The Future of Vacuum Switchgear

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***Abstract* — The paper looks briefly at the development of vacuum interrupters to date, discusses limitations to the existing technology of Vacuum Switchgear, what these are, and also how these may be overcome. It then moves on to discuss new developments in Vacuum Interrupter/ Vacuum Circuit Breaker technology which are likely to have an impact on the next generation of devices. Finally, it looks forward ten years to what the impact of these developments may be on the use of Vacuum Circuit Breakers, and what switchgear and power systems may look like in the future.**

***Index Terms* — Circuit Breaker, Electrical Power Systems, Future Technology, VCB, Vacuum interrupter, Vacuum technology**

I. INTRODUCTION

Vacuum switchgear has now been in commercial use for over 50 years, and presently is the dominant technology for medium voltage switchgear [1][2]. Like most technology Vacuum Interrupters & Circuit Breakers have evolved during that period until we now have an optimised design concept which matches our requirements. Historically technology in our field has changed quite slowly allowing us to adapt and absorb the changes over an extended period, however the situation is now quite different.

Today requirements of the supply network are evolving rapidly and the electrical system faces the most radical changes since its introduction in the 19th century. Switchgear must now change significantly to meet these new challenges and requirements.

In order to respond to this challenge we need to look at the historical limitations of Vacuum Circuit Breakers (VCB) and Vacuum Interrupters (VI) and reassess them in the light of the new requirements and propose new solutions meet these future needs.

In the early days of VCB many approaches and applications were tried and initially it was thought that VCB would be applied to all High Voltage (HV) requirements from 1kV upwards. In fact HV VCB were some of the first applications of the new technology with GE of the USA and AEI/VIL of the UK both developing and producing transmission VCB in the 1960's, as shown in Figure 1. However, at the time it was soon realised that for HV applications (>50kV) the other new technology of the time - SF_6 was simpler to apply and had a number of technical advantages [2]. Vacuum was instead developed for Medium Voltage (MV) applications (1kV – 50kV), and was so successful that today it is the technology of choice for MV and has dominated the market worldwide for many years. However, things are now changing, and in particular the requirement to consider environmental impact is modifying our thinking in the design of switchgear. This together with the changing nature of demand and generation of electricity is providing an opportunity for Vacuum to move into new fields of application, and the old restrictions on ratings and applications are reducing.

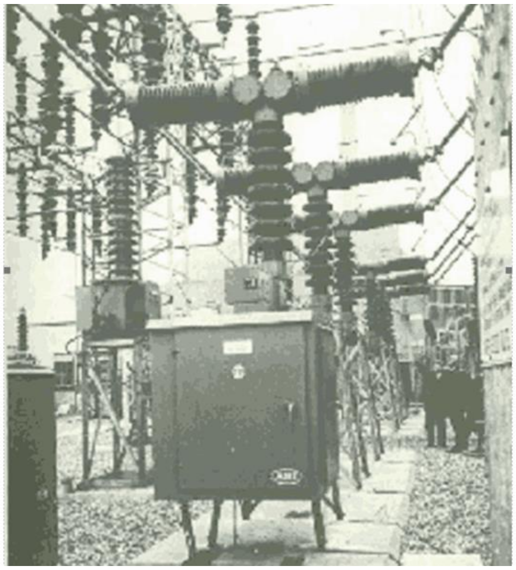


Figure 1. Early VCB; these are AEI 132kV vacuum circuit breakers in service in London in 1967. They remained in service for over thirty years.

II. THE EVOLUTION OF VI TECHNOLOGY TO DATE.

The heart of the VCB is the Vacuum Interrupter (VI), and this dominates the design of the VCB. So we will concentrate on the design of the VI, and how this impacts the VCB design [3].

Initially in the 1960's the VI were manufactured using glass insulators and pumped individually as shown in Figure 2.

