

Electric field design for high-voltage vacuum tubes

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Abstract: Well known in medium voltage applications up to rated voltages about 36 kV, vacuum tubes are seldom used for real high-voltage applications because a couple of technical problems have to be overcome like electric field design. A variety of electrode arrangements such as shields, field-grading electrodes and main contacts have to be considered. In general the withstand voltages of these electrode arrangements in vacuum are determined by the electric field distribution, which can easily be calculated. But local field intensification and electrode area decreases the withstand voltages by a considerable amount. The local electric field intensification is due to electrode material, surface treatment and condition. The area effect depends on the average density of local field intensification sites at the electrodes. Therefore experimental data are needed to obtain additional information. Lightning impulse breakdown voltages of shield electrode and main contact models made of copper-chromium or copper are measured. The field intensification factors of the tested electrode arrangements and an estimation of the area effect are presented. Finally the effects on the design of high-voltage vacuum tubes are discussed.

1. Introduction

Vacuum circuit-breakers have almost completely displaced other switching systems from the medium voltage range. Today it is becoming increasingly interesting to find out whether this concept is transferable to the high-voltage level or not. Current discussions about the contribution of SF₆-gas to the greenhouse effect call special attention to this question. Some experimental works with vacuum circuit-breaker show first applications of vacuum circuit-breaker to the high-voltage level [1]. Nevertheless there are obviously some problems in arriving at a high-voltage application. One of these is the limitation of X-ray activity in new and open condition at rated ac voltage in compliance with the regulations [2], but this should not be considered in this paper. The other – more technical – problems are caused by the electric field strength limitations of the present vacuum tube design. Of course in view of the users the original requirements are to carry high currents and to interrupt high fault currents. Thus the contact system design is mainly influenced by these current requirements. But obviously the ability to interrupt fault currents is strongly influenced by the electric design of the contact system. Properly speaking the electric field design of vacuum tubes is their functional basis.

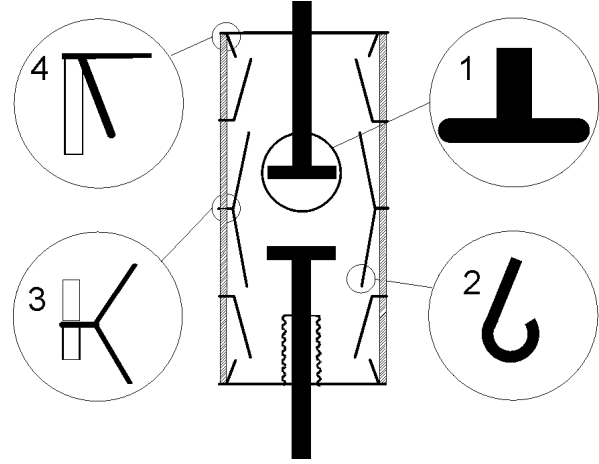


Figure 1: Critical points in regard to the electric field design of vacuum tubes (with partial enlargements: 1 – contact system / 2 – shielding ends / 3 – triple points / 4 – ceramic)

Figure 1 illustrates some critical points of vacuum tubes regarding electric field design. The withstand voltage of the whole vacuum tube is more or less influenced by these critical elements. Each part can be optimised by itself, but the performance of the whole system is given by the combination of all elements. The outer electric strength of vacuum tubes is no subject of this paper.

2. Electric strength of contact systems

The design of contact electrodes is mainly determined by their current carrying and switching capabilities. Thus contact material, diameter and form are predetermined by the ratings of vacuum tubes. Contact material is in most cases copper-chromium (CuCr), diameters are in the range between 50 and 100 mm and axial magnetic field or radial magnetic field contacts have their special shape. The remaining adjustable parameters are contact stroke, edge radius and initial surface roughness, which means the surface roughness after machining and conditioning. Therefore it should be possible to determine the initial electric strength of contact systems, if all parameters are given.

