Feasibility Assessment on Vacuum Insulated Switchgear

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Abstract: To find feasible alternatives to the use of SF_6 in medium voltage switchgear equipment, AREVA T&D and Tsinghua University has started a cooperation to investigate the feasibility of using vacuum. This paper focused on three main points of the design of the Vacuum Insulated Switchgear (VIS): the maintainability of vacuum system, the insulation performance, and the thermal behavior under operating conditions. In our work, such steps were followed: literature review, basic designs, calculation and analysis. The investigation results showed the feasibility of 40.5 kV/2 kA VIS, assuming that the thermal design and material choice are done carefully in order to fulfill the requirements: insulation rating, life time and rated current. Whereas, for High Voltage switchgear equipment, 126kV or higher voltage level, further experimental research work is still needed.

Key-Words: Vacuum Insulated Switchgear; Vacuum insulation; Vcuum lifetime; Vcuum thermal performance

1 Introduction

Because of the superior insulation and extinguishing performance of SF_6, Gas Insulated Switchgears (GIS), filled with this gas, are widely used in power system for electricity transmission and distribution (T&D). Since SF_6 was classified as a greenhouse gas at the Kyoto Summit in 1997, research on finding substitutes to SF_6 has been carried out. Recently, cooperation between AREVA T&D and Tsinghua University has started a program to investigate the feasibility of using vacuum as the primary insulation in medium and high voltage switchgears. Three fundamental technological problems have been investigated: vacuum lifetime, vacuum insulation, and thermal performance.

On high vacuum lifetime, vacuum material, design, manufacturing, sealing, getter, and pumping have been investigated. Basic models have been made to verify the influence of the materials and architecture.

For vacuum insulation, we focused on vacuum gaps breakdown and surface flashover. We have investigated the factors affecting vacuum breakdown, such as electrodes material and shape, gap, voltage ratings, conditioning of electrodes and vacuum level. About vacuum surface flashover, the influence of electrode profile and material, insulator's material, length, and cone angle, voltage ratings, and vacuum level, to vacuum surface flashover have been investigated.

We created a thermal model of VIS based on the characteristics of conduction, thermal radiation and temperature-dependent properties of metal and nonmetal materials. Long term and instantaneous temperature rise calculations were carried out using ANSYS — finite element analysis software. The effects of different design parameters of the VIS were considered.

Further to this research work, materials and designs, suitable for VIS were determined.

2 Design of VIS

Based on vacuum manufacturing technique, VIS can be built in two structures. One way is to fix all the components in one big vacuum tank; another is shown in Fig.1. Just like in a GIS, independent function parts including circuit breaker, insulators, earthing switch, and other parts are placed in a vacuum shell and jointed together to compose a VIS.

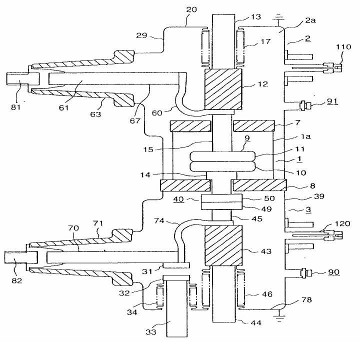

Fig.1 the structure of VIS (without bus) [1]

3 Vacuum Lifetime

The vacuum system must be designed in order to sustain a high vacuum level, typically 10^{-4} Torr or lower, for at least 20 years. The attenuation of the vacuum level depends on the gas reappearing in the vacuum system mainly from five sources: evaporation, permeation, degassing, leakage and backstreaming from the pumping system. Among these sources, the first three ones are related to materials used to build the system. The leakage is related to the sealing or defects in parts. Backstreaming depends on the used pumps and getters.

3.1 Materials used for VIS

Materials used in VIS include structural material, conductor material and insulation material. Structural materials are used to compose vacuum envelopes, separate the internal of vacuum systems from the atmosphere and endure the atmospheric pressure.

Stainless steels have come into fairly common use in vacuum practice, for pumps, piping and chambers. Essentially all stainless steel ultra-high vacuum systems are fairly common. Also, such steels are useful in tube work, not only as component parts, but also for making brazing jigs, where the protective layer of chromium oxide which is formed in the hydrogen furnace prevents the work from being brazed to the jig. Austenitic stainless steels are commonly used in vacuum work. Since they contain 18% chromium and 8% nickel. These steels are nonmagnetic. Stainless steels offer several advantages over low carbon steels [2].

