Vacuum Interrupter Design for HV and VHV Applications

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Abstract

Presently there is an upsurge in interest in the use of vacuum interruption at transmission voltages (< 100kV). This is due mainly to environmental concerns over the use of SF_6 gas, which is today the dominant technology for switching applications at these high voltages. Vacuum interruption has dominated the Medium Voltage range of switchgear (< 52kV) for many years, and it would appear logical to try to apply vacuum interruption technology to these higher voltage ranges. However applying existing vacuum interrupter technology to higher voltages is not straightforward and there are a number of technical and economic factors to be taken into account. There is some history of applying vacuum interruption to these high voltages and a second paper at this conference (ibid.) deals with this experience and the reasons why this technology was not universally adopted at the time.

This paper considers the technical aspects of designing vacuum switchgear for HV applications and examines the advantages and difficulties in applying vacuum interruption at these high voltages. In particular those factors which apply to vacuum interruption only, such as x-ray emission are considered along with the switching properties of vacuum interrupters when applied to HV systems.

1 Introduction

There is today a strong move to eliminate the use of SF_6 gas in all applications, principally based on environmental concerns over the use of SF_6, a gas listed in the Kyoto protocol. After a number of years of intensive research it has still not been possible to find an alternative fluid which has SF_6's remarkable electrical properties, and so researchers are turning towards Vacuum as a possible replacement technology. The selection of vacuum as a potential successor to SF_6 is based on its technical dominance at medium voltages, its low cost, and the widespread availability of vacuum interrupter technology. Vacuum switchgear is the dominant technology for MV distribution systems worldwide (below 52kV) and has been for many years, just as presently SF_6 is dominant for transmission voltages.

A large number of companies have produced single Vacuum Interrupters for system voltages up to 38kV since the early 1980's, and more recently Japan AE Power Systems Corporation (JEAPS) (Figure 1) as well as a number of Chinese manufacturers, have produced or are developing single break Vacuum Interrupter circuit breakers for voltages up to 145kV [2,3].

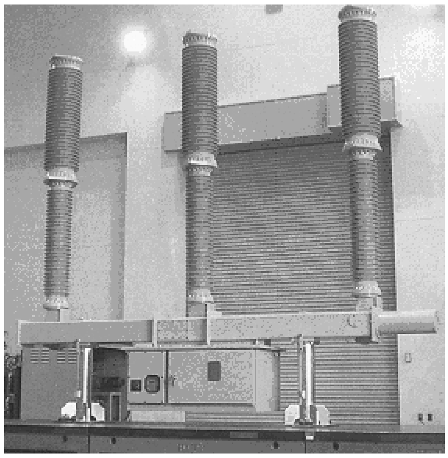

Figure 1. JAEPS Vacuum Circuit Breaker 145kV.

In the 1960's when Vacuum switchgear was first developed, few companies had mastered the technology and the R&D required was extremely costly. So costly that for example the UK companies involved in the research pooled their resources and formed Vacuum Interrupters Limited (VIL) as a joint venture to include all of the UK technology. However since that time the manufacture and development of vacuum interrupters for MV is now widely established internationally. This was achieved by means of license agreements and the general increase of technological capability worldwide, with an estimated 1,000,000 devices now manufactured every year (Figure 2 & Figure 3).

Figure 2. Manufacture of Vacuum Interrupters at VIL in London in c1978. Author in centre of group.

Figure 3. Manufacture of Vacuum Interrupters in South Africa c1990.

However, the use of Vacuum Interruption at transmission voltages brings with it a number of fundamental differences from MV applications and these are considered in the paper.

2 History

To begin we must go back to the 1950's and 1960's when Vacuum and SF_6 technology were both in their infancy. At that time both MV and HV circuit breakers were predominantly based on Oil interruption technology. Vacuum seemed to be a good candidate for the future of all switchgear, and so Vacuum circuit breakers were developed for applications around 132kV and put into service in the UK and the USA in the late 1960's [4], (Figure 4), the story of the UK circuit breakers being presented at this conference. However these Vacuum circuit breakers were not commercially successful at the time, and Vacuum technology became limited to the lower voltage (12kV –27kV) high volume markets, which it went on to dominate.