Field electron emission based breakdown voltage

The maximum macroscopic field strength E_{max} of an electrode system is given by the applied voltage U , the contact stroke s and the geometrical field enhancement factor $1/\eta$ if inhomogeneous field configurations are regarded.

$$E_{max} = U/s \cdot \eta \quad (1)$$

Surface roughness of electrodes via micro protrusions or other imperfections leads to local enhanced field strength i.e. at the tip of a protrusion. The ratio of this

microscopic value E_μ to the macroscopic field strength is defined by the local field enhancement factor β .

$$E_\mu = \beta \cdot E_{max} \quad (2)$$

Discharge mechanisms in vacuum are very complex and not understood in detail. Nevertheless there are two principal mechanisms like field emission and particle initiated discharge [3]. Field emission requires a microscopic electric field strength of approximately $E_\mu = 10^4$ kV/mm, which exists due to the local field enhancement factor β . Because this factor depends on the material and the processing line, its determination is of minor practical importance. A more suitable quantity is the macroscopic breakdown field strength of electrode systems, which is seen as inherent in an established technology. A typical value for the macroscopic breakdown field strength of plate electrodes in our experiments is $E_{bd} = 25$ kV/mm. The field electron emission breakdown voltage grows proportional to the contact stroke s .

$$U_{bd,fe} = E_{bd} \cdot \eta \cdot s \quad (3)$$

This breakdown mechanism predominates at small gap distances up to 5 or 10 mm.

Microparticle based breakdown voltage

High voltage applications demands large gap distances of several 10 mm and in this range particle initiated breakdown is the dominant process. The origin of the charged particles in the vacuum gap is still uncertain, but they need a sufficient energy density to initiate a vacuum discharge. Assuming microparticles with a charge density proportional to field strength and a minimum required energy density to initiate breakdown processes, the breakdown voltage has the following dependence:

$$U_{bd,p} \sim \sqrt{s} \quad (4)$$

which can easily be applied to obtain a regression fit of experimental data. Figure 2 gives an collection of available data.

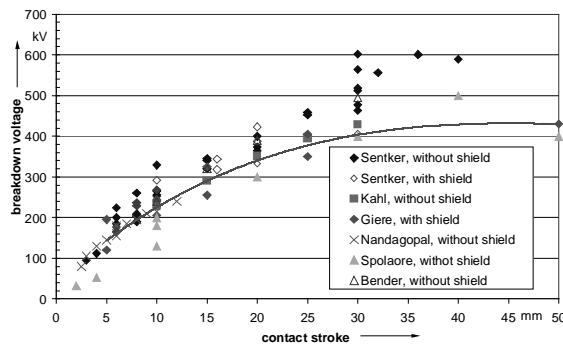


Figure 2: Collection of published vacuum electrode breakdown voltages in dependence of contact stroke [4]

The definition of two separated functions seems to be unpractical. Due to the microparticle charging process, which is also connected to the microscopic field strength, the same breakdown field strength E_{bd} is

applied. A simple transition function $\gamma(s)$ describes the dependence of the gap distance.

$$U_{bd} = E_{bd} \cdot \eta \cdot \gamma(s) \cdot s \quad (5)$$

$$\gamma(s) = (1 + s/s_0)^{-1}$$

Equation (5) provides a good fitting of experimental data and is shown in figure 2. The mathematical definition of a limiting maximum breakdown voltage for an electrode system seems to reflect practical experiences.

Area effect and breakdown voltage

The increasing probability of field enhancing micro protrusions with growing electrode area leads to a reduced breakdown voltage of larger electrode systems. The area effect is described elsewhere [5] and the influence on breakdown voltage of plate electrodes is shown in Figure 3.

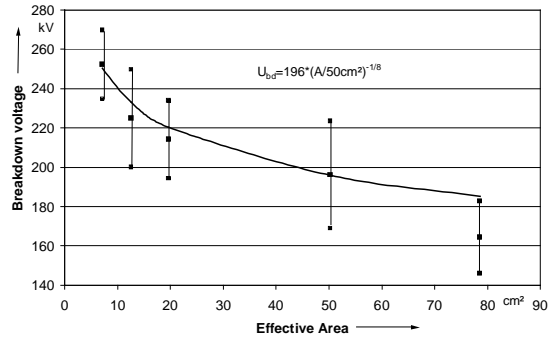


Figure 3: Reduction of plate electrodes breakdown voltage in vacuum in dependence of effective area (10 mm contact stroke) [6]

The effective area in Figure 3 is determined by the area, which is stressed by more than the 90 % value of the mean field strength between the electrodes as calculated by a field simulation program (ANSYS). The ratio of the breakdown voltage $U_{bd}(A)$ of an electrode system with surface area A to the reference value $U_{bd0}(A_0)$ with surface area A_0 is defined by the area factor $\delta(A)$. This factor can be worked out by the statistical analysis of the area effect.

$$\delta(A) = (A/A_0)^{-1/d} \quad (6)$$

The measuring results in Figure 3 can be estimated by (6) if $A_0 = 50$ cm² and $d = 8$ is chosen.

