HV DIELECTRIC STRENGTH OF SHIELDING ELECTRODES IN VACUUM CIRCUIT-BREAKERS

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Overview

The subject of this paper is the HV dielectric strength of shielding and field-grading electrodes in vacuum circuit-breakers. It describes the effects exerted by various geometrical parameters, the surface area and the material of the shielding on the breakdown behavior of shielding. The experiments were performed with a shielding electrodes model and were carried out under lightning impulse voltage. The dielectric results are discussed by means of field simulations.

I Introduction

Over the last ten years the use of the vacuum principle for interrupting fault currents and for dealing with the HV requirements of medium-voltage power supply systems has clearly forged ahead of oil and SF_6. Also, the permanent need to improve economics has helped to intensify the search for alternatives to existing technologies for use in high-voltage switchgear. The vacuum circuit-breaker could be a very interesting option in this connection and experimental work in Japan has demonstrated the physical feasibility of such an application [1].

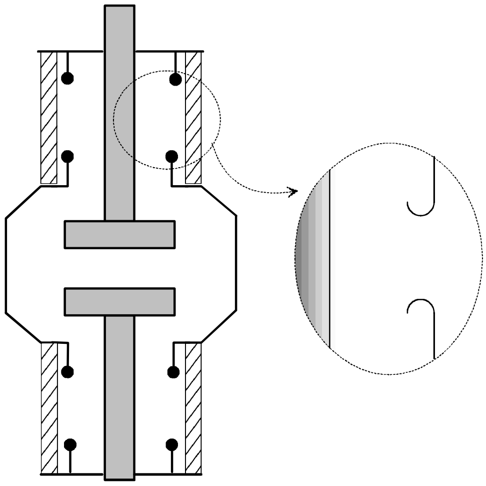

Fig. 1: Schematic arrangement of the shielding in a vacuum circuit-breaker (with a partial enlargement)

In view of the more severe demands on high-voltage systems, certain aspects of switchgear geometry - not necessarily yet regarded as weak points in medium-voltage equipment - are starting to gain in significance. Apart from the ability to interrupt fault currents, ensuring adequate dielectric strength depends not only on the contact system itself but also on the design of the shielding. Fig. 1 illustrates which particular parts of the vacuum circuit-breaker construction are involved.

II Experimental setup

In order to examine the various effects of the different parameters of the structure, measurements are taken on a model (Fig. 2) which represents a section of one possible type of geometry for vacuum breaker shielding (Fig. 1).

