core, the flow of gas is retarded at first. This permits the pressure in the high pressure region to build to an even higher than normal level.

As the current decreases, the volume of the arc core decreases, resulting in lower thermaldynamic forces. At a low level of current the external gas pressure is sufficient to move the arc core into the contact tubes. It is at this point that the processes described begin to take full effect, extinguishing the arc at the first current zero.



Puffer Type SF_6 Interrupter in advanced stages of interruption

Arc

FIGURE 9

It may be noted that the arc is interrupted inside a tube structure this affording an efficient heat sink necessary to remove energy from the system.

ADVANCED TECHNOLOGY FOR PUFFER TYPE SF_6 INTERRUPTERS

At this point, discussion has been related to the basic principles involved in SF_6 arc interruption, specifically of the puffer type. In order to produce an interrupter which meets present day requirements demanded of a modern circuit breaker, advanced technology has been developed.

ARCING CONTACTS

The arcing contact material is selected to yield minimum erosion and at the same time promote interruption. Particular attention is given to minimizing the amount of ionization contributed to the arc core, thus relying entirely upon the characteristics of the SF_6 gas for its interrupting characteristics.

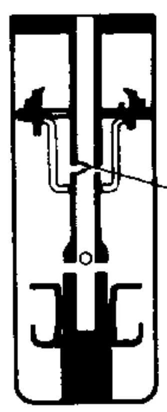


FIGURE 10

NOZZLE

At high levels of interruption where the "corking effect" predominates, it is important to move the gas from the high pressure chamber into the tubes as rapidly as possible. This is accomplished by providing a very carefully shaped nozzle to provide a smooth, aerodynamic surface to promote laminal flow of gas to the tubes. The minimizing of turbulence assures a higher rate of flow of fresh SF_6 gas into the arcing area.

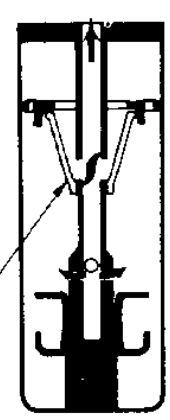


FIGURE 11

TULIP CONTACTS

In addition to the arcing contacts, a set of auxiliary contacts called "tulip contacts" (see Figure 12) are provided which circularly encompass the arcing contact tubes, and these contacts are arranged in such a manner that as the device is closed, the arcing contacts meet first, and then the tulip contacts. They slip over the arcing contact tip material and come to rest on the lower and upper portions of the contact tubes. The purpose of this is to shunt high momentary currents from the arcing contact tip material, assuring optimum performance under all operating conditions.

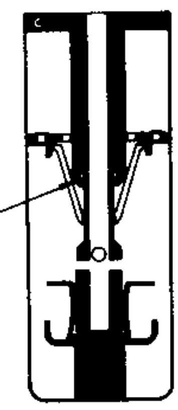


FIGURE 12

MAIN CONTACTS

In addition to the arcing contacts and the tulip contacts, a third set of contacts are provided for the purpose of carrying continuous current (see Figure 13). Again, the purpose of these multiple sets of contacts is to optimize the performance for which each is intended, and, thus, reduce the need for unwanted compromises over the entire range of operational requirements.

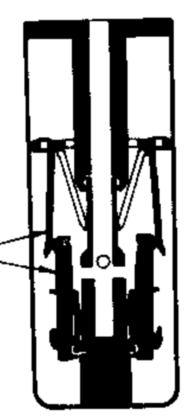


FIGURE 13

ABSORPTION MATERIALS

Certain materials such as activated alumina have an ideal property of absorbing and releasing certain gasses, depending upon relative differential pressures. Absorption materials tend to absorb SF_6 gas at relatively high pressures and liberate them at lower pressures. These materials have an affinity for the biproducts of interruptions such as fluorine. Therefore, the absorption material acts as a supply of new SF_6 gas while extracting excesses of unwanted gasses.