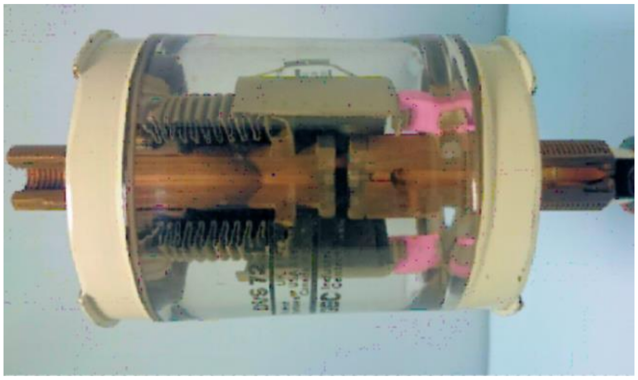


Figure 2. Early 1960's VI characterized by glass insulator, large contacts, welded construction and seal-off individually using a pump tube.

By the 1970's the technology had moved forward with high temperature glass ceramic allowing for batch seal off in large vacuum furnaces (figure3).

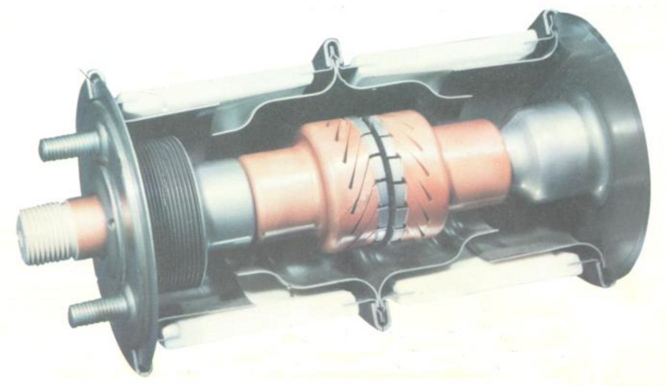


Figure 3. 1970's VI characterized by Glass Ceramic insulator, large contacts, welded construction with furnace seal-off of batches of devices

The 1980's showed the designs becoming smaller with higher ratings, and the manufacturing process was industrialised by means of brazable alumina ceramic insulators, and the invention of small high efficiency arc control such as Folded Petal and "One-Shot-Seal-Off" techniques (Figure 4).

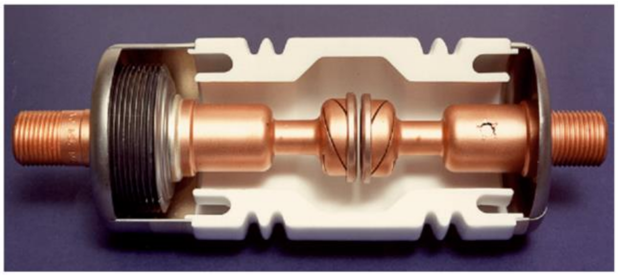


Figure 4. 1980's VI This is a "shieldless" design with Alumina ceramic insulator, brazed assembly, One Shot Seal-Off (OSSO) of batches of devices in a vacuum furnace.

By the 1990's designs were converging generally on a smaller device with Alumina ceramic insulator, furnace seal off, and Radial (RMF) or Axial (AMF) Magnetic Field arc control as shown in Figure 5.

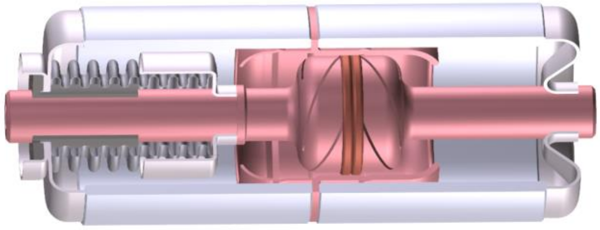


Figure 5. Contemporary 1990's onwards VI with Alumina ceramic insulator, brazed assembly, OSSO vacuum furnace seal-off of batches.

