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The Strengths and Weaknesses of Vacuum Circuit Breaker Technology

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***Abstract*- Vacuum switchgear is today the dominant technology worldwide for Medium Voltages up to 52kV, and is seen as the main candidate to replace SF6 circuit breakers at higher voltages. Vacuum switching technology was introduced into service in the late 1960's and since that time millions of vacuum circuit breakers have been manufactured. Today it is estimated that over a million vacuum circuit breakers will be manufactured worldwide annually. Vacuum circuit breaker technology now has been in large scale use for more than 40 years and has an enviable reputation for reliability in service. However amongst the very large numbers in service there are still occasional failures, and historically, particularly in the early days, there have been some problems due mainly to misapplication of the technology both by manufacturers and users.**

This paper examines the basics of Vacuum Circuit Breaker and particularly Vacuum Interrupter technology in order to identify their strengths and weaknesses. All technologies have their strengths and weaknesses and an understanding of what these are, and their effect on performance, permits the technology to be applied most effectively.

The paper concludes that what are considered strengths and weaknesses of vacuum switchgear specific to the vacuum technology, particularly related to the vacuum interrupter, are in many cases the identical phenomena. The concept of strength or weakness being mainly related to the application or specific situation.

***Keywords*-Vacuum Circuit Breaker VCB Interrupter Forensic Reliability Storage Life Application Strength Weakness**

I. INTRODUCTION

Since the original development of the vacuum Interrupter [1,2, 3] and the introduction of Vacuum Circuit Breakers (VCB) in the 1960's [4], very large numbers have been manufactured and put into service mainly in Medium Voltage (MV) applications. Vacuum is the dominant switching technology for primary MV worldwide, and increasing numbers are being applied at voltages of 72.5kV and 132kV, with VCB rated at even higher voltages under development.

II. THE VACUUM INTERRUPTER

Despite their high technology manufacture and special materials Vacuum Interrupters are essentially simple devices with only one moving part. Figure 1 shows the main components of a typical Interrupter. Vacuum Interrupters are "Sealed For Life" devices whereby they are manufactured with a suitable level of vacuum inside and must maintain an adequate level of vacuum throughout their life. In order to achieve this, the manufacturing process is quite sophisticated with the use of special cleaning and a Clean Room environment for assembly. This highly controlled manufacturing process contributes strongly to the extremely good reliability and consistency of performance of these devices [5].

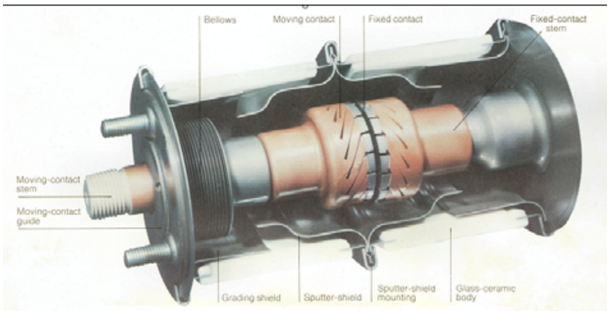

Fig. 1. VIL vacuum interrupter from the 1970's rated at 12kV;20kA;1250A.

In addition the simplicity in construction also contributes strongly to the consistent quality and reliability. However even this strength has a negative side, in that the sophisticated manufacturing process requires expensive manufacturing plant and some quite exotic processes which in turn add to the cost of manufacture of the Vacuum Interrupters, in fact until recent improvements in design and technology, this normally meant that Vacuum Interrupter plants needed to manufacture large numbers of Interrupters to keep the cost of manufacture down, making the manufacture of Vacuum Interrupters the monopoly of a few manufacturers. Today however this is no longer true.

Technically Vacuum Interrupters have a number of unique characteristics which contribute to their inherent reliability, the most important of which is the fact that they must be totally (hermetically) sealed for their operating life.