Ceramics are insulating materials that are commonly used in tube structures and systems to carry electrical power into vacuum systems. Most ceramics used in vacuum works are quite refractory, having softening point above 1400°C and a safe continuous operating temperature around 1000°C or higher. Some general types of ceramics are: steatites, alumina, zircon porcelains, porcelains, natural stones (lava, etc.), magnesium silicate, titanium dioxides and titanate. Alumina is the most used for industrial and vacuum applications. In general, drilling and machining are difficult because of the hard, brittle nature of these materials [3].

Oxygen-free high-conductivity copper (OFHC), which has good corrosion resistance, high electrical and thermal conductivity and easily to machine, is excellent for use in vacuum equipments. The preprocess techniques, as cleaning, baking, surface treatment, have big influences on degassing rate. Under a high enough temperature, the degassing process, most of the gas inside a material can be removed out [4].

3.2 Calculation results

To establish a relation between the system construction and vacuum lifetime, an estimate calculation was made. The construction of the vacuum system of VIS was simplified to a cylinder with a diameter D equal to its height H as shown in Fig.2. Three parameters of the system were considered as: diameter D, thickness of the envelope d and the percentage of vacuum volume inside the whole volume w%.w% is defined as:

$$w\%=\frac{V_{tot}-V_{part}}{V_{tot}}\times 100\% \qquad (1)$$

where V_{tot} is the total volume of the system and Vpart is the volume which is taken by the parts inner the system. The permitted change of vacuum level was set from 10^{-6} Torr and 10^{-4} Torr. The vacuum level of systems with bigger diameters, thickness, or bigger percentage of vacuum is easier to maintain. Fig.3 shows the pressure change with time for different diameter D with d and w% unchanged and the material of the shell is of stainless steel alloy. Obviously, the vacuum degree of systems with smaller diameters is more difficult to maintain.

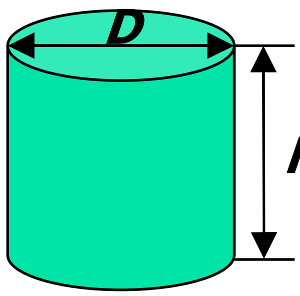

Fig. 2 Simplified vacuum system model of VIS

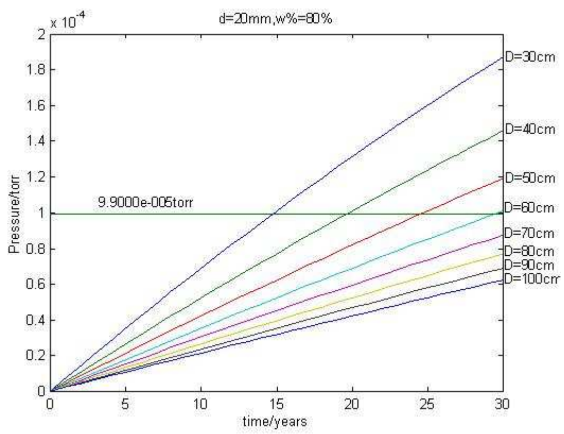

Fig.3 Pressure changed related to the size of the system

3.3 Analysis on the vacuum lifetime of VIS

Review of material for VIS showed that stainless steels can be used to build the envelope, oxygen-free copper can be used as the conducting materials and ceramics as alumina can be used as the insulating materials. The assembly of parts with no need of detaching should be connected by welding. Metal gasket and bellows can be adopted respectively for the detachable and moving parts. To improve the reliability of the whole system and the vacuum lifetime, Zr-Al16 getters and sputter ion pumps can be used.

It's established that the vacuum lifetime of vacuum interrupters can be maintained for a period of 20~30 years. From this experience and taking account of our investigations, we can derive some design rules for the VIS. The estimate calculations showed that the permeation and degassing rates are nearly linear with the ratio of surface to volume of the system. Since VIS has much larger volume than the one of a vacuum interrupter, a careful design of vacuum system can guarantee that these materials are matched for VIS. Same or similar materials, preparation and assembly techniques can be applied for VIS. At present, for vacuum interrupter the thickness of a ceramics envelope is in the range of 4~8 mm; the thickness of stainless end-cover is 0.5~1.5 mm; the thickness of oxygen-free copper is 0.2~1.5 mm and the thickness of the stainless bellows is 0.1~0.2mm. In addition, special requirements as mechanical constrains created by the atmospheric pressure over large areas must be taken in account.