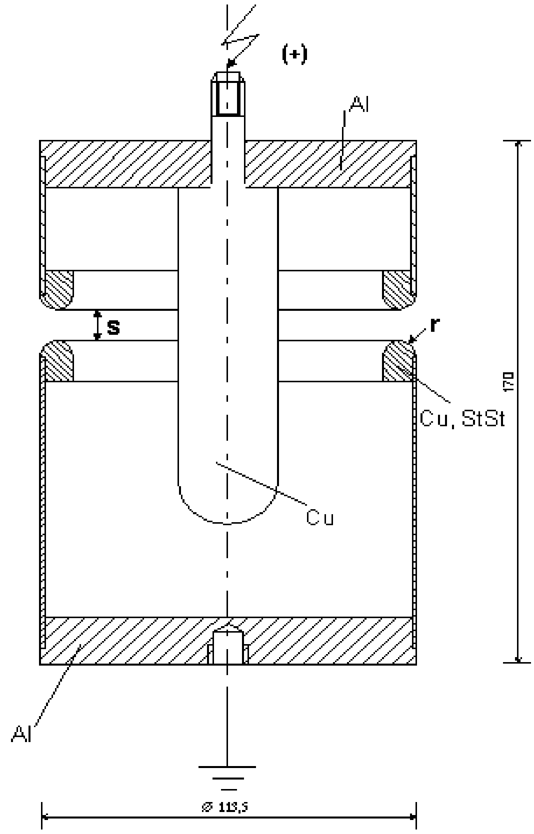

Fig. 2: Model for the geometrical dimensions of the shielding

The model has been designed to allow the ring electrodes to be changed, which has enabled different electrode materials and different radii to be tested. The task of the shielding is to protect the insulators of the vacuum interrupter chamber against vapor, to reduce the field strength at the triple point (metal/ceramic/vacuum) and to ensure that the potential grading is as uniform as possible. In sizing the fronting ends of the shields there is a conflict because optimizing the arrangement for low values of macroscopic field strength gives rise to large radii at the shield ends. However, this also increases the area of electrode exposed to voltage (the area effect). Past experience has shown that increasing this area actually reduces the dielectric strength. On the arrangement in Fig. 2 these effects have been investigated by varying the gap distance, the radius and the electrode material. In order to keep the parameters under investigation within technically sensible limits, the ring radius r is fixed at 2, 5 and 8 mm. The gap s is varied between 5 and 20 mm for the individual radii. Copper and stainless steel are used for the electrodes. The arrangement is installed in a test vessel (Fig. 3) which is evacuated to a pressure of 2 x 10^{-4} Pa. Below 2 x 10^{-3} Pa the pressure is unlikely to have any more effect on the breakdown voltage [2].

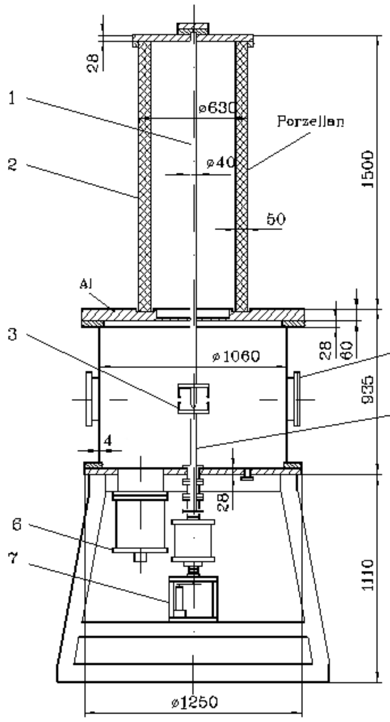

Fig. 3: Vacuum test vessel; 1 Power infeed, 2 Porcelain bushing, 3 Electrode assembly, 4 Observation window, 5 Earth connection, 6 Turbo pump, 7 Adjusting facility for electrode gap

III HV dielectric strength of the model

The high-voltage breakdown tests on the shielding model are performed with lightning impulse voltages (1.2/50 µs). Numerous tests have shown that this waveform is the most important one to be used when sizing electrode arrangements for use in vacuum [3]. The surfaces of both ring electrodes are cleaned with emery cloth (grade 1000) before the tests are conducted. After the surfaces have been prepared with the emery cloth the copper rings are etched in a bath for 90 s to remove any micro-protrusions. The surfaces of the stainless steel ring electrodes are electropolished with a current density of 1 kA/m^2. Preconditioning of the electrodes through the application of a power-frequency voltage before ascertaining the dielectric strength by means of lightning impulse voltages is not employed. The strength limit is ascertained by increasing the voltage in steps of 5 kV, each voltage step being checked with 3 hold values. The last step for which 3 hold values are ascertained is designated the strength limit.

Copper electrodes

The results of the breakdown tests on the copper ring electrodes are shown in Fig. 4. As the gap between the electrodes widens the strength increases significantly less than linearly. Whereas increasing the radius from 2 to 5 mm still produces an increase in dielectric strength, the step from 5 to 8 mm does not produce any more increase.