The main problem in the early days was that the circuit breakers were based on medium voltage interrupters, and because of their voltage limitations up to eight vacuum interrupters in series were needed per phase. Although the performance of the circuit breakers was fine, and indeed they remained in service until the 1990's, the cost of such a complicated mechanism needed to operate large numbers of interrupters simultaneously, together with associated maintenance issues meant that this was just not economical against an SF_6 circuit breake or indeed Oil breaker with just one or two breaks per phase.

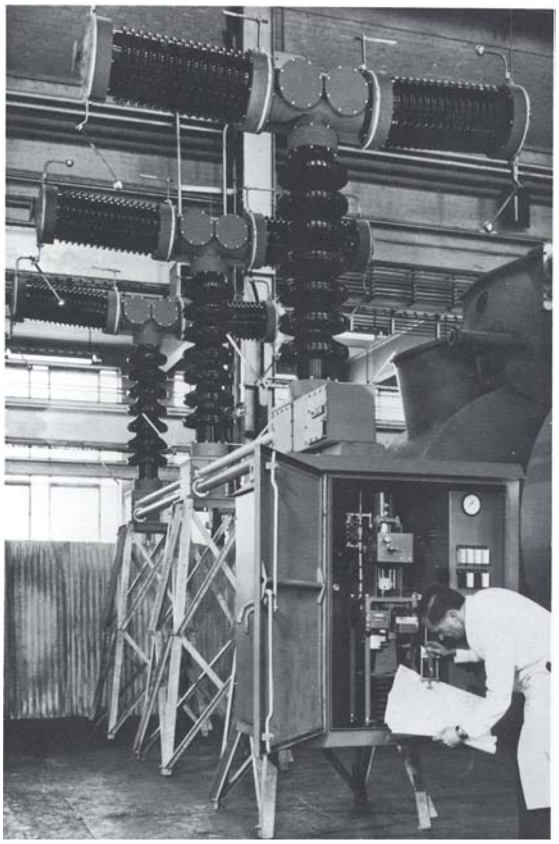

Figure 4. AEI 132 kV circuit breaker, 1967.

The obvious solution to this problem is to use less Vacuum Interrupters per phase, but at higher voltages this introduces new technical difficulties, which will be dealt with later.

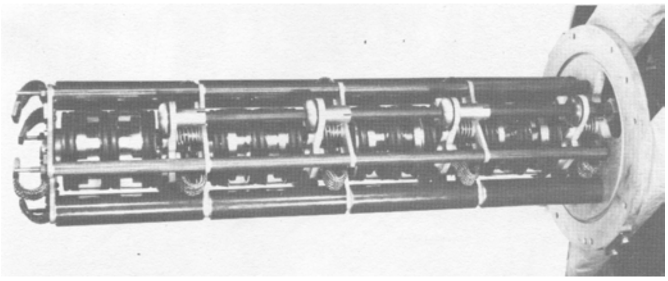

Figure 5. One arm of one phase of the AEI 132kV circuit breaker. Each arm had four vacuum interrupters in series, giving a total of eight interrupters in series per phase.

As the vacuum technology developed through the 1970's and 1980's, so single interrupters were developed for system voltages of 36kV, 52kV and even 84kV. Today in Japan JEAPS have developed a single 145kV Vacuum Interrupter for their SF_6 free circuit breaker (Figure 6), which effectively replaces the eight interrupters needed for the AEI circuit breaker (35 years later).

Figure 6. The Author with the JAEPS 145kV Vacuum Interrupter, 2004.

