THE SHIELDLESS INSULATION DESIGN OF VACUUM INTERRUPTERS

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SYNOPSIS:

The design of insulation systems for vacuum interrupters is quite complex due to the combination of demanding electrical and mechanical requirements together with the specific requirements of a vacuum device, and the fact that during the operation of a vacuum interrupter large quantities of metallic vapour are generated which will, unless prevented deposit on the inner surfaces of the insulator degrading its performance unacceptably. Normally this is prevented by incorporating a vapour condensation shield to protect the ceramic.

This paper discusses an alternative, quite radical, approach whereby the insulator itself is specially designed to self protect the internal surfaces, and to tolerate some deposition without compromising its insulation properties. The self protection feature is entirely due to the design of the Alumina ceramic insulator and completely eliminates the need for shields or other protective devices. This " Shieldless" concept has now been successfully used in vacuum interrupter design for a number of years to withstand voltages up to 45kVrms, and 95kV bil at ratings of up to 31.5kArms. The development of this concept is discussed together with the design of the insulator, and subsequent manufacturing experience.

INTRODUCTION:

Vacuum interrupters are devices which form the key interrupting component in High Voltage electrical distribution switchgear for voltages up to 40.5kV. They use the superb dielectric properties of vacuum together with electric arcs in vacuum to perform commutation of currents from a few amps up to many kA. The basic components of a Vacuum Interrupter are shown in Figure 1, and a typical sectioned vacuum interrupter is shown in Figure 2.

The design of vacuum interrupters has been described elsewhere [1,2], but a brief description here is necessary to an understanding of the insulator application. Vacuum Interrupters are sealed for life vacuum devices which perform current interruption at the next available current zero once the contacts have been separated. Due to the extremely high dielectric strength of vacuum, it is normally necessary to open the contacts only 6-8mm for 12 kV systems and 12mm for 36kV systems. These gaps are sufficient not only to withstand the applied TRV after arcing, but also the appropriate bil 1.2/50 waveform for the voltage across a cold gap (75kV for 12kV systems, and 170kV for 36kV systems) [3].

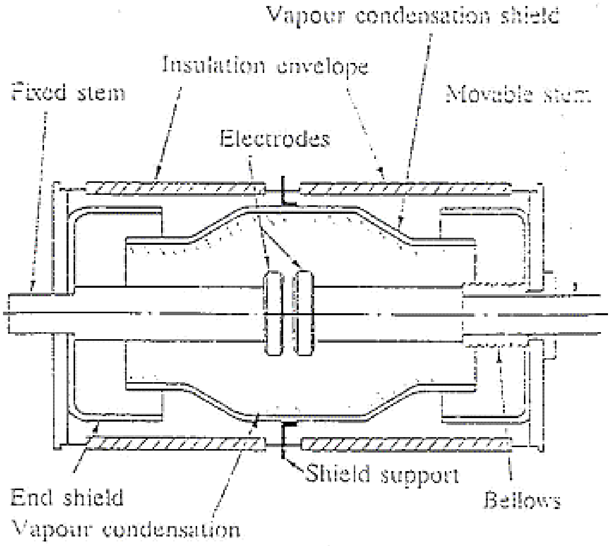

Figure 1. Basic Components of a Vacuum Interrupter

However the solid insulation components in a vacuum interrupter must be designed to fulfil a number of vital tasks, under a number of changing conditions. The design of electrical insulators used in vacuum interrupters for medium voltage vacuum switchgear is quite complex, as this not only includes the mechanical, electrical, and atmospheric pollution requirements of normal insulators, but also internally the specific requirements of a high voltage vacuum device. This is further complicated due to the fact that during a switching operation of a vacuum interrupter metallic vapour is generated in the vacuum which will then deposit on the internal surfaces of the insulator compromising its insulation properties.

Traditionally vacuum interrupters and switches incorporate a metallic shield within the vacuum zone to prevent this metallic vapour from condensing on the inner surface of insulators. A typical design can be seen in Figures 1 & 2, incorporating metal shields both at the centre of the two insulators, and also at the other ends of the insulators. The end shields are there to reduce the electrical stress at the triple point on the outside of the insulator (Ceramic/metal/air) and also the triple point on the inside of the insulator (Ceramic/metal/vacuum).

