A Brief History Showing Trends in Vacuum Interrupter Technology

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ABSTRACT

Vacuum interrupters have been in continuous development since the 1950's[1234], and manufacture since the early 1960's. This paper attempts to identify the trends in the technology over this period by means of a brief overview of work carried out in this field by ALSTOM and its predecessor companies. The paper concentrates mainly on work carried out in the United Kingdom with which the author is fully familiar, having been personally involved in the design and development of vacuum interrupters in the UK over the past twenty years. Work by other R&D teams active in this field has been described elsewhere[56].

Introduction

The properties of the metal vapour arc in vacuum which Sorenson and Mendelhall had discovered in 1923 made vacuum an almost perfect medium for the interruption of currents at high voltages[7]. In an AC circuit breaker the extinguishing media normally absorbs the energy generated by the arc and cools it until such time as a current zero naturally occurs. Then the arc extinguishes naturally and the interruption relies on the dielectric strength of the extinguishing media recovering faster than the applied voltage can appear across the contacts. If this is so then the circuit breaker has successfully performed an interruption. If however the contacts or dielectric overheats then reignition may occur. The problem lies in the energy generated during the arcing. This is basically Volts * Amps * time. with the voltage in question being the arc voltage.

The arc in vacuum appeared to be vastly superior to the conventional technologies basically because vacuum had such an excellent dielectric strength[8]. This allowed a very small contact gap to be used giving rise to a much lower arc voltage which in turn generated less energy during arcing. This is vital as the mode of failure of circuit breakers tends to be due to overheating of the contacts, and obviously the less energy dissipated during arcing, the easier it is for the interrupter to interrupt the current. Also a vacuum gap had a very much faster rate of recovery of dielectric strength than conventional gaseous interrupting media, which greatly assisted in the ability to perform interruptions. In addition vacuum invariably interrupted at the first available current zero, whereas oil and air tended to wait for later current zero, significantly increasing the energy to be absorbed.

Vacuum appeared to have all of the advantages. Due to the low arc voltage and high rate of recovery interruption was greatly facilitated. The high dielectric strength gave rise to physically small interrupters, allowing the possibility of size reductions in switchgear. The small contact gap, and low energies required to open the contacts meant simpler lighter operating mechanisms. The sealed for life characteristic of the interrupter meant that it was truly maintenance free, and the hermetic sealing of the contacts meant that environmental conditions made no difference to the performance of the interrupter.

Although fundamentally sound the vacuum interrupter concept took many years to bring to fruition. The reason for this is that although the concepts and design of interrupters are relatively simple, virtually every aspect of their design and manufacture required very careful development and testing, and the development of commercially viable products with a maintenence free life of over 20 years proved difficult. However since the 1960's these problems had been solved, and today vacuum interrupters are established as the main switching technology in medium voltage switchgear around the world[9].

Discussion

Vacuum Interrupter technology splits naturally into four main parts;

Contact Material.

The material used for the interrupter contacts is vital in defining the properties of the interrupter. In other technologies it is the dielectric medium which breaks down and provides the conducting path for the arc. Thus in Oil technology the oil dissociates and the arc is carried in ionised vapour and Hydrogen. In Air technology, by ionised Nitrogen, and in SF_6 by the ionised breakdown products of the SF_6. In vacuum, as we know, the physics of the arc is quite different. The arc consists of a cloud of ionised metal vapour supplied from the contacts themselves. Thus the properties of the contact materials dominate the characteristics of the interrupter.

A contact material for use in a vacuum interrupter are needs to be both gas free and yet not suffer from problems such as welding and high current chopping which would cause severe problems in service. It must also exhibit a fast rate of recovery of dielectric strength immediately after interrupting fault currents. A combination of properties which are to some extent contradictory. It must also be fairly low cost, and have a high electrical and thermal conductivity. It was soon established that one material alone could not comply with all requirements.