From the 1990's onwards generally VI design has stabilized with the main developments being related to smaller size and lower manufacturing cost. The exception being work associated with higher voltages which is dealt with in the next section. This period defined the limits of VI technology generally as being;

- Medium Voltage (3kV – 50kV)
- Interruption Current (< 80kA)
- Load Current (< 4000A)
- AC interruption only

Although exceptions to all of these limits do exist, in the main, VCB are limited to these ratings. The limits being formed from a combination of technology, cost, and the availability of other suitable competing technologies.

III. NEW CHALLENGES

A number of factors have conspired to significantly change the requirements for switchgear over the past few years, all of which are directly or indirectly related to the environment.

A. *Embedded Generation*

The introduction of embedded alternative generation into the MV distribution network is fundamentally changing the way we use the network and driving the development of new equipment to meet these new requirements. Off shore wind farms pose their own individual problems and in dealing with this, engineers are now considering new solutions such as DC transmission from the windfarms to shore.

B. *Global Warming*

At the same time, the emphasis on minimizing global warming has led to efforts to replace SF_6 worldwide in all applications, including HV switchgear. Power dissipation in switchgear is also becoming more important as is lifetime costing which again changes the status quo for all voltage ratings.

The effect of these changes is for engineers to now question the assumptions made when originally developing our existing electricity networks, and to now reassess the technical advantages and disadvantages of existing and new technologies in order to see if innovative designs of switchgear can be devised to better meet these new requirements. Table 1 shows the three normal voltage classes for electrical distribution systems, and their preferred technologies today. Different switching technologies are used for each voltage class as historically they gave the optimum combination of attributes, i.e., cost, size, reliability, maintenance, etc., to meet the present

Requirement	Existing Tech.	Limit Factor
High Voltage (>72.5kV)	SF_6	Technical/ Environmental
High Current (>3150A)	SF_6	Technical/ Environmental
Low Voltage (<3kV)	Solid State	Cost
Low Voltage (<1kV)	Air	Environmental
DC Interruption (>6kV)	?	Technical
Smart Grid Switchgear	?	Technical requirements.

Table 1. Voltage classes and existing technology

In addition, for switching DC circuits air magnetic is used up to around 6kV but at present there is no commercial solution for DC over 6kV.

IV. NEW SOLUTIONS

As well as embedded generation, another response to Global Warming is the increasing requirement for a smart grid. This in turn means that we need to move away from the dumb switchgear of the past and move towards intelligent switchgear. These changes offer both a challenge and an opportunity, and it is now time to reassess switchgear technologies and to see what vacuum technology could contribute to this brave new world.

Due to vacuum's exceptional dielectric strength, vacuum technology gives the opportunity to make the switching chamber very small and compact, and this can translate to small switchgear units. Because of the small contact mass and short contact strokes needed, we can design switchgear with with low energy short movement mechanisms. This in turn allows the use of Permanent Magnetic Actuators which use very low energy to operate and are ideally suited to self-diagnostic functions. In addition, the introduction of non-conventional sensors such as Rogowski coils for current and capacitive voltage sensors further allows intelligence and more compact equipment. Many manufacturers are working in this direction, and an example of this is shown in Figure 6.

However, the advantages of this approach are limited as these are examples of incremental development.

Figure 6. Etalon Compact intelligent 12kV;25kA;1250A VCB. Courtesy Tavrida Electric.

To meet the new requirements, it is necessary to think outside of the box, and to go back to basics. Vacuum switchgear comprises a set of functions;

- Switching chamber
- Actuator
- Voltage & current sensors
- Control & communications

The theoretical minimum size is to incorporate all of the above functions in a single unit. This seems not possible, but it is however possible to combine the actuator, voltage and current sensors in the switching chamber, as shown in Figure 7 & Figure 8

A. SAVI Concept

This Self Actuating Vacuum Interrupter (SAVI) greatly reduces the size and complexity of the switchgear. It only needs connecting to a control unit which contains the control, communications, and energy source for the actuation [3].

