SF6 versus vacuum the serious contenders

Vacuum circuit-breakers have been used for over 40 years and have proved a reliable means of load switching and short-circuit interruption for a wide range of medium-voltage operations, says Philip Dingle, utility segment manager of Eaton's European Electrical Division

Vacuum circuit-breakers have typically been used for medium-voltage operations from 1kV to more than 40kV, from 100A to more than 4,000A with fault levels from 6kA to 63kA. They are suitable for power frequencies ranging from 16.66Hz to 400Hz.

Continuous development has seen the size of a typical 15kV vacuum interrupter come down from a diameter of 180mm in 1967 to a mere 50mm. Use of Cu-Cr contact material since 1980 brought about dramatic improvements in performance over the earlier pure copper and alloys such as Cu-Bi contact materials.

Vacuum technology is one of four commonly used medium-voltage technologies for circuit interruption. The others are air, oil and SF6. Use of oil and air circuit-breakers has declined significantly over the last 30 years (see figure one) leaving vacuum and SF6 as the only serious contenders. While SF6 reigns supreme at high voltage, vacuum is the preferred technology in the range 1-40kV, on both technical and environmental grounds.

LIMITATIONS OF SF6

Even when vacuum technology is used for interruption, many manufacturers use SF6 gas as the insulating medium in 'gas insulated switchgear' (GIS) including ring main units and substations. Many of the environmental factors that militate against SF6 for interruption are even more relevant here – SF6 is a serious greenhouse gas (one of the six listed under the Kyoto Protocol) and it is heavier than air so could cause suffocation if it leaked into a confined space.

While the concentration of SF6 in the atmosphere is much lower than that of other greenhouse gases, such as carbon dioxide (CO_2) and methane (CH4), it has a global warming potential (GWP) 24,000 times that of CO_2 and an atmospheric lifetime estimated at up to 3,200 years compared with 50-200 years for CO_2. Gas-insulated switchgear should be monitored regularly to ensure there is no gas leakage and special precautions must be taken when decommissioning. In contrast, vacuum interruption with solid insulation results in safe, maintenance-free systems.

Another disadvantage of SF6 is that arc interruption or an internal arc will produce a number of dangerous and toxic decomposition products that necessitate special precautions when working on SF6 filled apparatus. The risks of using SF6 filled equipment in urban areas, or even within buildings, are obvious. Even more serious is the disposal at the end of life – this has been compared with the problems of disposing of PCBs in transformers.

VACUUM INTERRUPTION

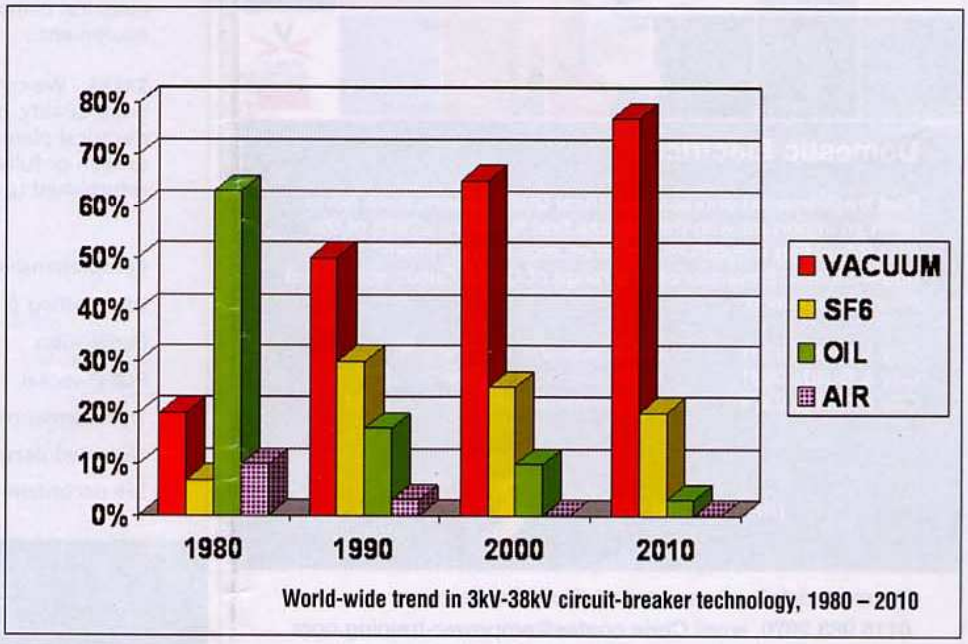
The principal benefits of vacuum interruption at medium voltage are long life, superior electrical performance, maintenance-free operation and environmental acceptability.