CuBi

Oxygen Free High Conductivity copper (OFHC) was an initially promising candidate, but suffered from a fatal tendency to weld when required to close on to a high current fault. This was overcome by the simple expedient of adding a small quantity of bismuth to the copper, which tended to precipitate at the grain boundaries, and produced an embrittlement. This meant that although the interrupter still welded, the weld was weak and could be easily broken by the switchgear mechanism. This work was done by General Electric, (GE) of the USA and CuBi has since been widely used in power interrupters made by many manufacturers around the world[10].

CuCr

In the UK, English Electric (EE) were also working on this problem and came up with a radically different solution[11]. EE were interested in the properties of binary materials, and produced one based on infiltrating liquid OFHC copper into a previously sintered matrix of Chromium powder under vacuum, code named CLR. This resulted in a binary material with a virtually ideal combination of properties needed for this application. Good dielectric strength, low gas content, plus low welding ability. This material was immediately available to Westinghouse as a result of a technology agreement with EE and later Siemens were allowed to both use and make the material as part of license agreement with Vacuum Interrupters Limited which inherited the technology. The usefulness of Chrome Copper has since been confirmed as, once the patent protection ran out, many other vacuum interrupter manufacturing companies changed to this material, eventually even GE, the inventors of CuBi. both ourselves and other manufacturers have since further developed the CuCr material by adding third or even fourth materials in small quantities to modify specific material properties affecting the arc, such as chopping current levels[12 13].

Arc Control Systems

Radial Magnetic Field

The control of high power arcs in commercial vacuum interrupters started in 1960 with the Dr Schneider or "Spiral Petal" contact by GE[14]. This geometry is based on Fleming's left hand rule, and uses the high levels of current during a short circuit to drive the arc across the surface of the contact.

Because the magnetic field is radial to the direction of the arc, these contacts are termed Radial Magnetic Field, (RMF). In the Spiral Petal geometry this is achieved by a series of slots in a disc of special contact material such as CuBi, or CuCr.(Figure 1).

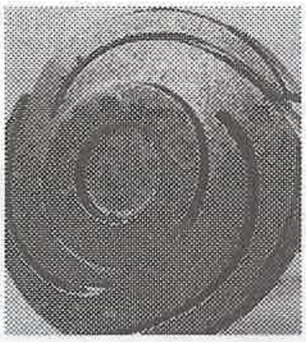

Figure 1 - GE Spiral Petal Contact.

In principle the geometry provides a radial component of magnetic field in the plane of the arc which causes the energy of the constricted arc to move over the surface, reducing the total energy absorbed at any point to below a critical value preventing reignition of the arc after current zero. In the UK at the same time Dr M.P.Reece[15] working at the Electrical Research Association (ERA) in collaboration with Associated Electrical Industries (AEI) developed a cup shaped "Contrate" RMF contact geometry which provided a radial magnetic field to make the constricted arc move in a similar way, except in this case the arc moved around a ring of contact material at the lip of the cup.

The Contrate geometry has been subject to continuous development over the last thirty years giving ever higher interruption abilites on smaler contacts.

In the early 1980's a new contact, the "Folded Petal" was developed which by means of a new geometry incorporated the best featues of the Spiral Petal and the Contrate contact, giving very good arc interrupting ability on a very small contact diameter[16]. The folded petal contact on the left is just 35mm in diameter compared to the 55mm diameter Contrate. Both are rated at 20kA;12kV.(Figure 2)

Figure 2 - Folded Petal v's Contrate contact geometry.

Axial Magnetic Field

Later a different principle was established to allow the interruption of high currents. This tehnique used a high magnetic field in the direction of the axis of the arc, Axial Magnetic Field, (AMF) which does not make the arc move, but instead diffuses it, spreading the energy across a large surface area, and thereby reducing the total energy absorbed at any point to below a critical value preventing reignition of the arc after current zero. This technique was pioneered by Toshiba[17 18] of Japan, and since then other companies have developed different means of achieving the AMF such as Holec, Hitachi, Cutler Hammer (formerly Westinghouse) and AEG (now part of ALSTOM)[19].