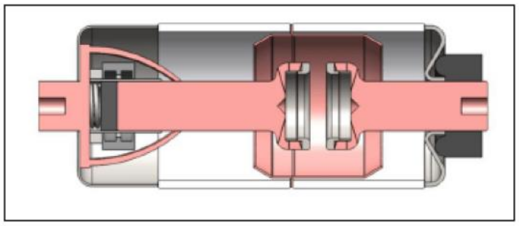


Figure 7. Section of SAVI design showing built in magnetic actuator, Rogowski coil, and voltage sensor.

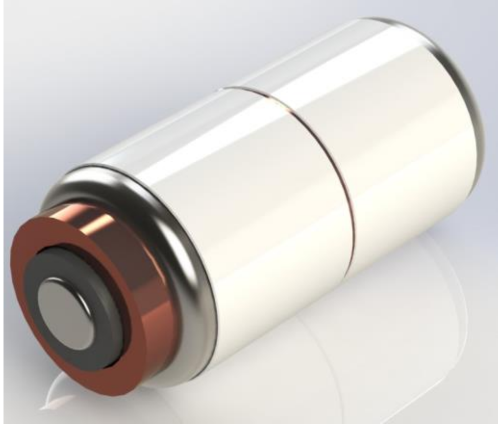
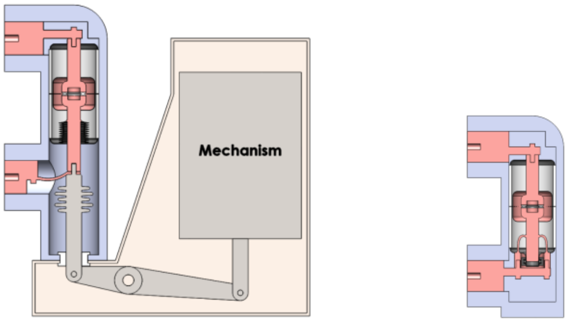


Figure 8. Self Actuating Vacuum Interrupter (SAVI) design. This is rated at 12kV;25kA;1250A, and is only slightly larger that the present technology Vacuum Interrupter for this rating.

By taking this radical approach, it is possible to greatly reduce the size and complexity of conventional switchgear as shown in Figure 9.



Conventional VCB SAVI

Figure 9. Size comparison of conventional indoor circuit breaker truck with SAVI design. The SAVI design removes 80% of the required volume.

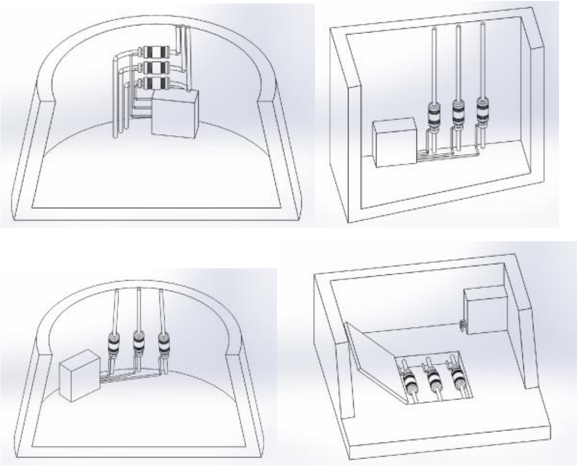


Figure 10. SAVI Devices in possible configurations

Figure 10 shows posible switchgear configurations using the SAVI approach, allowing for a radical rethinking of the design of switchgear, which leads on to new concepts for substations, a point which will be dealt with later.

B. High Voltage VCB

Figure 11. Design concept for a 245kV Vacuum Circuit Breaker.

Today VCB are available for high voltage applications up to 145kV, and a recent CIGRE study [5] showed that the penetration of vacuum into higher voltages has been happening for some time. With 145kV single break VCB already available, it is not a big leap to design a 245kV double break device as shown in Figure 11 [6]. The main weakness of vacuum interrupters for thee high voltages is the relatively high resistance of the conductors and arc control systems which presnetly limit these VCb to around 3150A nominal current. However new designs of arc control systems are being developed specifically to remove this limitation and soon we should see capabilities of 4,000, 5,000, and even 6,300 A nominal current designs with similar resistance.heat dissipation to the existing SF6 devices.