Calculation of breakdown voltage

To sum up the discussed effects, the breakdown voltage of electrode systems in vacuum is determined by the following equation:

$$U_{bd} = E_{bd} \cdot \eta \cdot \gamma(s) \cdot \delta(s) \cdot s \quad (7)$$

But electrodes have no uniform surface field strength distribution. The question is how to apply (7) for electrode geometries. A simple example of an electrode is shown in Figure 4. The plate electrode has a rounded edge. The simple electrode in Figure 4 is separated into two parts. A homogeneous plane

electrode A1 and the inhomogeneous rounded edge A2 with field strength enhancement.

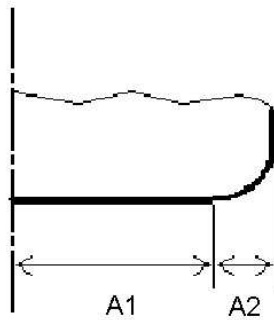


Figure 4: Principal separation of the electrode area in homogeneous (A1) and inhomogeneous parts (A2)

For each electrode part the electric field strength (η) and the area factor δ is calculated. Table 1 presents the results. The effect of field enhancement at the electrode edge is more than compensated by the area effect. These finding are supported by experimental results, that contact edges have minor influence on the breakdown voltage.

Table 1: Field enhancement factor η and area factor δ for the electrode in Figure 4 (gap distance = 10 mm)

Area	η	δ	$\eta \times \delta$
A1	1	1.03	1.03
A2	0.9	1.20	1.08

The area of more complicated electrode forms has to be separated into several parts, to approximate the field strength with a box profile. The findings above enables the following electric strength calculation procedure for vacuum electrode systems.

- Choose contact stroke, electrode diameter and edge radius
- Define effective electrode part areas with constant electric field strength
- Apply transition function γ and area function δ
- The minimum value of all electrode part areas represents the electric strength

3. Electric strength of shield and field grading electrodes configuration

The shield should be placed near to the main contacts to support the condensation of the metal vapour onto it. On the other hand the shield influences the electric field distribution in the vacuum tube. In open position the electric field strength between contact border and shield may be higher than between the contacts. Furthermore the electric field strength between the contacts may be increased due to the surrounding shield.

Shielded contact system

The influence of the shield on the static electric field distribution of the contact system can be determined by an electric field simulation. Figure 5 shows an example for such a simulation of a 72.5 kV vacuum tube prototype [6].

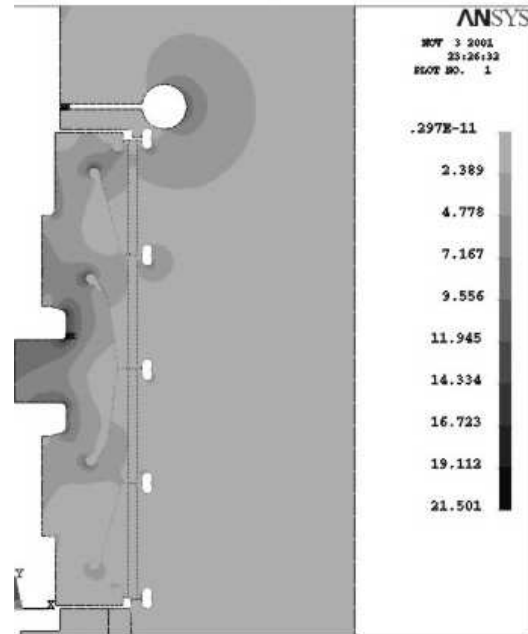


Figure 5: Example of an rotational symmetrical electric field simulation of a vacuum tube with one contact system in open position, shield and field-grading electrodes