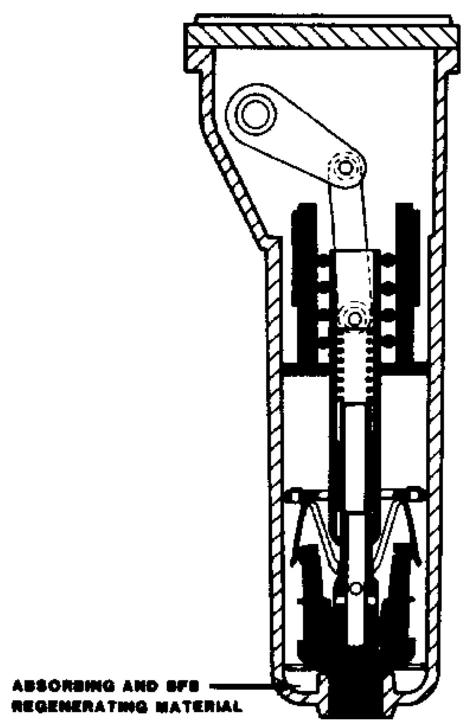


FIGURE 14

ENVELOPE

Fortunately, SF_6 is a rather heavy gas with relatively large molecular structure, making containment a relatively easy job. Epoxy castings have been selected for their insulating qualities, stability, and freedom of design. Current carrying inserts are designed in such a way that epoxy curing stresses are employed to provide a permanent gas seal. The surfaces as cast are adequate to provide the cylinder in which the puffer piston operates. Mechanical mounting as well as other necessary features are molded into the casting. Due to the freedom of design afforded by epoxy castings, many individual functions are combined into a single part, thus providing an economical system.

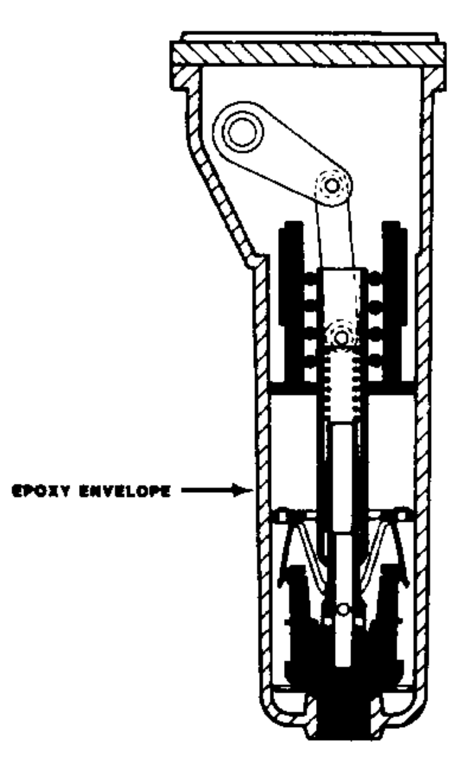


FIGURE 15

OPERATOR SEAL

As with any closed system interrupter, it is necessary to transmit mechanical motion into the gas tight envelope. On certain models, a gas to oil seal is provided. The mechanical motion is transmitted by means of a rotating shaft. The shaft is sealed in the envelope by two quadra seal "O" rings, a reservoir of oil, and two additional "O" rings. The surfaces of the seals are constantly wetted with a film of oil through which the SF gas is virtually impervious. Such a system offers almost unlimited numbers of mechanical operations. Mechanical tests would indicate life well beyond twenty years of normal service.