Long life: Vacuum interruption is a mature technology with proven reliability. Vacuum sealing using modern vacuum furnace brazing techniques ensures that units retain their vacuum for at least 20 years, exceeding the mechanical life of the circuit-breakers of which they form a part. Experience has shown that if seal leaks occur, they normally manifest themselves early in life so rigorous production testing ensures that such faults are identified before units reach the field. Eaton's vacuum interrupters also satisfy the latest IEC requirements for extended short-circuit operating life.

Superior performance: Vacuum interrupters are suitable for a wide range of medium-voltage applications, including transformer secondary protection, short-line fault switching, capacitor switching and motor switching. Rated AC power frequency withstand voltage is typically 2-4 times normal operating voltage while rated lightning impulse withstand voltage is 4-12 times normal operating voltage.

Maintenance-free operation: There is no requirement for regular inspection or costly monitoring equipment to check for gas leaks as there is with SF6 switchgear.

Environmentally benign: Vacuum interrupters are constructed from materials that can be recovered and recycled at the end of life. They do not contain greenhouse gases, like SF6, nor do they present potential health risks



World-wide trend in 3kV-38kV circuit-breaker technology, 1980 – 2010

due to the production of decomposition products following arcing. No special precautions are necessary to protect the environment from the results of leakage or during end-of-life disposal.

GAS OR SOLID INSULATION?

The ability of a vacuum interrupter to withstand very high voltages means that a very compact design is possible, for example a 9mm contact gap offers a 24kV rms withstand voltage for one minute or 185kV basic insulation level (BIL). However, the limiting factor as far as size is concerned is the external dielectric insulation strength, for example an interrupter ceramic length of 150mm will only have a BIL of 125kV in air.

For this reason, it is common practice to surround the vacuum interrupter with a dielectric medium – SF6 gas or oil – to allow a short interrupter length and closer pole spacing. The basic insulation level for a 150mm interrupter is increased to 170kV. The use of oil is being phased out due to the fire hazard but SF6 gas is still in widespread use despite the environmental problems outlined above. Furthermore, if there is a gas leak, the insulating properties will unfortunately be negated.

An alternative approach, employed by Eaton for more than 25 years, relies on enclosing the vacuum interrupter in a potting compound such as polyurethane and/or epoxy to achieve even smaller dimensions. Use of a contoured profile, similar to the 'sheds' used on overhead line insulators, extends the creepage distance for applications in urban and industrial environments involving heavy atmospheric pollution or condensation. In some cases the entire vacuum interrupter and associated busbar are encased in solid insulation, in other cases the vacuum interrupter is housed in a solid insulator and the space between the interrupter and the insulator is filled with a material such as polyurethane.

HIGH-VOLTAGE WITHSTAND

Vacuum interrupters will normally withstand a rated AC power frequency voltage (an overvoltage due to power system switching operations) of 2-4 times rated system voltage and a rated lightning impulse voltage of 4-12 times rated system voltage.

In service, the breakers are normally closed so overvoltages such as lightning are mostly seen by the line-to-ground or line-to-line insulation. In the rare event of a lightning impulse appearing across the open contacts of the vacuum interrupter, which would create a breakdown of the gap, only a half cycle of power frequency follow-through current will flow before the next current zero when the current will be broken by the open contacts. This behaviour is not exhibited by SF6 puffer-type, air or minimum oil circuit-breakers, as they will probably explode.

Another inherent characteristic of the vacuum circuit-breaker is self-conditioning of the contacts. Rough spots that can occur on the contact surfaces due to the mechanical touching of the contacts are smoothed out by the discharge when the contacts are opened on-load. Eaton takes advantage of this feature during manufacture by subjecting the open contacts to a high voltage from a high-impedance source in order to condition the contacts.