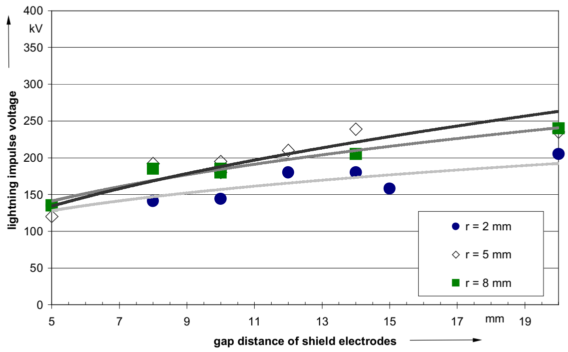

Fig. 4: Breakdown voltage of the ring electrodes in relation to the contact gap and the radius of the ring electrodes (copper)

Stainless steel electrodes

The results of the breakdown tests with radii of 2, 5 and 8 mm are shown in Fig. 5. Here too the degressive increase in dielectric strength with increasing ring electrode gap is evident. Whereas the strength still increases significantly when the ring radius is increased from 2 to 5 mm, there is no increase in strength at radius 8 mm compared with radius 5 mm.

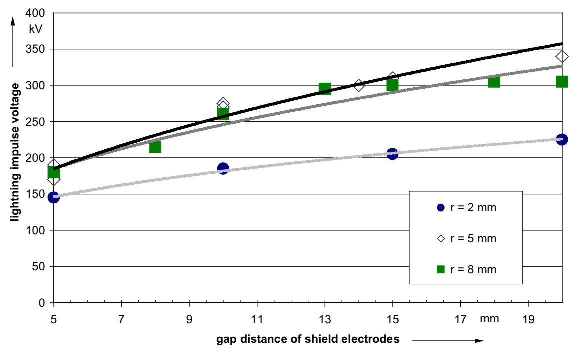

Fig. 5: Breakdown voltage of the ring electrodes in relation to the contact gap and the radius of the ring electrodes (stainless steel)

Comparison

The comparison of the results of the breakdown tests shows an improvement of 15 to 40 %, depending on the geometrical arrangement, when stainless steel is used instead of copper (Fig. 6).

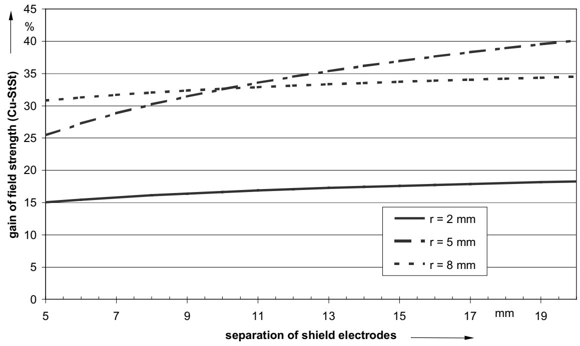

Fig. 6: Improved strength with stainless steel electrodes compared to copper electrodes

IV Electrostatic simulation of field strength

The simple geometry of Fig. 2 allows electrostatic simulations to be carried out with a finite element program. With the help of these simulation on the rotationally-symmetrical arrangement it is possible to determine the macroscopic field strength at the radius of the ring electrodes. Fig. 7 shows an image of the field strength for a ring electrode radius of 5 mm and a gap of 15 mm. The maximum field strength occurs at the radius of the bottom ring electrode. Fig. 8 shows the development of the electric field strength along the surface of the bottom ring electrode for gaps of 5, 10 and 20 mm starting from inside the radius of the electrode. The diagram clearly shows that, with a constant voltage stress and increasing gap size, the maximum values of field strength fall.

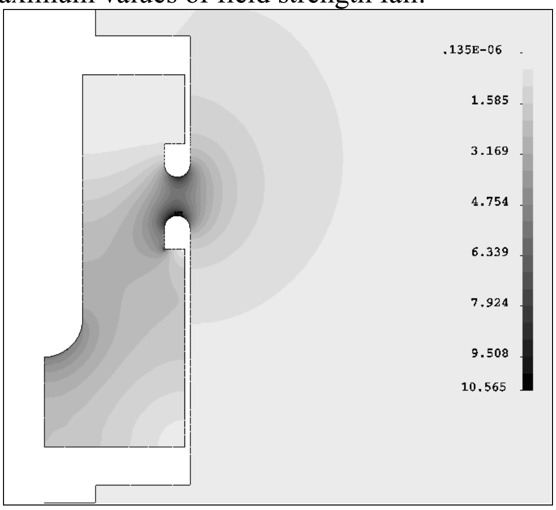

Fig. 7: Field strength pattern of the model arrangement for sizing the shield radii; in this case a radius of 5 mm and an electrode gap of 15 mm (field strength values for 100 kV)