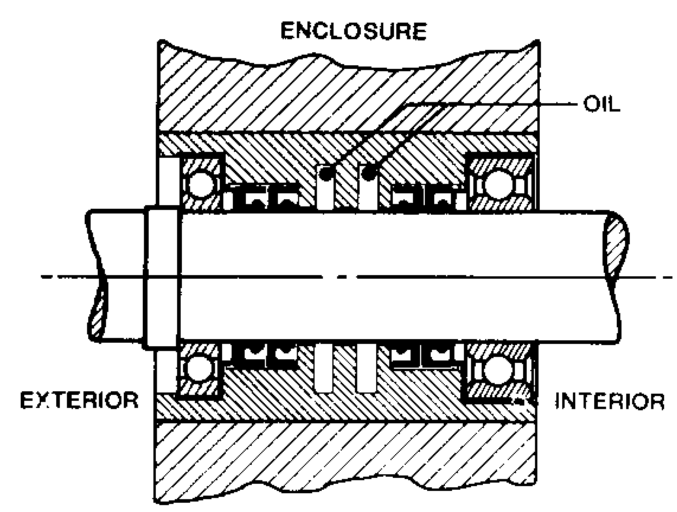


FIGURE 16

Oil Seal

GAS PRESSURE VS. OPERATION

Considering puffer type interrupters as discussed with advanced technological features, the gas pressure is relatively low. Depending upon the rating, the initial pressure as injected at the factory ranges between 20 and 45 PSIG. These interrupters are capable of performing their full performance characteristics at half the initial gas pressures. Most breakers are capable of interrupting at least one full fault interruption at zero gage pressure. All breakers are capable of interrupting their full load continuous current ratings at zero gage pressure. During manufacturing, each finished device receives a six hour leak test. Each unit is placed in an individual sealed chamber. If, after six hours, SF_6 gas is detected in the chamber, the unit is rejected. Due to extensive laboratory and field testing, permanent sealing of the envelope is justified and further maintenance or inspection of the SF_6 gas is not required or recommended. The existence of pressure can be detected by feeling the force on the end operator shaft. There is a slight amount of end play provided for this purpose. One simply pushes in on the end of the shaft and if the shaft pushes back, then one is assured internal pressure exists. On high pressure devices used for high fault interrupting, a pressure switch is provided.

RATING STRUCTURES

Single SF_6 devices are capable of operating in the range of 10 to 38kV with appropriate BIL ranges at each level. Continuous current capacities range from 600 to 2500 amperes. Interrupting capacities range from 8 to 40 KA, depending upon specific type.

Testing continues to verify these ratings to those recognized by ANSI Standards.

ELECTRICALLY MAINTENANCE FREE OPERATION

Of significant interest is the fact that such breakers as discussed can qualify as electrically maintenance free devices without recommended times of periodic inspection or maintenance. This classification can be substantiated with accepted methods of design and conformance testing. Several utilities throughout the world have adopted this philosophy and, at this time, IEC is considering procedures for recognizing breakers for electrically maintenance free operation. Many of the concepts already exist. ANSI C37.09, however, recognizes breakers with relatively limited electrical endurances. In the new IEC standard being drafted, electrically maintenance free breakers would be recognized in three classes; A, B, and C. Each class requires a series of electrical interrupting endurance tests with increasing severity from A through C. Each test series requires a number of short circuit interruptions, without maintenance, at various levels of current, including tests at near full fault ratings. The summation of the interrupted currents during this test sequence must be 500% of the short circuit current to be considered a Class A maintenance free breaker. This test sequence is similar to ANSI C37.09 test duty 8 except the ANSI Standard requires a demonstration at 400%. A Class B breaker would require a 1000% test while a Class C breaker requires 2000%.

Many of our SF_6 breakers have already been qualified for Class C performance with all others qualifying for Class B.

The life of SF_6 breakers can best be illustrated by the curve shown in Figure 17.

$$n = N\left(\frac{I}{i}\right)^{2.5}$$

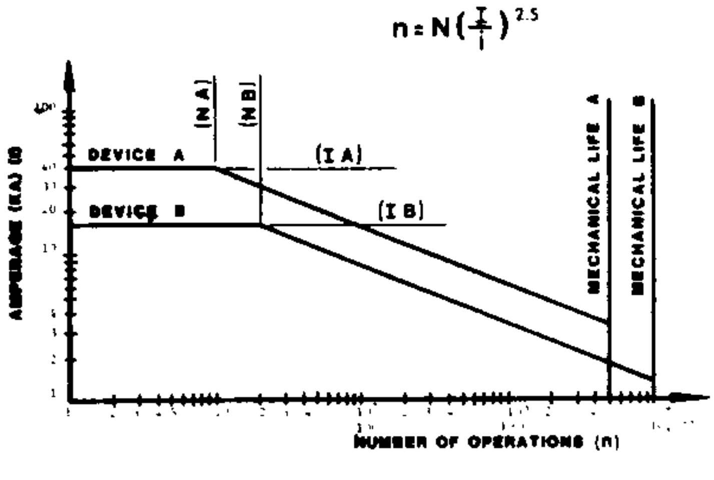


FIGURE 17

CONCLUSION

The use of SF_6 as an interrupting medium in devices designed for the distribution voltage levels offers significant advantages over other interrupting media. Because of the characteristics of this gas and techniques employed, circuit breakers of this type offer a superior degree of reliability and performance.

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