III. THE TECHNOLOGY

A. Vacuum

Vacuum Interrupters as the name suggests, use vacuum as the interrupting dielectric. The dielectric

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strength of a vacuum gap follows the Paschen curve shown in Figure 2. This shows how the dielectric strength of a fixed gap varies with pressure. The curve shows clearly the extremely high dielectric strength when the pressure is better than 10-3 mbar. This allows the vacuum interrupter to withstand the Transient Recovery Voltage with a very small gap enabling compact devices with short contact strokes. For example 6mm gap for 12kV and 12mm for 36kV are typical. However even this fundamental strength of vacuum has a disadvantage, Looking at the curve it is clear that the dielectric strength around 100 and 10-1 mbar is extremely low, measured in tens of volts/mm. This "Paschen minimum" means that if the pressure rises due to a leak, the dielectric strength deteriorates quickly to a very low level, much lower than the system voltage. The consequence of this is that any increase in pressure over 10-3 mbar is considered a catastrophic failure.

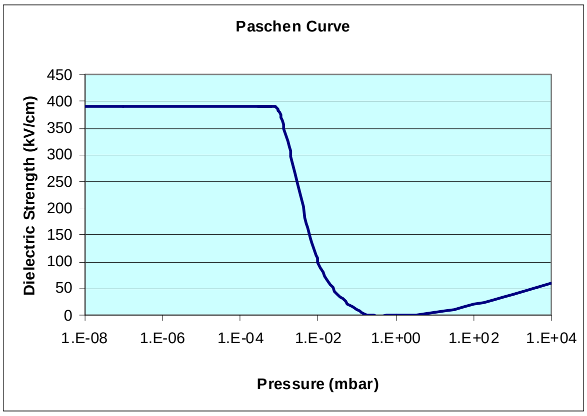

Fig. 2. The Paschen curve

B. *Contact Material*

Although Vacuum interrupters use the vacuum as insulation, unlike all other types of switchgear Vacuum Interrupters do not arc in the insulation medium, instead Vacuum Interrupters arc in metal vapour provided by the arcing contacts. This means that a fundamental difference with Vacuum is that it is possible to change the arcing properties of a Vacuum Interrupter by simply changing the contact material. In this was the interruption ability, voltage withstand and even properties such as conductivity and current chopping can be modified by using different materials. This is seen as a huge advantage for Vacuum Interrupter technology from the designer's point of view, and allows Vacuum Interrupters to be "tuned" to give optimum performance for specific applications. However this strength is also a great weakness. The problem is that many users have the perception that all Vacuum Interrupters behave the same. This is not true, in fact changing the contact material can have as big an affect as for example changing the SF_6 in a gas breaker for N_2. The result of this was that in the 1960's there was confusion in the application of Vacuum Interrupters. At that time GE made Vacuum Interrupters which used Copper-Bismuth contact material which chopped the current during interruption at around 18A, causing significant switching transient voltages. As a consequence of this GE recommended the use of surge suppression with their VCB. However at the same time VIL produced Vacuum Interrupters using Copper-Chromium contact material which chopped at 4A and produced much lower switching transients. As a result VIL did not propose using surge suppression. This caused confusion in the application of VCB with the result that some GE style VCB were applied without surge suppression and for some time VCB had a bad name for switching transients. This poor reputation was entirely due to the lack of understanding of the way Vacuum Interrupters works and the affect of contact material [6].

C. *Switching Performance*

Vacuum Interrupters have the capability to interrupt very fast rising voltages. This high dU/dt capability is both a strength, and a weakness. During the interruption of load or short circuit currents this ability enables the Vacuum Interrupter to withstand fast and high Transient Recovery Voltages (TRV) as shown in Figure 3, which contributes greatly to the excellent interrupting capability of Vacuum Interrupters and is a clear advantage for vacuum as an interrupting medium over other technologies, for example SF_6 can typically interrupt TRV with rise times of micro seconds whereas Vacuum can interrupt pico second rise times. However this ability under the wrong conditions this apparent strength can also be a disadvantage. When closing the Circuit Breaker onto an inductive load, for example, a number of high frequency breakdowns and recoveries can occur, which may damage equipment and insulation in the circuit [7] [8]. Similarly multiple breakdowns can occur when switching inductive loads, and in this case significant switching over voltages may be created [9]. These transients are shown in Figure 4. Although transients such as this are not restricted to Vacuum, SF_6 for example may also exhibit this behaviour, due to the "excellent" high frequency interruption capability of vacuum many more transients may be created with a VCB and the overvoltages generated may also be considerably higher.