4 Vacuum Insulation

High vacuum has been increasingly used as an insulator and arc-quenching medium. For a proper utilization of vacuum as an insulator, it is essential to have a clear understanding of the various factors that affect the discharge properties in vacuum. This includes vacuum gaps breakdown and surface flashover.

4.1 Breakdown voltage of vacuum with different gap spacing

Literature [5] describes dielectric experiments on vacuum interrupters for HV applications. The investigations were performed with two different vacuum bottle designs: single and double break unit. The values in Fig.4 indicate the maximum breakdown values achieved by the conditioning process. The curves of Fig.4 showed that a total contact of 20mm is necessary to fulfill the ANSI requirements (185 kV) for the HV level. Up to 15mm there is no difference between single or double-break unit. The results show clearly that the requirements for AC voltage are relatively easy to fulfill designs, the double as well as the single-break unit.

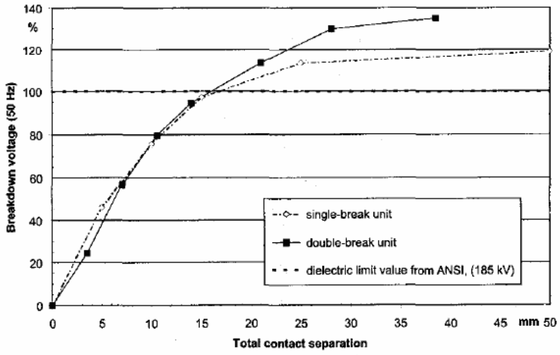

Fig.4 AC voltage limit of double and single-break units as a function of contact separation [5]

One important dimensioning parameter is the lightning impulse voltage (LIV) (1.2/50μs). According to reference [5], tests were performed with waveforms of positive and negative polarity. Fig.5 shows the relationship between the breakdown voltage and the length of vacuum gap. From the figure, we can see that when the length is 50mm, the negative polarity breakdown voltage of single-break unit is about 406 kV. The negative polarity lightning impulse test is more critical for the design of VIS.

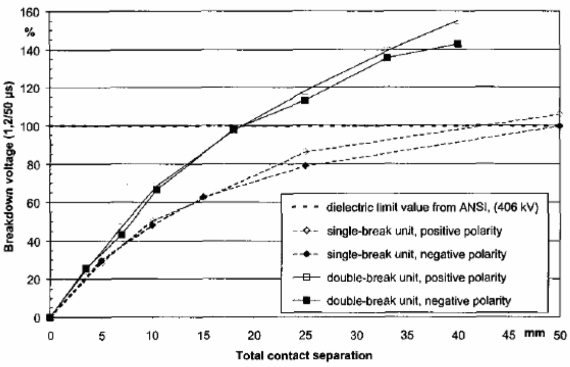

Fig.5 Lightning impulse voltage limit for double and single-break units as a function of contact separation[5]

4.2 Influence of insulator on vacuum surface flashover

The shape of an insulator has a strong effect upon surface flashover [6]~[8]. The simplest shape, cylinder, has lower flashover voltages than do more complex shapes. The lowest flashover voltage seems to be for cones with slight negative angles. The cone angle has a great influence on the flashover voltages, especially under narrow pulses [9]. Comparing convex cylinder and concave cylinder, the flashover voltage of former is higher than that of later [10].

The relationship between flashover field strength and insulator's length of different insulators under dc, ac (60 Hz, peak voltage), and lighting impulse (1.2/50 μsec) were shown in Fig.6 [11]. The flashover field strength E_f could be expressed as an exponent of the insulator's length d, i.e. $E_f \propto d^{-0.5}$, where $E_f=V_{50}/d$, V_{50} is the 50% flashover voltage.

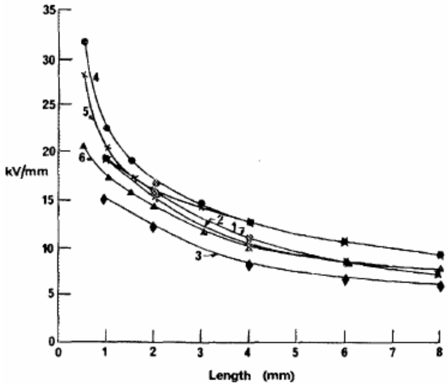

Fig.6 Relationship between the flashover field strength and insulator's length [11]
1-3: PTFE; 4-6: Glass ceramic; 1-4: DC voltage;
2-5: Impulse voltage; 3-6: AC voltage

It has been proved experimentally that the flashover voltage of vacuum, gaseous, and liquid gaps decrease with increasing the cylinder's diameter [11]. The result of lots of experiment for dc, ac (60 Hz, peak voltage), and lighting impulse (1.2/50 μsec), is shown in Fig.7.