However there are a number of disadvantages with this approach. Vacuum Interrupters for MV applications are small and lend themselves to mass production, due to their specialised manufacture requirements However very large Vacuum devices made in small quantities are normally very expensive. At this point it is appropriate to look briefly at the generic design of Vacuum Interrupters, and how they work.

3 Vacuum Interrupter Technology

Figure 7 shows a typical Vacuum Interrupter design. The operation of these devices is extremely simple. The contacts are separated by moving one contact by 8-12mm from the other contact. The arc then burns in vacuum until the next current zero, at which point it extinguishes naturally. Interruption is achieved due to the incredibly fast dielectric recovery of the contact gap, which recovers faster than the applied TRV can appear.

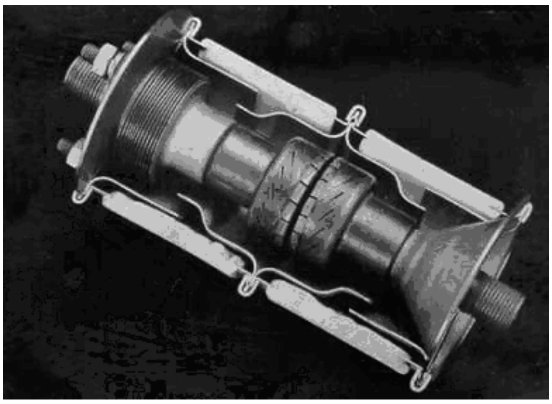

Figure 7. Typical 1970's Vacuum Interrupter rated at 12kV 20kA Manufactured by VIL Finchley.

The slots in the contacts generate a radial magnetic field (RMF) at higher short circuit currents and make the arc move around the periphery of the contacts preventing overheating of the contact surfaces. The metallic shields are there to prevent the interrupter's overall dielectric performance from degrading due to deposition of metallic vapour on the inside of the ceramic insulator body, and additionally act to control the electric fields for bil and Power Frequency Test voltage performance [5].

Figure 8 Shows a Higher Voltage V506 interrupter designed at VIL in 1982 for 36/38kV application in GIS or solid external insulation. Note the curved edges to the high voltage internal shields, the bellows protected by a shield (behind the right hand contact) and the floating potential centre shield.

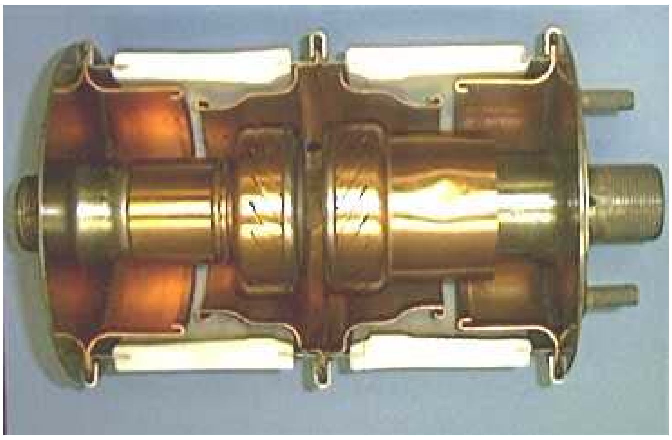

Figure 8: V506 Interrupter Rated at 36kV 31.5kA.

Vacuum interrupters are sealed for life during manufacture and normally have an operating vacuum life of 20 years. Very little wear occurs even during short circuit interruption, giving a life of 50 or more full short circuit interruptions, and tens of thousands of load current switching operations for most designs. Vacuum Interrupters are manufactured under clean room conditions (as shown in Figures 2 & 3) and normally in significant quantities (tens of thousands per year) to justify the large capital investment needed on specialist plant. Also for MV applications they are small and light facilitating manual handling. For example, a 24kV 13.1kA interrupter is typically just 60mm in diameter.

More detailed descriptions of how vacuum interrupters are constructed and operate can be found elsewhere [6,7,8].