This has proven to be an effective solution providing acceptable electrical stresses and interrupter performance, and the majority of vacuum interrupter designs use this approach, with a typical example designed in the 1970's and still in manufacture today, shown in Figure 2.

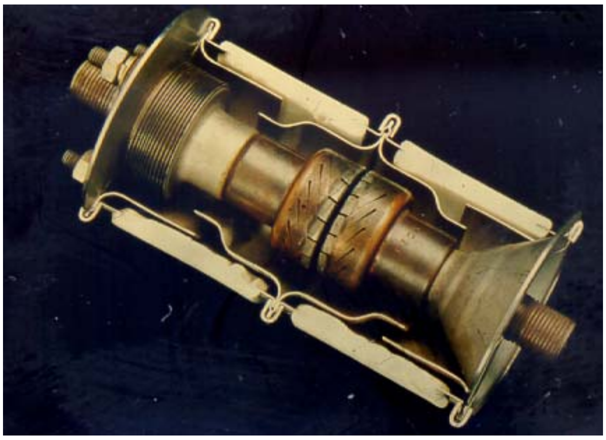

Figure 2. Typical Vacuum Interrupter c.1975.

However, although simple in concept, this solution has significant disadvantages in that the mounting of the centre shield in particular causes difficulties in the design of the interrupters, necessitating the use of a split insulator, with the consequent disadvantage of extra vacuum seals and difficulty in assembly, in addition the anti vapour shield which is at floating potential can charge to a significant voltage which can cause some difficulties in service. An alternative approach with a single insulator is sometimes used, whereby a special insulator incorporates a mounting point for the metallic electrically floating potential vapour condensation shield. This approach also adds complexity and cost to the ceramic and difficulty in assembly, and is less generally less favoured by manufacturers than the two ceramic approach.

DISCUSSION:

The Vapour Deposition Shield

In the 1980's VIL in London performed a fundamental review of the design of Vacuum Interrupters and came up with a radical alternative to the metal vapour shield approach [4]. In evaluating the need for a vapour deposition shield, the following key requirements were identified.

1. Structural integrity.
2. Vacuum compatibility.
3. Ease of assembly.
4. Compatibility with existing manufacturing processes.
5. Ability to maintain dielectric ability after many switching arcs in the interrupter.
6. Reduction in cost over existing solution.
7. Extremely high reliability in service.

It was postulated that a single ceramic geometry which mimicked the two insulator concept including vapour deposition shields could meet all of these requirements. In principle this idea was to replicate the total geometry of two insulators together with vapour deposition shields, all in one piece of ceramic. The simple approach was to use a proven material, such as Alumina ceramic for the insulator, as this was well proven and met the basic material requirements. A new interrupter incorporating the so called Shieldless ceramic insulator was designed, and is shown in Figure 3.

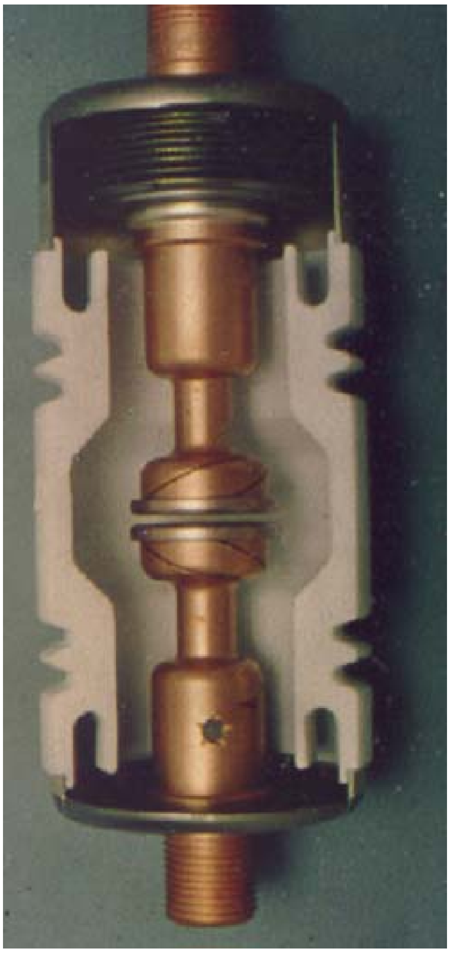

Figure 3. V204 The world's First "Shieldless" vacuum interrupter.