Construction

Classical

From the very beginning the basic design of interrupters was set out as shown. (Figure 3). The interrupters consist of a pair of contacts in special material, a pair of conductors with one contact moveable by means of a bellows, an insulator in glass or ceramic, and sputter shields to protect the inner surface of the insulator from degredation by metal vapour deposition after arcing forming a conducting layer. With a few exceptions this general arrangement has remained true for over thirty years of development.

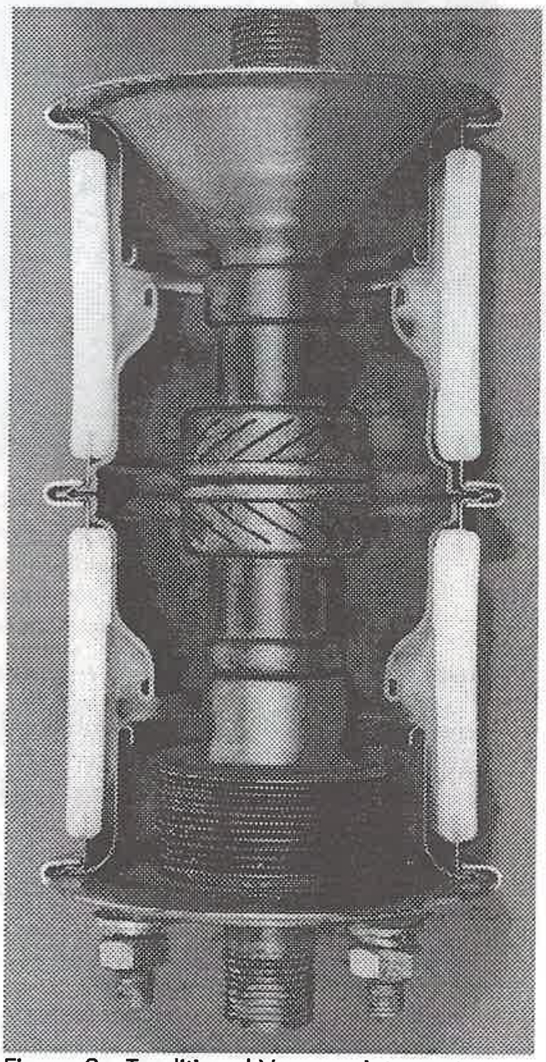

Figure 3 - Traditional Vacuum interrupter design.

Originally the interrupters used Glass insulators. But these limited the maximum baking temperature possible. This was acceptable for manifold pumped devices, but not accptable for funace seal off. So a special Glass-Ceramic material was used for the first furnace seal off devices. This allowed a seal off temperature of approximately 625°C using a special braze material. All of the more recent designs are now based on metallised Alumina ceramic which allows higher seal off temperatures of approximately 800°C using commercially available braze materials.

In an attempt to simplify the construction of the vacuum interrupter, while providing a design suitable for One Shot Seal Off a radical design concept was persued and developed in which the shield function was incorporated in a specially shaped ceramic. (Figure 4).

