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VACUUM CHAMBER DESIGN FOR HV CIRCUIT BREAKERS

ABSTRACT   *The paper presents a vacuum chamber model for a HV circuit breaker. Manufacturers of vacuum circuit breakers apply the axial magnetic field (AMF) to stabilise the electric arc diffusion during current breaking process. The model was analyzed and partly tested to assure its mechanical and electrical withstand. The results of the preliminary calculations of thermal behavior of the vacuum chamber in short-circuit conditions, the magnetic field distribution between contact plates as well as in the contact gap and the dielectric stress inside of the vacuum chamber are shown. The bipolar contacts were tested in a dismountable vacuum chamber. The aim was to determine geometry and to recognize technology and manufacturing facilities required.*

Keywords: *vacuum chamber contacts, AMF distribution, diffusion arc, circuit breaker*

1. INTRODUCTION

Progress in the application of high voltage vacuum chamber technology is shown in Figure 1 [1].Vacuum chambers for electric arc extinction were used in circuit breakers for the first time in 1965. Since then vacuum chambers have been developed and used for ever higher voltages. At present vacuum chambers for up to 145 kV are produced with a steady rise in their interrupting ability [1]. Such a progress results from

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the fast rate of rise intransient recovery voltage, and the fact that vacuum circuit breakers are an environmentally friendly method of guaranteeing safe arc extinction enabled by the excellent properties of vacuums, i.e., their very high electrical withstand, which therefore means only a small distance is required to be maintained between the contacts.

The optimization of vacuum circuit breakers started in 1987. Also in some European countries vacuum circuit breakers for 72.5 kV were developed as shown in Figure 2 [2].
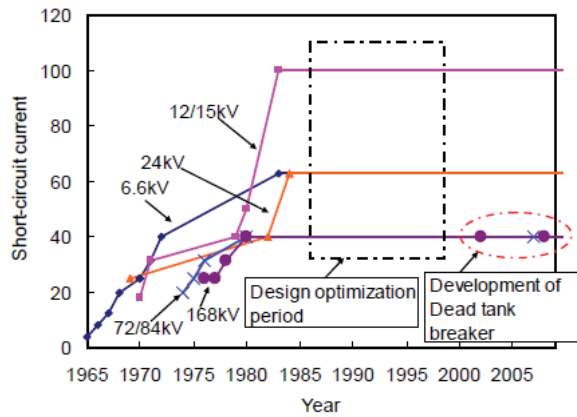

Fig. 1. Progress of VCB rating [1]

Fig. 2. Sectional view of vacuum circuit breaker pole with cross section of this pole [2]

This circuit breaker has an external ceramic insulating jacket and a vacuum chamber supported at both ends by two insulating tubes. The moving contact of the vacuum chamber is directly connected to an actuator placed under the circuit breaker pole. There are other types of vacuum circuit breakers for 123 kV and 145 kV produced in Japan – an open air circuit breaker and a dead tank circuit breaker [1]. Thanks to

continued advances in vacuum technology and new solutions for vacuum chambers, a 245 kV circuit breaker can be expected to appear on the market in the near future. Most probably such a construction will involve using two vacuum chambers in series.

The excellent properties of vacuums, especially their high electrical withstand voltage, make them eminently suitable for developing vacuum chambers for rated voltages of up to 145 kV. The electrical withstand of vacuum has been published in [3] and is shown in Figure 3.
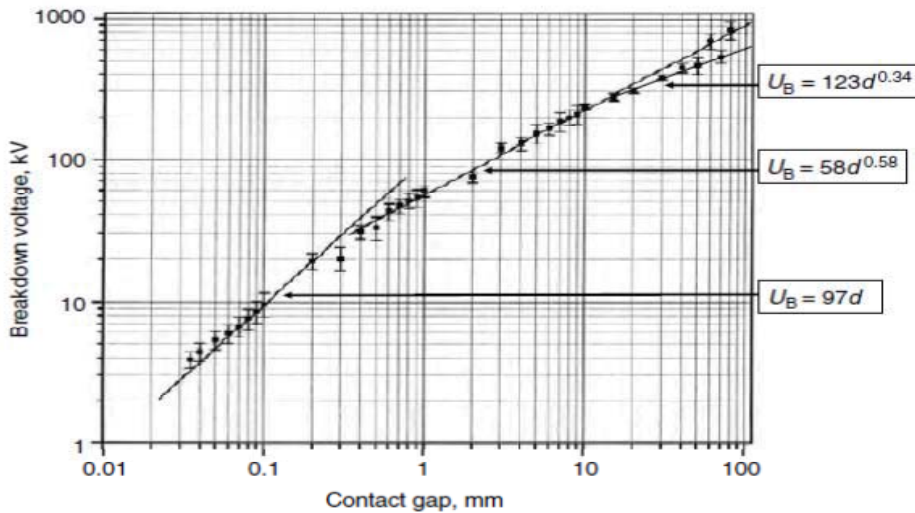