The design concept, although simple, resulted in a more complex Alumina insulator whereby the insulator itself is specially designed to self protect the internal surfaces, and to tolerate some deposition without compromising its insulation properties. The self protection feature is entirely due to the design of the Alumina ceramic insulator and completely eliminates the need for shields or other protective devices. In detail the design worked by including internal fins at each end of the ceramic which protected a small area of the surface of the ceramic. When metal vapour from the arcing arrived at the ceramic it coated the central section, but did not coat the ceramic protected by the fin. This small length of protected ceramic in vacuum is more than sufficient to meet the dielectric requirements of the device (75kV or 95kV bil).

The design was carried out using a combination of computer modelling and prototype testing. It was initially modelled using Finite Element software, as shown in Figure 4, to optimise the fields, and then prototypes were constructed and subjected to a rigorous test programme.

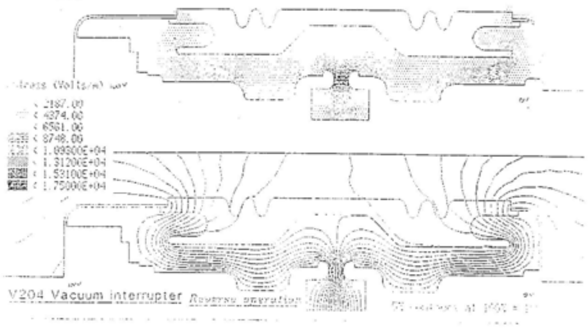

Figure 4. Finite Element plots showing equipotential lines and surface stresses for the "Shieldless" insulator.

Apart from the normal vacuum interrupter tests, it was decided to fully validate the design concept by performing a number of special tests.

The first was to subject a number of prototypes to 50 full short circuit operations at 20kA(rms). This was in order to confirm that the interrupters would meet or exceed the performance of vacuum interrupters incorporating conventional metallic vapour shields. This test included confirming that the high current arc would not damage the ceramic, as well as confirming that the large quantities of metal vapour generated when interrupting short circuit currents would not degrade the insulation performance of the interrupter. The test was completely successful, and as can be seen in Figure 6 the small area behind the protective fin is unaffected by metal vapour deposition and the insulation properties are fully maintained.

Figure 5 shows the difference between an unarced ceramic and photos of the protecting fin at the end of the ceramic taken from prototype Shieldless Vacuum Interrupters. The top photo shows the deposition after 50 times 20kA short circuit interruptions. It can be clearly seen that the deposition ends on the fin and the groove behind the fin is not compromised by metal vapour deposition.

In addition, as part of this programme a number of tests were made where the high current arc was deliberately made to hit the ceramic to ensure survivability under extreme conditions.

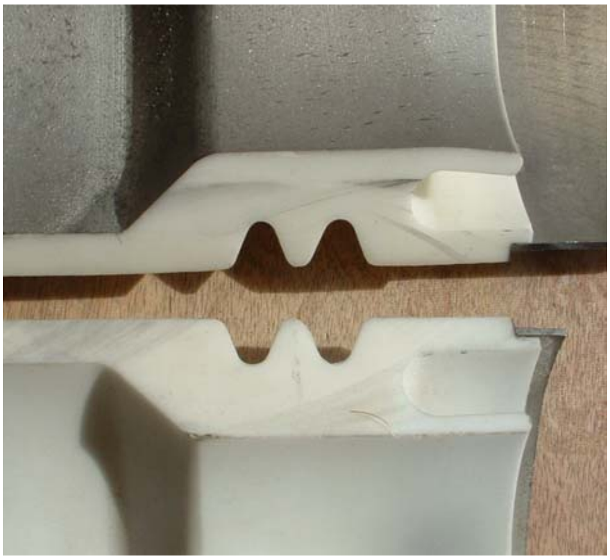

Figure 5. Photos of the ceramic fin and groove in the Arced (20kA) – top, and unarced condition – bottom.

It was also necessary to perform 10,000 switching operations at maximum load current (1250A) in order to confirm that in more normal use the insulator was not progressively degraded by lower levels of vapour, but in much larger quantities over time, and which behaves differently to the large cloud of vapour and droplets generated by short circuit currents. In this case once again the metal vapour deposition was found not to degrade the insulation of the Vacuum Interrupter.