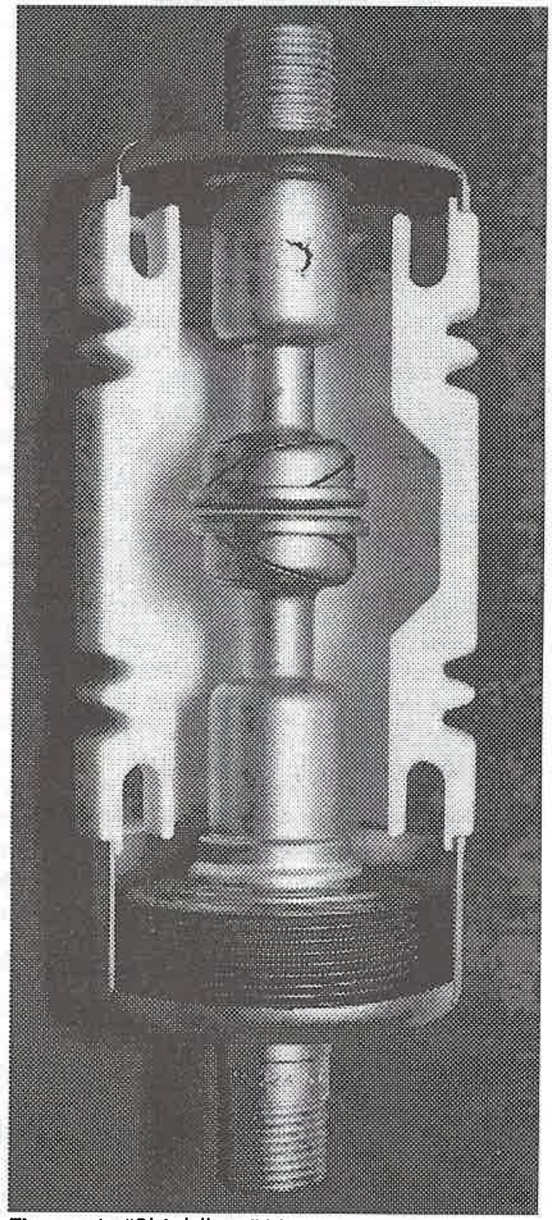

Figure 4- "Shieldless" Vacuum Interrupter

The design uses folds in the ceramic to shield part of the surface from metal vapour deposition, this small protected part of the ceramic is sufficient to maintain the dielectric requirements of the insulator. The rest of the surface is coated with a film of metal after arcing and in effect acts as a pseudo shield[20]. This design is complely self jigging and has only ten components plus six braze washers. This compares with the previous design which had 21 components plus six braze washers. This

"Shieldless" design was first developed in the early 1980's in the UK and is still in manufacture around the world for ratings up to 12kV;25kA, with over 100,000 units produced to date.

Manufacture

In the UK the first commercial interrupters were manufactured in the late 1960's using a system taken from the valve industry, whereby the interrupters were individually pumped using a manifold, while being baked to remove gas and contamination. (Figure 5).

Figure 5.- Pinching off a Manifold Pumped vacuum Switch at ALSTOM, Rugby, England.

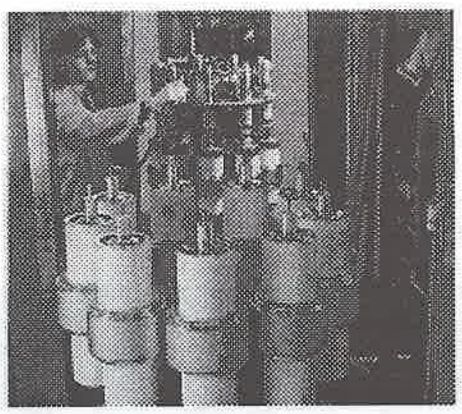

Figure 6- Manifold Pumping at ALSTOM, Ulm, Germany

This technique is still in use by some manufacturers, (Figure 6), but was replaced in the UK in the early 1970's by a system of furnace seal off whereby a large vacuum furnace was loaded with a number of fully assembled interrupters, each of which had a copper insert in the moving endplate incorporating a number of small holes, the interrupters being otherwise sealed. This "pumping port" had a pellet of special braze material (Gold-Indium) placed on it, and the quantity of interrupters (up to 57 at a time) were then loaded into the furnace. After evacuation the furnace temperature was raised to just below the melting point of the seal off pellet, and the load allowed a period to outgas. After a fixed time the temperature was raised slightly, the pellets melted sealing the holes, and all 57 interrupters were sealed off. This technique was seen to give the advantage of batch production to the main manufacturing process, and led to a significant cost reduction. The disadvantage was that the assembly of the interrupters was complex and required one or two additional subassembly brazes prior to the final assembly and seal off. (Figure 7)

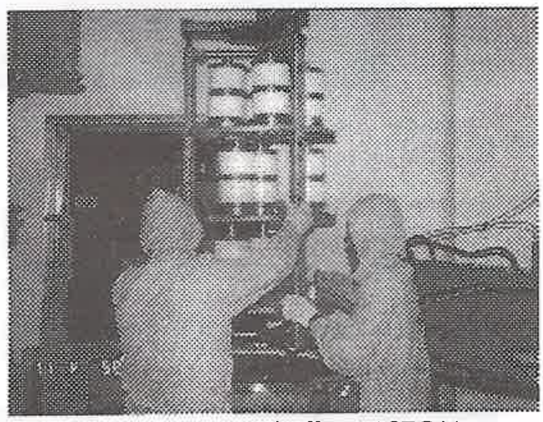

Figure 7 - Furnace seal off at ALSTOM, Calcutta, India.