The graph shows lines labeled:
$$U_B = 123d^{0.34}$$
$$U_B = 58d^{0.58}$$
$$U_B = 97d$$

Fig. 3. A log-log graph of breakdown voltage U_B as function of contact gap in vacuum [3]

The contacts used for the measurements of these characteristics were probably carefully cleaned and polished and had a possibly uniform field distribution across them. It is well known that the initial conditioning of vacuum chambers can improve their electrical withstand voltage.

Currently circuit breakers for higher voltages than 245 kV are produced with the use of SF_6 gas because the electrical withstand voltage of vacuum is lower than SF_6 [3–5].

2. VACUUM CHAMBERS FOR HIGH RATED VOLTAGES

Vacuum chambers have some advantages. They have a very high endurance, being capable of dealing with about 1000 rated current interruptions and more than 40 or even 50 short circuit currents. Vacuum circuit breakers can be used in both high and low temperature environments with no difference in their breaking ability. Another advantage of the vacuum circuit breaker is that if an atmospheric discharge causes

a breakdown in an open contact position, the short circuit current will still generate a magnetic field in the vacuum chamber and interrupt it at the nearest current zero. However, an SF_6 circuit breaker is not able to interrupt such a short circuit current, which in this case would generate a temperature and pressure high enough to cause an explosion and the destruction of other substation apparatus.

3. RISE IN TEMPERATURE OF THE VACUUM CHAMBER CONTACTS

The authors decided to investigate bipolar contacts (see Fig. 4) installed in a vacuum chamber from the point of view of the rise of temperature in load and short circuit conditions. The model of well-known unipolar contacts of 90 mm diameter has been considered. The contacts have been connected together by the cylinder of 90 mm diameter and 50 mm height (conductivity $\gamma = 2 \cdot 10^3$ S/m). The analysis focused on the coils used for axial magnetic field generation and on the contact plates used. The contact plates directly soldered to the coils were designed for a rated current of 2000 A.
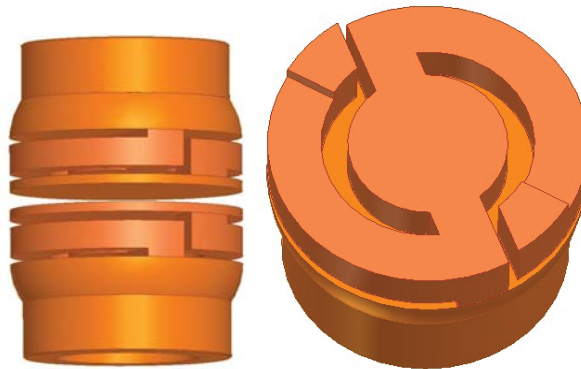
Fig. 4. Bipolar contacts

The analysis of the temperature rise was made using 3D electro-thermal FEM numerical model of the vacuum chamber contacts, which is the coupling of Steady State AC Magnetic module with Transient Thermal module and external electric circuit. The stabilization of the temperature is much faster and the temperature increase is lower (Fig. 5) when radiators are applied. The radiators increase the cooling surface of about 3.8 times.

In case of short circuit, the heat exchange with the surrounding atmosphere was not taken into account. The current density in the contact coil and in the contact plate was calculated and results of the temperature rise for different number of half-waves of a 40 kA short circuit breaking current are shown in Figures 6 and 7. The rise in temperature during a short circuit shows that when the short circuit current duration is longer than 15 ms the temperature in the contact coil and contact plate rises steeply as shown in Figures 6 and 7. However, the rise in temperature of the contact coil and the