4 Vacuum Interrupters for HV Applications

The fundamental problem with the HV Vacuum circuit breakers of the 1960's was the need to have up to eight interrupters in series per phase. An obvious way to overcome these problems is to design large high voltage vacuum interrupters. If one interrupter per phase could be used this immensely simplifies the design and reduces the cost of the circuit breaker substantially. Unfortunately this is not quite so simple to achieve. Up to a point this is quite feasible and indeed what JAEPS and others have done up to 145kV.

However Vacuum interrupters have a number of important design features, each of which face difficulties as the voltage increases.

4.1 Vacuum Design

Vacuum interrupters are sealed for life devices. That is, they are not attached to any pumping system after seal off, and instead rely on being hermetically sealed. As the devices become bigger, physically they are more difficult to handle, and normally need more seals, this in turn requires more careful design of the components, seals, and assembly techniques. Although it is possible to build very large vacuum devices, this adds to the cost, and the difficulty in handling, particularly where the interrupters must be fitted on site. Due to the extreme cleanliness and special processing required during manufacture it is not possible for an interrupting unit to be final assembled on site as may be done with an SF_6 unit. The Vacuum interrupter unit must be completely sealed and manufactured in the factory. Transportation and handling can cause serious problems, indeed this was an issue even with the small interrupters used thirty years ago by AEI in their 132kV circuit breaker, and damage to the interrupters before assembly into the circuit breaker was a contributing factor to their decision not to pursue Vacuum for HV applications.

4.2 Arc Control Design

Vacuum interrupters are designed with special contact geometries which use the high magnetic fields generated during a short circuit to control the arc and prevent it from causing the contact surfaces to overheat which would result in a failure to interrupt. These geometries work in one of two ways. They either use a magnetic field which is radial to the axis of the contacts (RMF), or a magnetic field which is in the axis of the contacts (AMF). Although the effect on the arc is different both types of geometries rely on strong magnetic fields on the contact surfaces and across the contact gaps.

Over thirty years of development these contact designs have been optimised for MV applications, and indeed contacts are available which can interrupt faults of over 100kA repeatedly without difficulty. Alternatively more modest currents can be interrupted on quite tiny contacts as shown in Figure 9, which is of a 32mm diameter Folded Petal contact interrupting 20kA

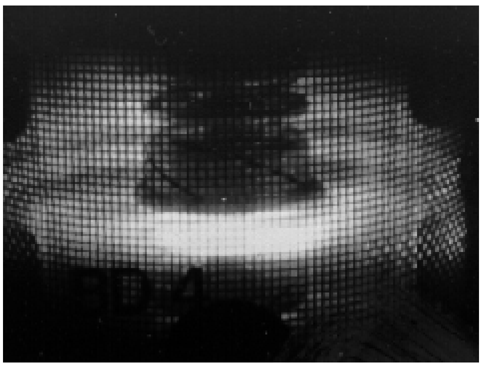

Figure 9. Folded Petal contact 32mm in diameter interrupting 12kV:20kA.

At higher voltages however, in order to cope with the much higher Transient Recovery Voltages (TRV) it is necessary to use significantly larger contact gaps, this in turn effects the arc control systems. For 12kV ratings a contact gap of 8mm is quite normal, and 12mm is used successfully for 36/38kV ratings. However significantly larger gaps are needed for the higher transmission voltages, and this poses a considerable difficulty. As the arc length is increased, so the effective magnetic field at the centre of the contact gap is diminished. This in turn affects the interrupting ability of the device. As an additional problem, the magnetic fields are used to provide stability to the arc, and it is more difficult to ensure this arc stability with a greater arc length. This can lead to an unstable performance in interruption, and necessitate a larger diameter interrupter.