The next step was the development of "One Shot seal off" during the 1980's. This was developed independently by both VIL, and by GEC Industrial Controls, both of which are now part of ALSTOM[21]. "One Shot Seal Off" is the logical progression of the furnace seal off technique and means that the interrupter is designed such that the internal components are self jigging, and it is possible to assemble the interrupter components completly prior to entering the furnace. No welding or pre assembly is needed, as the interrupter is completely assembled by brazing in one operation. (Figure 8).

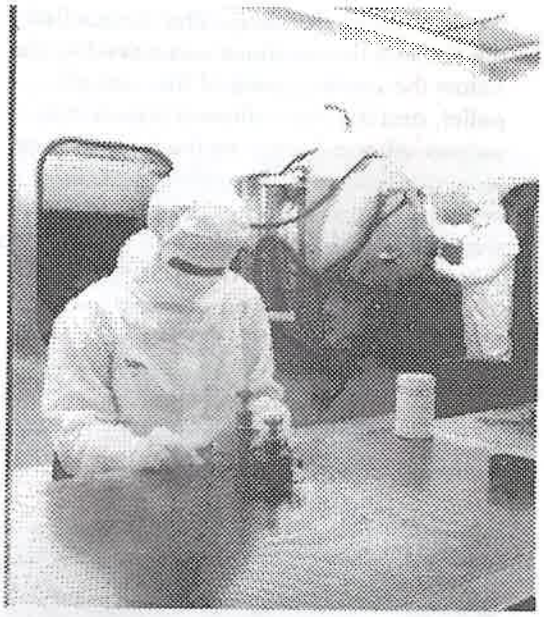

Figure 8- One Shot Seal Off Assembly at ALSTOM, Johannesbourg, South Africa.

The assemblies are loaded into the vacuum furnace and go through a seal off cycle as before, except that the pumping port is no longer necessary, and venting takes place at the braze interfaces with the ceramic. (Figure 9).

Figure 9- One Shot Seal off at ALSTOM, Rugby, England.

The furnace cycle followed is shown, (Figure10), and up to 96 interrupters can be sealed off at one time. The limit being effectively the volume of the furnace.

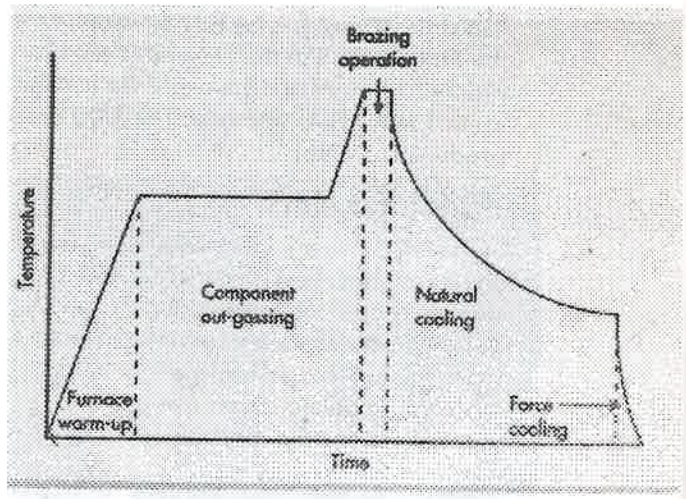

Figure 10- One Shot Seal Off Cycle

This process has greatly simplified manufacture of the interrupters, removing many manufacturing steps and allows maximum utilisation of the vacuum furnaces. Since 1985 all new UK vacuum interrupter and switch designs have been based on One Shot Seal Off technology.