contact plate due to a symmetrical short circuit current of 40 kA does not exceed the recommended value. During auto-reclosing tests the rise in temperature is higher but still does not exceed admissible values. Cooling of the circuit breaker contacts is only possible through external radiators.
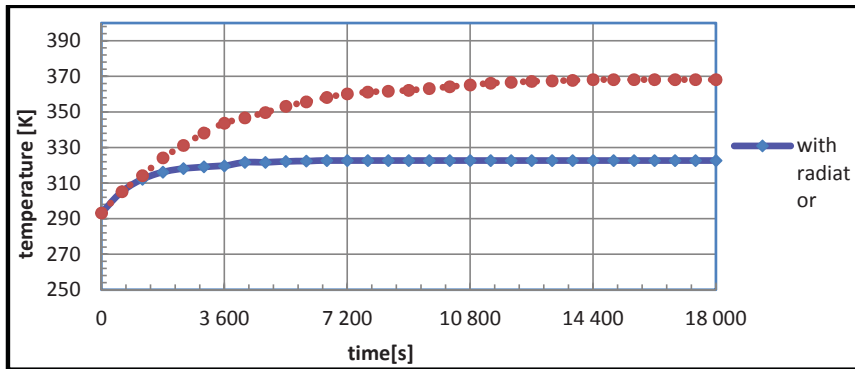

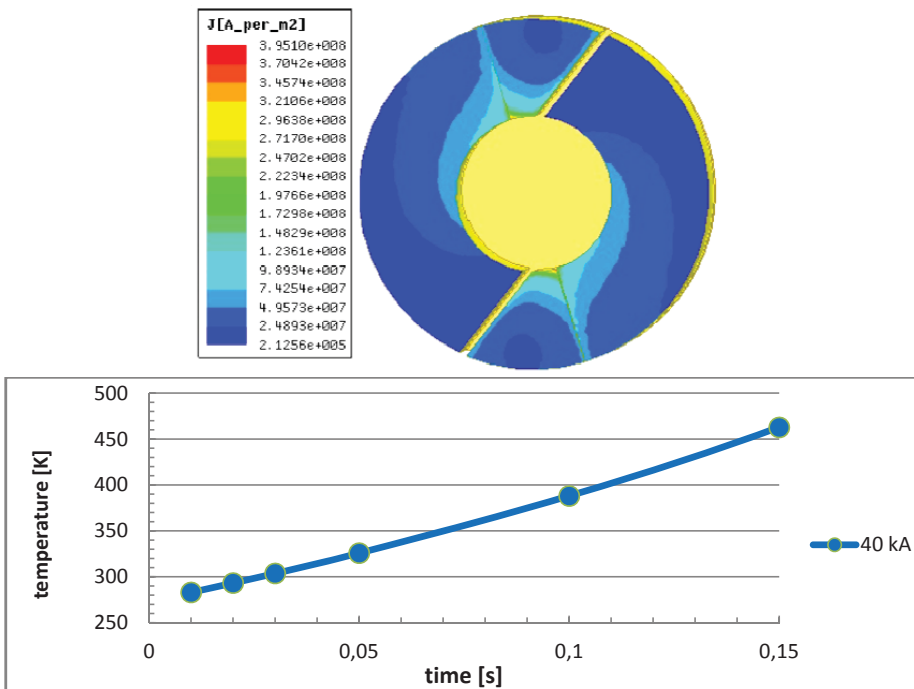**Fig. 5. Rise of temperature with continuous current of 2000 A**

Fig. 6. Distribution of current density and rise of temperature in bipolar contact coil at short circuit breaking current of 40 kA
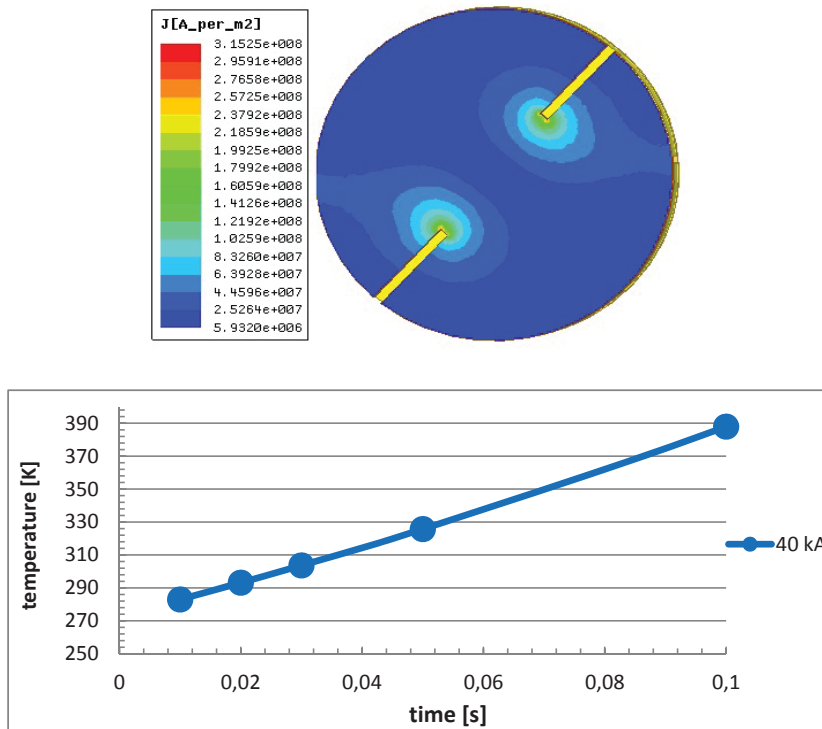
Fig. 7. Distribution of current density and rise of temperature in the contact plate at short circuit breaking current of 40 kA