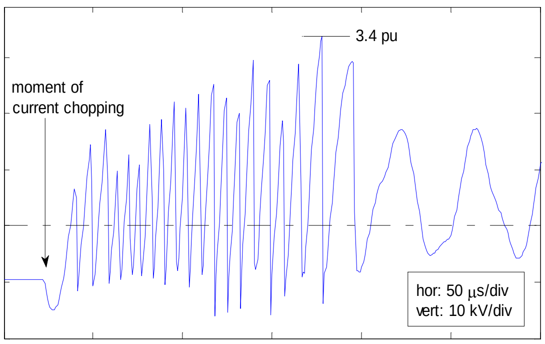

Fig. 4. Multiple reignitions during inductive switching (courtesy KEMA)

D. Vacuum Interrupter Life

Vacuum interrupters are by their nature sealed devices, and it is not possible to perform maintenance on the interrupter unit. This is not a problem however as VI are designed to be capable of very large numbers of mechanical and electrical switching operations, and in fact is seen as a great advantage as it means that the interrupting chamber is completely protected from the environment and also from problems caused by maintenance. A large proportion of problems on switchgear and indeed other equipment occurs during or immediately after maintenance. However as keeping the vacuum is essential to the operation of the device loss of vacuum is a critical failure. Thus the “Sealed For Life” concept is both an advantage and a disadvantage. This is made worse by the fact that Vacuum Interrupters do not normally have a vacuum gauge built-in to give warning of a deteriorating vacuum. Instead a simple voltage test is performed periodically to confirm that the vacuum is still ok, but this does not give any indication of future life. Although Vacuum Interrupters are extremely reliable devices with a MTTF of the order of 44,000 Interrupter-Years failures still do occur and this inability to predict individual Vacuum Interrupter life beyond the original life calculation, which has been typically 20 years can be seen as a weakness [10].

Mechanical life is determined by the stainless steel bellows which is used to maintain the hermetic seal when the VI operates. These have a finite life and eventually will fatigue fail resulting in loss of vacuum to the device. Even so, minimum mechanical lives of VI of between 30,000 and 50,000 operations are normal, (for contactor applications this life may be as high as 3,000,000 operations!).

Falkingham, L T; Reeves, R; "Vacuum life assessment of a sample of long service vacuum interrupters” Page(s): 1-4, (2009).


[6]

Fig. 5. A bellows damaged during assembly into the circuit breaker

E. Arc Control & Welding

Vacuum Interrupter contacts use the magnetic fields generated by the short circuit current to either diffuse the arc (Axial Magnetic Field) or to make the arc move over the contact surface (Radial Magnetic Field), these work extremely well allowing successful interruption up to 100kA or more. However these “coil” contact geometries result in “butt” type contacts which require the circuit breaker to apply a significant force to keep the contacts closed against the repulsion force generated by a short circuit in the closed position, this is a disadvantage as if the force is insufficient this could result in contact welding. This requirement means that it is normally necessary to have extra force from the circuit breaker to prevent welding and also normally some form of weld breaking capability.

IV. CONCLUSIONS

The experience of Vacuum Interrupters in Medium Voltage since their introduction over 40 years ago has been excellent, and has resulted in this technology dominating primary switchgear from 5kV to 40.5kV. However, as with all technologies, Vacuum Switchgear has both strengths and weaknesses, but in the majority of cases, due to some unique properties of Vacuum Interrupters, whether these are strengths or weaknesses, depends primarily on the circumstances and application.

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