However the presence of a "pseudo" metallic shield on the surface of the ceramic formed by metal vapour deposition was in fact found to be beneficial to the interrupter design in a number of ways. Firstly it acted to control the electrical fields of the interrupter across the insulator much as a true metallic shield does in a classical design. Secondly it is necessary to have a metallic ring surrounding the contacts in order to use the Inverse Magnetron pressure measuring system which is universally used in the measurement of vacuum interrupter pressure and vacuum life determination. Thirdly it would appear anyway due to switching operations performed during the service life of the interrupter as it operated normally over 20 years. As a result of this it was decided that the interrupters should be manufactured with a "pseudo" shield already existing prior to sale, and so all "Shieldless" interrupters are arced a number of times after seal off to coat the inner surface of the ceramic and establish the "pseudo" shield. This means that after processing the interrupters will not change while in service, regardless of the service duty, the "pseudo" shield merely becoming a little thicker.

The Voltage Grading Shields

The second insulation problem concerned the voltage grading shields mounted at the ends of the insulators away from the vapour deposition shield.

These worked to protect the ceramic/metal/ vacuum triple point, and were found to be necessary to prevent breakdown across the insulator surface. The breakdown of a ceramic insulator surface in vacuum is dealt with in [4].

Tests revealed that the breakdown level was significantly improved if the triple point was protected. This was the result of experiments performed on a number of different geometries. To give an indication of the difference this can make two of the geometries modelled and tested are shown in Figure 6.

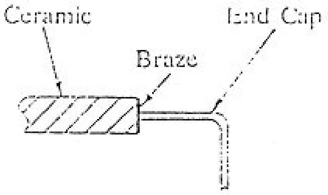

Figure 6. Classic braze joint.

Figure 6 shows a classic braze geometry. Although simple and low cost this has the disadvantage that the brazed end of the ceramic forms effectively a knife edge electrode pointing into the interrupter.

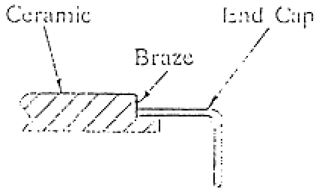

Figure 7. Shielded braze joint.

Figure 7 shows a design where a wall of ceramic is used on the vacuum side to protect the triple point and remove the “knife edge” effect. This is the design used in the V200 series vacuum interrupters, and had the added advantage of providing accurate self alignment of the end caps to the ceramic (Figure 8).

Figure 8. Actual shielded braze joint

During the evaluation of different triple point geometries, bil tests using a standard 12/50 waveform showed that the classic braze joint had a very poor performance, only reliably withstanding 65kV, whereas the shielded geometry withstood 105kV reliably on both polarities, all other factors being the same. Further tests showed that this geometry also was not affected by metal vapour deposition.

The “Shieldless” concept

Putting together the concepts and results from the work on the vapour deposition shield and voltage grading end shields resulted in a single insulator design which fully met all of the design criteria. Although the complex ceramic geometry resulted in a component which was significantly higher cost than the plain cylinders used previously, the ”Shieldless” ceramic insulator as shown in Figure 3 was considerably lower cost than the two insulators, four shields, and additional minor components it replaced.

The added complexity of the ceramic also proved challenging for ceramic manufacturers, and the original development of the ceramic itself was performed by GEC Ceramics Limited (now Advanced Ceramics Limited (ACL)). Later the design was and is fabricated by a number of ceramics manufacturers around the world including ACL. Since the introduction of the “Shieldless” vacuum interrupter concept in the 1980’s a range of interrupters of different ratings have been developed to meet different needs and which have been manufactured around the world for over 20 years. This is a significant number as the design life of a vacuum interrupter is 20 years, which means that the first “Shieldless” vacuum interrupters have now come to the end of their service life. The experience in the field has been excellent and the interrupters have fully validated the original concept of the “Shieldless” insulator design.

CONCLUSIONS:

This " Shieldless" concept has now been successfully used in vacuum interrupter design for 20 years, to withstand voltages up to 45kVrms, and 95kV bil, and with a short circuit rating up to 31.5kA

By this innovation the size and complexity of the vacuum interrupters was significantly reduced. This radical innovation in insulation design has been a considerable technical and commercial success, with in excess of 250,000 “Shieldless” vacuum interrupters manufactured around the world over the past twenty years, with the original design still in manufacture today.

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