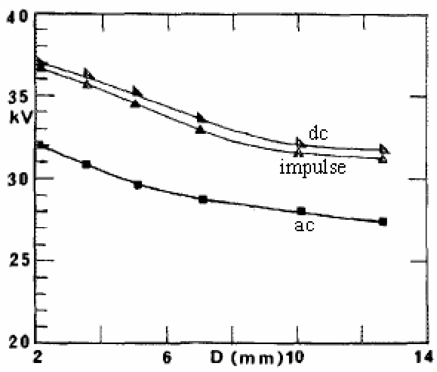

Fig.7 Relationship between flashover voltage and insulator's diameter [11]

4.3 Feasibility analysis on vacuum insulation of VIS

According to the investigation and analysis mentioned above, the following conclusions about VIS insulation can be derived:

(1) The requirements for ac voltage are relatively easy to fulfill, while the negative polarity lightning impulse withstand voltage is the most important basis for the design of VIS.

(2) For 40.5kV VIS, the insulation distance of phase to earth can be 20mm, which is enough to withstand the negative polarity lightning impulse voltage (215kV); 50mm can only withstand 406kV negative polarity lightning impulse voltage, which can not fulfill the requirement (550kV) of 126kV VIS.

(3) In order to avoid the surface flashover of insulator applied to 40.5kV VIS, the surface length should not be less than 30mm, and 40mm may be appropriate.

5 Thermal Effects

Exceptional temperature rise may affect the physical and chemical properties of materials and thus weakens their mechanical strength and electrical performance leading to equipment faults and operation accidents. The maximum permitted temperature in the whole system should not be higher than 145℃, according to GB763 and IEC60694 [12].

Heat transfer is different from a GIS as there are no conduction and convection trough the vacuum environment. The heat in the live conductors can only be transferred to the outside by conduction through solid material and radiation. To analyze this phenomena and the influence of various design parameters, thermal analysis of a VIS have been performed.

5.1 Thermal model of VIS

The sketches of the model and the conductor are shown in Fig.8 and Fig.9. The basic thermal model is a hollow conductor in a vessel.

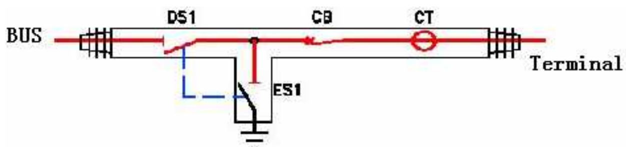

Fig.8 typical structure of switchgear
(CB: circuit breaker, DS: disconnector switch)

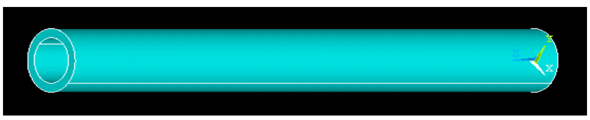

Fig.9 The model of conductor of VIS

The model was created with oxygen free copper as the conductor, and stainless steel as the vessel. The basic design parameters are:

- Conductor length: 3m
- Inner and outer radius: 0.05, 0.06 m
- Current through the conductor: 2000A
- Ambient and terminals temperature: 60, 80°C
- Location of contact points: 1/4 length of the conductor for CB and 3/4 for DS
- Electrical contacts resistance:10μΩ for CB and 5μΩ for DS
- Emissivity: 0.1 for the conductor (polished) and 0.15 for the vessel (polished)[13].

The effects of each parameter were investigated while other factors were hold at values mentioned above.

5.2 Long Term thermal effect [14]

Long term thermal effects calculation showed that the size, the temperature of the vessel and of the terminals had no obvious or little influence. The change of other factors had a great effect to the maximum temperature. The results showed that the current through the conductor had tremendous effect to the maximum temperature. According to the model, for 2000A, the maximum temperature is nearly 200℃. The maximum temperature rises to about 420℃ with 3150A.

Decrease of the contact resistance and of the number of contact points, location of the contact point near the terminal of the conductor, are helpful to decrease the maximum temperature of VIS.