The large contact gap/movement leads to other problems. A bellows normally made of thin stainless steel is used to provide a moving seal for the vacuum. The short movement of MV interrupters is quite easy to cope with and large numbers of operations, tens of thousands, can easily be achieved. However as the stroke increases so the life of the bellows decreases. This is easily seen by comparing vacuum switches with vacuum interrupters. 6.6kV vacuum switches have a stroke of 4 or 5mm and achieve a bellows life of over 3,000,000 operations. 12kV vacuum interrupters have a stroke of 8mm and have a life of 50,000 operations. Very long strokes have much lower lives. This problem is exacerbated by the fact that the mechanism must move much faster to achieve full opening in the same time over a longer gap. This also significantly reduces bellows life. Finally, long bellows have another problem. A very long bellows with many convolutions can suffer from resonance and oscillations being set up during operation. These also act to significantly reduce bellows life.

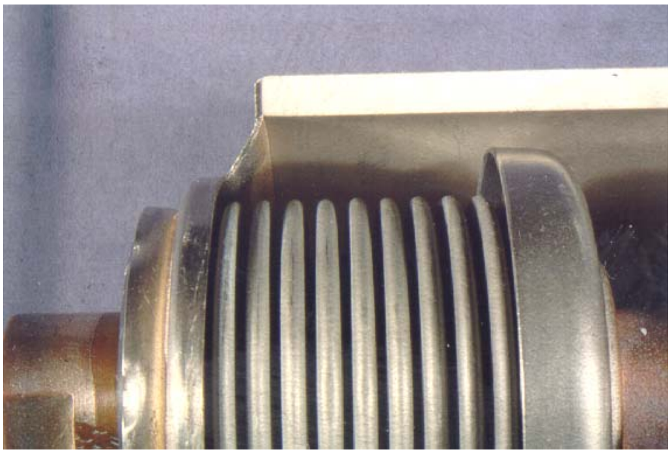

Figure 10: (typical Vacuum interrupter bellows)

4.3 Contact Material Design

The third key area is that of contact materials. A fundamental difference between Vacuum Interrupters and all other types pf switchgear is that in a vacuum interrupter the arc is entirely created using the material of the contact. Changing the material can totally change both the characteristics of the arc, and also the interruption process. For example, by selecting different contact materials it is possible to change such parameters as current chopping level, dielectric strength of the gap, contact wear, and interruption performance, in an otherwise identical interrupter. Designers of vacuum interrupters use this property of the Vacuum Interrupter to customise the performance of interrupters depending on the application, so for example for motor control applications, at 12kV and below, contact material of WCAg (Tungsten Carbide–Silver) [Figure 9] is widely used, whereas for power interrupters of 12kV to 72.5kV CrCu (Chromium Copper) [Figure 10] is now almost universally used due to its excellent interruption and dielectric performance. Both Figures are to the same magnification and as can be seen the structure is quite different.

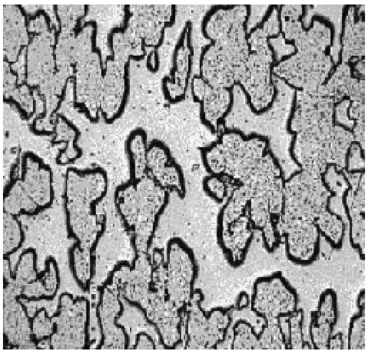

Figure 9. Photomicrograph of CrCu contact material originally developed and patented by English Electric in the 1960's.

But as arc lengths increase to cope with higher voltages, so these materials may not provide optimum performance. It may be necessary, as in the past, to develop new materials for these new requirements. The difficulty with this is that The requirements of the materials are such that there are conflicting requirements, and so all vacuum interrupter contact materials are a compromise. The introduction of two new parameters – the long contact gap and the very high voltage stresses, means that a new balance needs to be struck between the different material properties, this is unlikely to result in superior performance than the MV devices today which means that a significant de-rating of the interrupter is likely as the contact gap and the system voltages increase. This in turn leads to bigger more expensive vacuum interrupters.

Figure 10: Photomicrograph of WCAg contact material.