Vacuum interrupters offer exceptional performance under load switching operations, far exceeding the mechanical life of any circuit-breakers and reclosers of which they form a part. Consequently, they are used in railway switching applications, where electrical and mechanical life in excess of 250,000 operations is required, motor switching duties in excess of one million operations, arc furnace switching and capacitor switching.

The vacuum interruptor will always interrupt the arc current at the first current zero, once the contact gap has opened sufficiently to withstand the recovery voltage. Contact erosion only occurs at the cathode where multiple cathode spots move randomly across the cathode, resulting in uniform erosion. Eroded material is deposited uniformly on the anode. However, the contacts act randomly as cathode and anode so the effects of erosion even out as material moves back and forth.

This low and uniform erosion, and the fact that arc interruption takes place in a vacuum, means that contact resistance (Rc) remains low throughout the life of the vacuum interruptor. In contrast, the contact resistance in SF6 devices increases during life due to chemical processes that take place at the contact surface during and after arcing. Furthermore, metal fluoride powders, produced as a by-product of arcing, may inhibit operation because they are insulating materials.

SHORT CIRCUIT INTERRUPTION

The vacuum interruptor also offers superior short-circuit performance over the range 2-63kA rms. Eaton vacuum interrupters are designed to perform at least 100 full short-circuit operations. In practice, a fault of 80% full fault rating is a rarity and most faults are much lower.

Above 5kA it is necessary to control the arc because it tends to form a constricted column. Two techniques are employed – a transverse magnetic field (TMF), which causes the arc to rotate around the contact surfaces, and an axial magnetic field (AMF), which forces the arc into a diffuse pattern. Eaton favours an axial magnetic field because it can be shaped for the best possible high-voltage performance and maintains this shape after short-circuit interruption.

TRANSIENT RECOVERY VOLTAGE

Vacuum interrupters with Cu-Cr contacts have an exceptional ability to withstand rapidly rising transient recovery voltages (TRVs) associated with secondary faults on transformers, generators and short line faults on overhead lines.

Secondary faults on transformers: when a vacuum interruptor is close to a large power transformer, the high natural frequency of the transformer combined with low capacitance in the connections can result in a very fast transient recovery voltage, less than 10_s for a secondary fault where the rated (T3) time for indoor circuit-breakers is 60_s. It has been shown that vacuum interrupters with Cu-Cr contacts will reliably interrupt more than 99.9% of transformer secondary faults.

Short overhead line faults: overhead lines produce a sawtooth TRV with a very fast leading edge when a fault occurs close to a circuit-breaker. In SF6 interrupters, the decay of gas temperature is of the same order as the rate of rise of recovery voltage (RRRV), making it difficult to withstand the RRRV. With vacuum interrupters, however, decay of the plasma temperature and cathode spot temperature is faster, making it easy for the vacuum interrupter to handle transient recovery voltages in short overhead lines.

Consideration has to be given to the interaction between vacuum interrupters and inductive elements in a distribution circuit (motors, transformers and shunt reactors) when voltage surges appear at the terminals. These surges may be lightning-induced or may be caused by closing or opening a circuit switch. Normal surge suppression techniques applied to distribution networks should handle lightning surges so it is opening and closing of circuit switches that demand consideration.

In general the problems that occur when closing and opening circuits are common to all interrupter technologies – vacuum, SF6, oil or air. When a circuit switch is closing, a prestrike can arise across the closing contacts and, as a result, a travelling wave can appear at the inductive element where it is reflected back to the interrupter. Waves can travel to and fro a number of times and may reignite the interrupter. Surge suppression techniques are available to protect motors, transformers and shunt reactors against surge effects.

Capacitor switching: vacuum interrupters with Cu-Cr contact materials have proved very effective for switching capacitor banks despite the frequent switching duty demanded of power-factor correction systems.

Vacuum circuit-breakers and reclosers offer proven reliability and superior performance over a wide range of medium-voltage applications up to 40kV. Meanwhile, solid insulation is technically compatible, but environmentally preferable, to SF6 gas insulation. ■