Due to the geometrical arrangement of the electrodes the maximum value of field strength at the bottom electrode moves from the mid-point of the ring towards the interior of the ring electrode as s increases. In addition, it is clearly apparent from the patterns that, with larger electrode gaps the maximum value of field strength fall and the distribution of field strength becomes more homogenous. Due to this the area exposed to 90 % of the maximum field strength is higher than for the case of small gap distances. This area is called the “effective area” (A_{eff}). The curves gradually flatten out as the size of the gap increases.

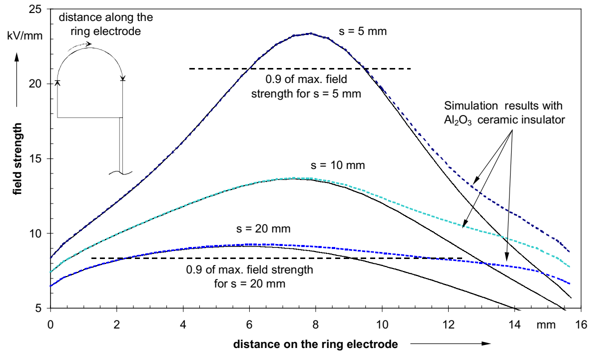

Fig. 8: Field strength at the bottom ring (r = 5 mm) of the shielding arrangement with different gaps between the ring electrodes (field strength values for 100 kV), with and without ceramic insulators

The results of the simulation are shown in Fig. 9.The diagram shows the trend of the maximum value of electric field strength and of the effective area for the three different radii and the different ring electrode gaps. The electric field strength falls as the gap increases but the effective area increases.

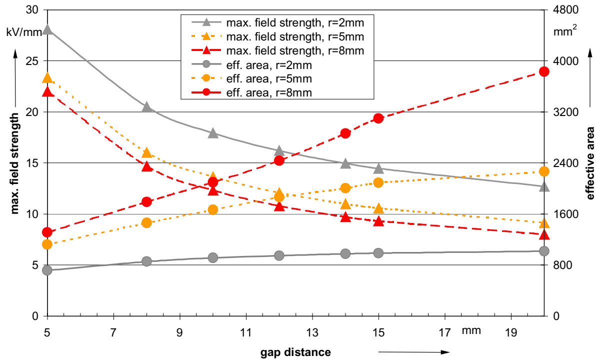

Fig. 9: Simulation results for maximum field strength and effective area at the bottom shielding ring electrode

To demonstrate examples with these three gaps and a radius of 5 mm a ceramic insulator is added to the model. The simulation calculation makes it possible to take this into account although it was not used in the actual breakdown tests. In the calculation the effect of the ceramic insulator on the variation in macroscopic field strength is estimated. In Fig. 8 the curves of field strength at the bottom ring electrode are also plotted for taking the Al_2O_3-ceramic insulator into account (dotted lines). Whereas the effect of the ceramic insulator is negligibly low with small values of ring electrode gap, it is clear in the case of the 20 mm curve that a considerable increase in the effective area must be anticipated. The effect of the ceramic insulator on the peak value of field strength is negligible. The reason for the widening of the field curve is illustrated in Fig. 10. The Al_2O_3-ceramic insulator ($\varepsilon_r = 9$) gives rise to compression of the lines of equipotential at the ring radius before they penetrate the insulation material. This is caused by the relative permitivity jump from 1 for vacuum to 9 of the ceramic insulator. Due to this the field strength between shield electrode and ceramic insulator increases.