4.4 Mechanism Design

One clear advantage of using Vacuum Interrupters is that they need very low energy to actuate them. This is due to a number of factors:

1. They have very low moving masses (a 12kV 20kA contact is ~ 100g),
2. There is no gas pressure/fluid resistance to overcome, and of course, no puffer action.
3. At all voltages the contact gap needed for a Vacuum Interrupter is a fraction of that needed for the equivalent SF_6 Interrupter. For example, for 36/38kV systems a contact gap of only 12mm has been used for many years.

This means that low energy mechanisms needing low or zero maintenance can be used and are now in common usage for MV Vacuum circuit breakers. One particular mechanism applied to vacuum is the Magnetic Actuator, a bi-stable permanent magnet based unit, which uses extremely low energies to obtain the required movement. Unfortunately the longer strokes needed for HV applications are not so ideal and although Magnetic actuators can be used there is significant added cost and complexity.

4.5 Other Factors

X-Ray Emission

Similarly potential x-ray emission at higher voltages must also be considered. At all voltages X-ray emission is zero when the interrupter is in the closed position. At MV voltages (up to 36kV) X-ray emission is zero or negligible. Significant X-rays could only be generated at test voltages and these are infrequent occurrences, which are harmless under controlled conditions. However once the system voltage gets to higher voltages such as 145kV then the possibility of X-ray emission at system volts becomes significant. Potential consequences of this need to be considered. Firstly, exposure to the public is not a real issue as the electrical safety distances provide an adequate reduction in X-radiation level, although an exception to this would be HV vacuum in GIS. The real issue is that it is possible for the interrupters to irradiate their local surroundings over a long period, and this may have a detrimental effect on polymeric components or electronics mounted in the circuit breaker locally to the interrupters.

Application & Circuit Parameters.

The use of Vacuum Interruption at high voltages also introduces a number of additional factors, which must be taken into consideration. Different interrupting media do not all behave exactly the same, despite the best efforts of the international standards organisations to treat them as such. Oil, Air, and SF_6 all have their unique differences, and this needs to be taken into account in their application. Vacuum is no different and also has unique features, which must be understood and taken into account when applied to transmission circuits. For example, vacuum has extremely fast dielectric recovery, and can commutate a circuit very quickly, which is some circumstances can be very advantageous, but in other circumstances may result in significant switching overvoltages. The experience of Vacuum Interruption for MV distribution applications has been excellent, and there have been limited experience of Vacuum up to 132kV, but the application of this technology to transmission applications needs to be studied further to ensure that no misapplications occur leading to unforeseen problems.

5 Conclusions

The present drive to find an alternative environmentally friendly alternative to SF_6 HV circuit breakers is pushing manufacturers to develop the proven MV Vacuum Interruption technology to transmission voltages. For the lower end of the HV market, from 52kV to 132 kV Vacuum circuit breakers already exist. Above 132kV, as has been discussed, there are a number of technical problems which still need to be resolved. Up to 400kV it is possible to envisage solutions using existing or extrapolations of existing technology, perhaps using multiple Vacuum Interrupters per phase, and it is expected that vacuum circuit breakers up to this rating will appear over the next few years, provided that economic solutions can be found. For system voltages over 400kV the problems are considerably magnified. The use of Vacuum Interruption at these levels is currently at the basic research stage, with a great deal to be done to understand the problems faced before technical solutions can be developed. Additionally for these voltages the numbers of circuit beakers needed are very small and the effort required to develop economically viable solutions may not be justified except if driven by political or legislative actions. Despite this, work is presently being actively pursued in a number of countries to evaluate the use of Vacuum Interruption at the very highest voltage levels. This effort is most apparent in China where a number of Universities, Government Laboratories and Manufacturers are working together at this moment to develop a 750kV vacuum circuit breaker [9]. Although a commercial circuit breaker for this rating is certainly a number of years away, the fact that money and resources are being poured into this indicates a desire to overcome the undoubted technical difficulties and to pursue the goal of Vacuum Interruption as a solution for all HV voltage ratings.

Acknowledgements

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