C. Low Voltage VCB

The application of VCB to low voltage has been very limited due to the extremely low cost of air and air magnetic circuit breakers. Although technically switching ow voltage is no problem, conventional Vacuum Interrupters simply could not compete on cost. This is now changing, as new specific designs for low voltage are being created, with the advantages of very small size, design for large scale automated production, and of course, very low cost.

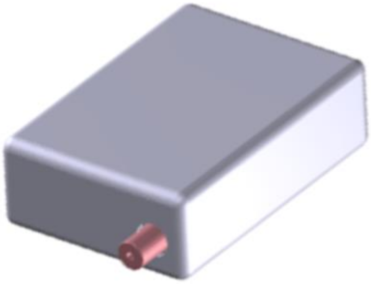


Figure 13. Design for a DC Vacuum Interrupter

However as can be seen from Figure 12, these VI are actually very different from conventional designs.

D. DC VCB

Finally, we come to DC interruption. Interrupting DC is very difficult for Vacuum as the interruption on process relies on a natural current zero to occur, after which the extremely rapid dielectric recovery of a vacuum gap ensures interruption. But no current zero means no interruption, which has limited VCB to AC systems, except where a current zero is artificially forced on the system. To date this has required a special circuit to resonate the circuit and force a zero, however there is work in progress to investigate creating a current zero within the Vacuum Interrupter. If successful this will allow for VCB to interrupt DC circuit s up to 30kV or more. Figure 14 shows a concept which is bigger than a conventional VI for a similar current rating.

V. THE NEXT TEN YEARS

The trend for new equipment is becoming clear. Switchgear of all ratings needs to be compact, intelligent, reliable, and environmentally friendly. Being environmentally friendly is not just a function of low pollution, and minimum use of resources. It also includes the visual impact on the environment. In the 21st century it is expected that the impact of technology on the perception of the countryside and cities should be minimized to the greatest extent possible.

Because of this together with the application of vacuum switchgear more widely into the power system, I believe that we will see a trend towards radically new forms of Vacuum Circuit Breakers (VCB) which will meet our growing expectations. Rather than making smaller, more efficient, more cost-effective versions of the existing equipment, we will prioritise different approaches which include all of the new requirements.

As an example we can take the SAVI concept. While Figure 9 shows the huge impact that this approach can make on conventional switchgear, we can move further, by removing the need for the switchgear and indeed the substation building itself. Figure 15 shows a SAVI device encapsulated as a cable joint.

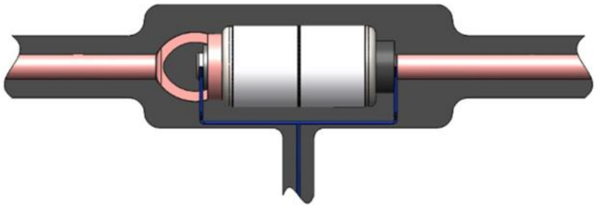


Figure 15. SAVI molded into a cable joint for underground cable networks.

In this approach no substation as such is needed. The SAVI devices can be buried with the cables and just a control cabinet would be located nearby.

Figure 11. A 21st century substation – completely invisible. The visual environmental impact is zero.

VI. CONCLUSIONS

When it was originally introduced, Vacuum switchgear adapted quickly to the system requirements of the time and for medium voltage became the technology of choice with several millions of VI now being manufactured every year. The new requirements for the 21st century electricity supply network are equally challenging, but vacuum interrupter technology is adaptable, and fully capable of rising to the new challenges. The future for Vacuum is good, with new developments expanding vacuum interrupters capabilities ranging from 110V and below, up to transmission levels of 245kV and above, and also possibly including DC as well as AC. It is now possible that, finally, we shall now have one switching technology for all voltage ratings.

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