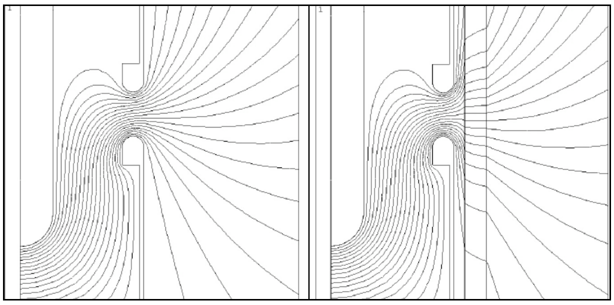

Fig. 10: Equipotential lines in the model, r = 5 mm and s = 20 mm, (left) without ceramic insulator, (right) with ceramic insulator (100 % ⇒ 0 % with 5 % steps)

This simulation shows clearly that, even if the processes at the triple point are neglected, using the ceramic insulator does give rise to a reduction in the high-voltage strength. With an increasing ring electrode gap the effect of the ceramic insulator will increase.

V Comparison with results from previous studies

It is well known that the electrodes area influences the dielectric strength in vacuum. With increasing area the dielectric strength decreases because of the existence of more micro-protrusions and particles who could initiate the breakdown.

Experiments on the area effect carried out in Japan have revealed the following mathematical relationship between the breakdown field strength (E_b) and the effective area (A_{eff}) for a wide range of geometrical arrangements [4]:

$E_b = 58 \times A_{eff}^{-0.25}$ for stainless steel (stst),

$E_b = 38 \times A_{eff}^{-0.23}$ for copper.

Comparing the results of the Japanese experiments with the values measured during the present work shows good concurrence between the two.

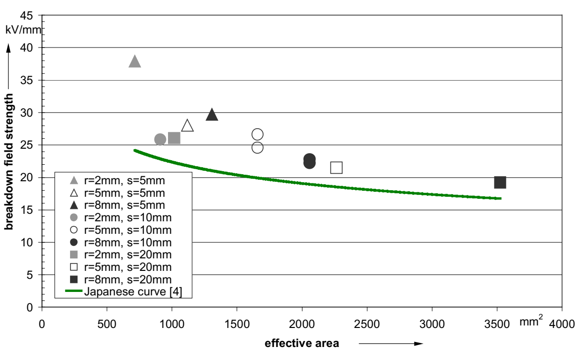

Fig. 11: Breakdown field strength *vs.* effective area for copper

This is evident from Figs. 11 and 12 where, for the two materials investigated, the values of field strength from the breakdown tests carried out here and the results of the Japanese experiments are plotted.

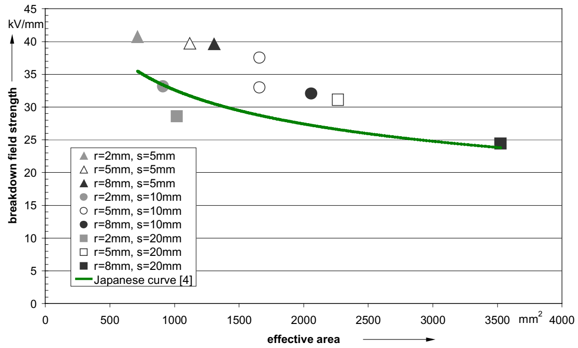

Fig. 12: Breakdown field strength *vs.* effective area for stst

It means that this relationship can be regarded as a "limit curve".

VI Conclusion

The results of measurements indicate the existence of an optimum shield electrode radius for dielectric strength of the investigated arrangement The one with a 5 mm ring radius at the ends of the shielding showed the best high-voltage strength.

The comparison of the strength results for copper and stainless steel shows that, depending on the particular geometrical arrangement, between 15 and 40 % higher strength can be anticipated with electropolished stainless steel electrodes.

For increasing the high-voltage strength of the shielding, widening the gap between the electrodes is to be preferred over enlarging the electrode radius.

The impact of the effective area can also be seen in the arrangements that have been investigated here.

Simulation on the effect of the ceramic insulator on the breakdown characteristics show a relationship to the effective area, especially when the gap between the electrodes is large.

VII References

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