Optimization of conductor length or cross section allows decreasing the maximum temperature. Fig.10 showed the effect of cross section of the conductor. The maximum temperature decreases more than 20℃ and 10℃ when the radius increases by 1cm with the thickness being respectively 1cm and 2cm. Increasing the emissivity of the outer surface of the conductor and the inner surface of the vessel will be helpful to decrease significantly the maximum temperature.

Some sets of design parameters with 2 or 3 contact points (including the one of circuit breaker and disconnector switch) are presented in Table 1 and 2.

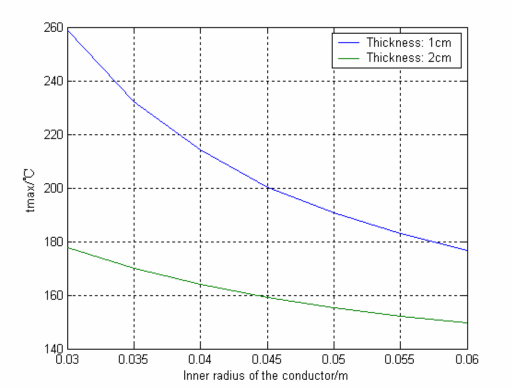

Fig.10 Relationship between tmax and radius of the conductor

Table 1 Sets of parameters for 2 contact points

I /A	R_I /m	R_O /m	*Ks*	T_t /℃	R_{CB} /μΩ	L /m
1600	0.05	0.06	1.05	60	7	6.2
2000	0.05	0.06	1.05	60	7	3.4
2000	0.05	0.07	1.54	60	7	7.6
2500	0.05	0.07	1.54	60	7	3.6
3150	0.06	0.08	1.55	60	7	<2

I: Current through the conductor; R_I: Inner radius of the conductor; R_O: Outer radius of the conductor; *Ks*: the skin effect coefficient of the conductor; T_t: Terminal temperature; R_{CB}: Contact resistance of circuit breaker; L: Length of conductor

Table 2 Sets of parameters for 3 contact points

I /A	R_I /m	R_O /m	*Ks*	T_t /℃	R_{CB} /μΩ	L /m
1600	0.05	0.06	1.05	60	7	4.1
2000	0.05	0.06	1.05	60	7	2.2
2000	0.05	0.07	1.54	60	7	4.5
2500	0.06	0.08	1.55	60	7	<2

5.3 Short time thermal effect

The process of short-circuit current flowing through the conductor of VIS can be considered adiabatic because of the short time. During this process, the temperature of the conductor will go up. It is necessary to calculate the temperature rise in case that the conductor be softened. The softening temperature is 190℃ for copper. [15]

Set the short time as 5s, current equal to 31.5kA, and the starting temperature equal to 145℃, which is the maximum permitted temperature for long term thermal effect. The calculation showed a 5℃ increase. This has no significant influence.

5.4 Feasibility analysis on thermal effect of VIS

Short time current has negligible influence to VIS temperature, while long term temperature rising should be considered carefully. To increase the rated current of VIS, measures to decrease the resistance of the conductor and the contact points should be taken. For the same reason, the emissivity of the outer surface of the conductor and the inner surface of the vessel should be increased. The terminal temperature of the conductor should be limited by cooling fin or other methods. The CB and DS should better be fixed near the terminals. Based on the model, the thermal problem can be solved for the current up to 2000A, while it becomes quite difficult for larger currents.

6 Conclusions

According to our literature research and simulation analysis mentioned above, the following conclusions can be derived:

(1) Vacuum maintenance methods are mature. The vacuum can be maintained for a needed long time (10 to 30 years). It is mainly determined by manufacturing process.

(2) A 40.5 kV level of VIS is feasible. A 72.5 kV one seems to be difficult and a 126 kV one seems to be not feasible due to the saturated like characteristics of vacuum insulation. Although greatly increasing the size and areas of VIS, it will be difficult to guarantee a low probability of breakdown and flashover.

(3) Scientific literatures and data about vacuum insulation needed for 126kV or higher voltage level is very limited. Further experimental research work on vacuum insulation is needed.

(4) Thermal analysis shows that the design of the VIS is critical. For example, to keep the temperature below 145℃, the length of the conductor should be limited in several meters (smaller than 7.6 m, pipe with inner radius 5 cm, outer radius 7 cm) and the current is below 2000 A.

(5) A 40.5kV/2kA VIS is feasible currently.

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