4. MAGNETIC FIELD DISTRIBUTION BETWEEN BIPOLAR CONTACTS

As mentioned above for 123 kV circuit breakers, bipolar contacts were analyzed, for which the gap between the contacts at the fully open position was assumed to be 60 mm. In the open position, the magnetic field distribution was analyzed using the Maxwell 3D (Ansys) software. The highest magnetic field generated by the contact coil is at the central part of each contact (Fig. 8). For the same as in the previous section bipolar contact set the magnetic field profile within the contact gap of 60 mm was also calculated − see Figure 9. The magnetic field strength is at its lowest value in the halfway between the contacts and then increases as it gets nearer the opposite contact (the anode). The highest magnetic flux density at the magnetic profile (yellow) is equal to 418 mT for a short circuit breaking current of 40 kA.
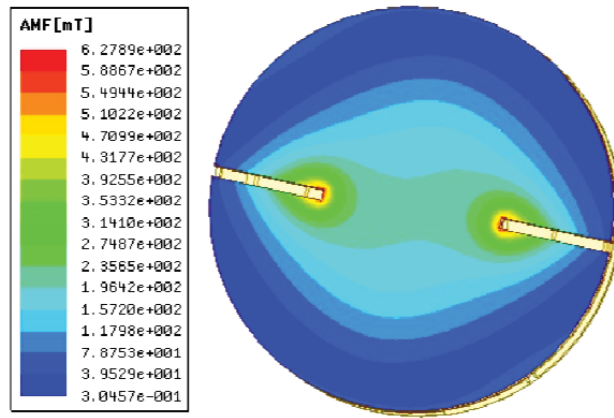
Fig. 8. Magnetic field distribution at the surface of bipolar 90 mm diameter contact at short circuit breaking current of 40 kA
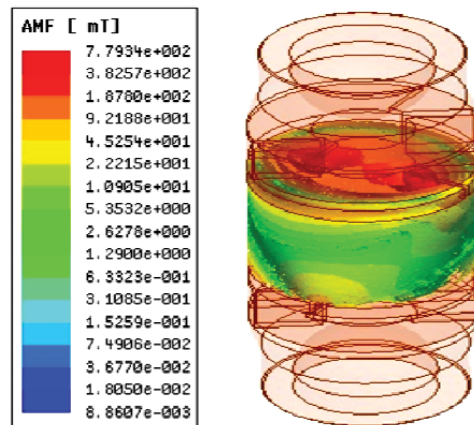
Fig. 9. Magnetic field distribution within contact gap of 60 mm

Further analysis is concentrated on the magnetic field distribution at the very beginning of the contacts' separation, when the arc is initiated between the contacts. The initial location of the arc is important in this regard. At such short distances between the contacts, in the presence of very high electric field, the arc can be initiated at different points on the contacts surfaces. Therefore, after several short circuit current interruptions the surfaces of the contact plates are changed and are no longer polished as it was at the beginning. This effect was proved several times in experiments (Fig. 11) with the dismountable vacuum chamber shown in Figure 12. Theoretically, at the first

moment of contact separation, the AMF distribution is as shown in Figure 10. The highest magnetic flux density is at the centre of the contact plates and the lowest is at the edge of the plates.

For the contact tests a dismountable vacuum chamber was used. The bipolar contacts were located inside the dismountable vacuum chamber in which a vacuum of 10^{-6} mbar was created and a current of 15 kA was interrupted. A typical view of a diffusion arc is shown in Figure 13.