Once the basic performances had been achieved, the drive behind vacuum interrupter development over the past thirty years has been to reduce cost. This has resulted in a continuous uprating of existing interrupters to meet the higher ratings and the successive introduction of ever smaller interrupters for the lower ratings. (Figure 11). As can be seen the progression over this period has been quite dramatic, and translates into an interesting situation (Figure 12).

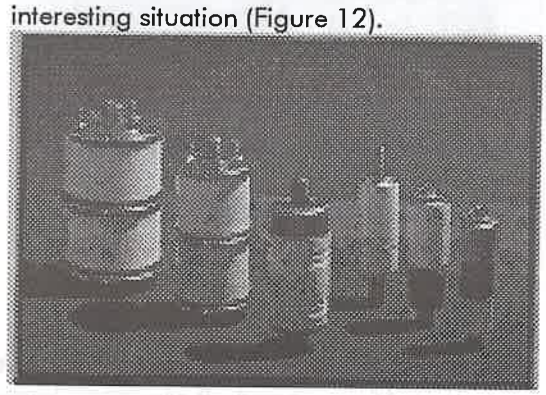

Figure 11- Interrupter Size reduction for 20kA;12kV rating.

It is interesting that, as shown, the diameter of UK interrupters for a particular rating (12kV:20kA) has reduced almost linearly over a 30 year period. However although the contact diameter initially reduced in proportion and was the driving factor in size reduction, it has now effectively bottomed out in this case, and the continued reduction in body diameter was due to constructional changes in the interrupter design, (Figure 13).

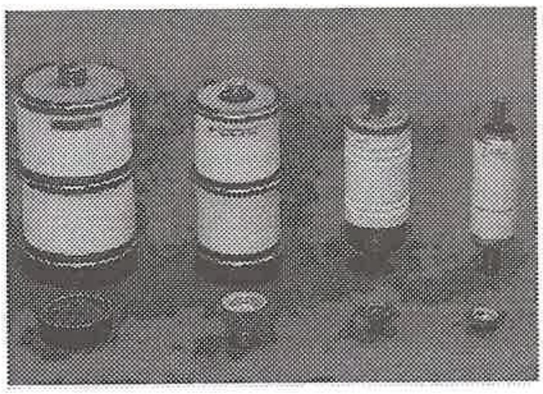

Figure 12- 20kA;12kV interrupters showing size of contacts.

From the graph it appears that we may be reaching the limit of the technology as far as interrupter size is concerned at this rating. The interrupter on the far right is a working development interrupter of only 50mm diameter and demonstrated the possibility of further size reductions, but at additional cost, and so this has not been pursued commercially. Even in vacuum there must be some gap between the contact and the body of the interrupter, and unless an even smaller contact can be developed this limits the possibility of further reductions in interrupter diameter.

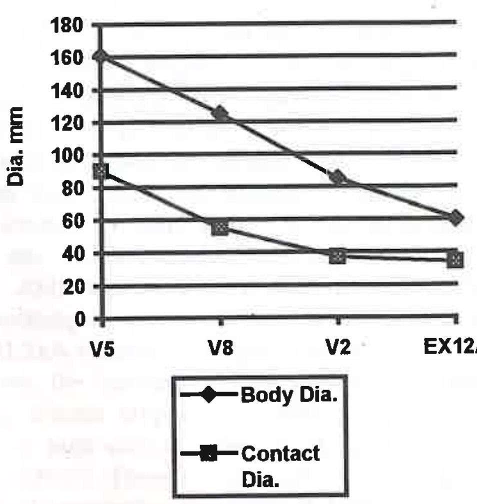

Figure 13 - Reduction in size for the same rating. 20kA;12kV.

In conclusion, the development of these devices has changed over the thirty years or so that they have been in manufacture. In the early days the challenge was to make the devices work! After that the next stage was to develop the designs to meet more difficult ratings. Finally we entered the third, mature stage of development essentially to reduce cost. This is being continuously achieved by changes in design and also by occasional dramatic leaps of technology. The vacuum interrupter will continue to be developed to give higher performance from a lower cost, normally smaller device, and altohugh this becomes more difficult with time, it just means a more interesting challenge for those of us fortunate to be involved in this technology.

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