The shields (used as general term for shields and field-grading electrodes) are floating and the resulting shield potential has to be simulated regarding the outer stray capacitances in operating condition. The electric field enhancement at the electrode edges caused by the shields can be seen in Figure 5. It is also shown that the gap between upper electrode and middle shield is stressed by a high electric field strength in open position. The task is here to adjust field enhancement factor η and area factor δ of electrode-electrode and electrode-shield arrangements to obtain a well balanced electric field. The negative influence of shield configurations on contact system breakdown voltage is shown in Figure 6. The breakdown voltage of a real contact system is continuously increasing with contact stroke. But if the electrodes are surrounded by a shield the breakdown voltage decreases when the value of contact stroke reaches the gap distance between electrodes and shield [7]. A further shield influence on the electric performance of vacuum tubes is the formation of a discharge path in parallel to the contact system.

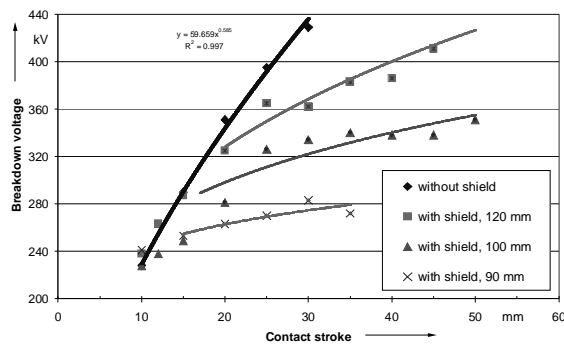


Figure 6: Breakdown voltage of vacuum contact system in open position versus contact stroke (electrode diameter 75 mm) and different surrounding shields (shield diameters 90, 100, 120 mm)

Shield and field-grading electrode configurations

The maximum electric field strength between the different shields can be calculated by electric field simulation. The breakdown voltage can be estimated with the concept given above. Figure 7 shows the electric field simulation result of an experimental shield arrangement with simplified contact arrangement and ceramic insulator [4]. Different shield electrodes are used to vary the radius of the shield ends and the gap distance. The field enhancement factor η is calculated for several shield configurations (radius/ gap distance). The effective area is defined as the shield end area, which is stressed by more than 90% of the maximum field strength between the shield ends. The area effect is then calculated according to (6). The influence of the geometry can be determined in this way without knowledge about material data or surface influence.

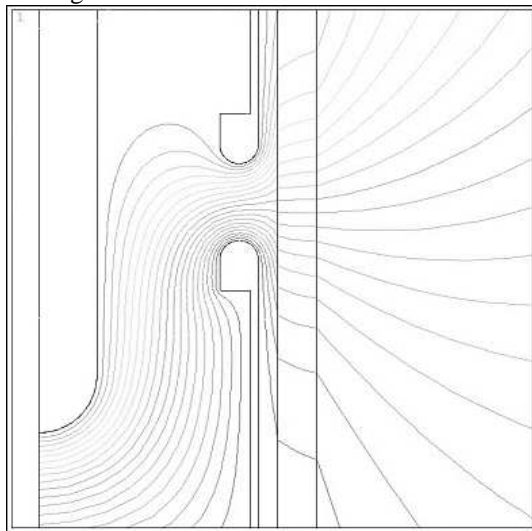


Figure 7: Electric field distribution between shield ends with simplified contact systems and ceramic insulator (gap distance = 20 mm, radius = 5 mm, potential steps = 5%)

Table 2 gives some data for the shield arrangement with 20 mm gap distance and 114 mm shield diameter. These results are in accordance with measured

breakdown voltages [4]. The increase in radius from 2 mm to 5 mm yields a 30% higher breakdown voltage, whereas the influence of a further increase to 8 mm get lost within the measuring uncertainty.

Table 2: Field enhancement factor η and area factor δ for shield arrangement in Figure 7 (gap distance = 20 mm)

radius	η	δ	$\eta \times \delta$
2 mm	0,40	0.95	0.38
5 mm	0.55	0.89	0.49
8 mm	0.63	0.83	0.52

4. Conclusion

A concept to determine the electric strength of high-voltage vacuum tubes during the development process is presented. The electric design is checked with an electric field simulation. Electric field strengths at the electrode surfaces are determined. To include the area effect, the electrode must be divided up into different parts with approximate constant electric field strengths. In the next step the data collection is used to determine the electric weakest point of the design. If necessary the design may be changed successively to obtain the optimum electrode or shield configuration.

5. References

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