The arc ignition at the edge of the contacts, seen in Figure 11, is not a diffusion arc as in Figure 13, but a constrained arc, and melts the contact material. The arc ignition at the edge of the contacts, seen in Figure 11, is not a diffusion arc as in Figure 13, but a constrained arc, which causes erosion of the contact material.
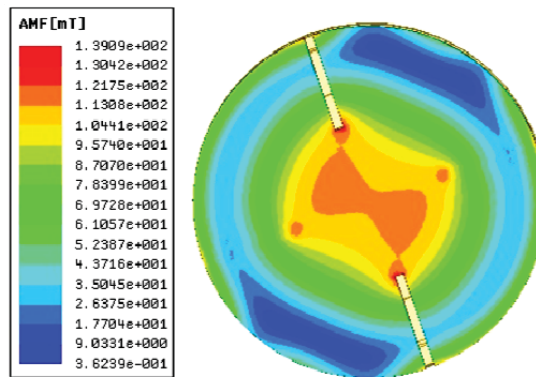

Fig. 10. Magnetic field distribution on the surface of closed contacts at 40 kA
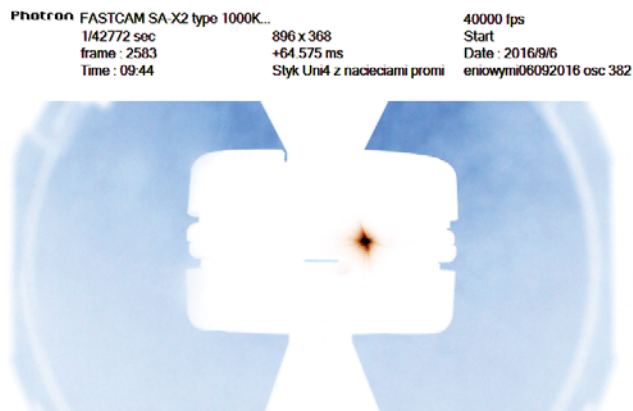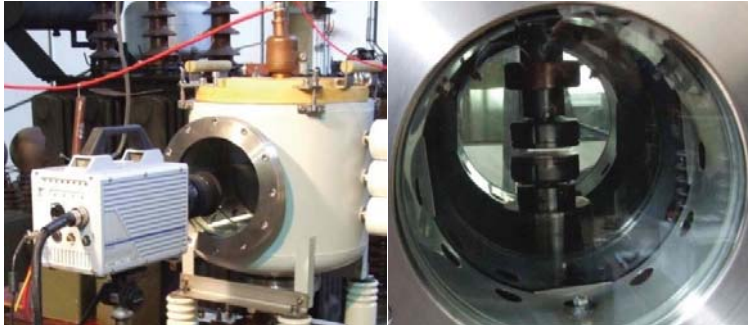

Fig. 11. Arc initiation at the contact edge – picture recorded in a dismountable vacuum chamber using a high speed Photron camera

**Fig. 12. Laboratory test stand with a dismountable vacuum chamber**

Fig. 13. Diffusion arc recorded with high speed Photron camera

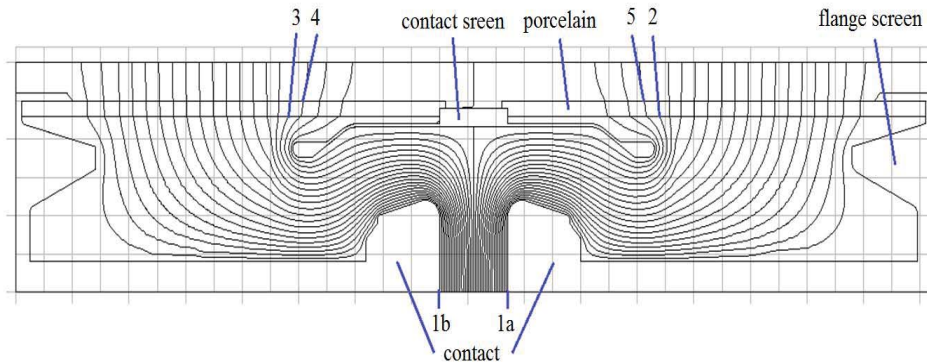# 5. ELECTRIC FIELD DISTRIBUTION INSIDE OF THE VACUUM CHAMBER

The electrical withstand voltage between electrodes in a vacuum at a distance of 60 mm is equal to about 700 kV, see Figure 4, but the recommended electric lighting withstands voltage 1.2/50 is only 450 kV and between contacts 520 kV. The recommended 50 Hz withstand voltage is 185 kV and 210 kV respectively [6]. Vacuum chambers have to satisfy stringent requirements throughout their life time. To ensure the electrical withstand of the vacuum chamber one has to prevent even partial discharges inside. It is well known that the lifetime of vacuum circuit breakers is much longer than those of any other kind of circuit breakers such as pneumatic or SF_6 types. This consequently means that the contact materials have to be carefully selected.
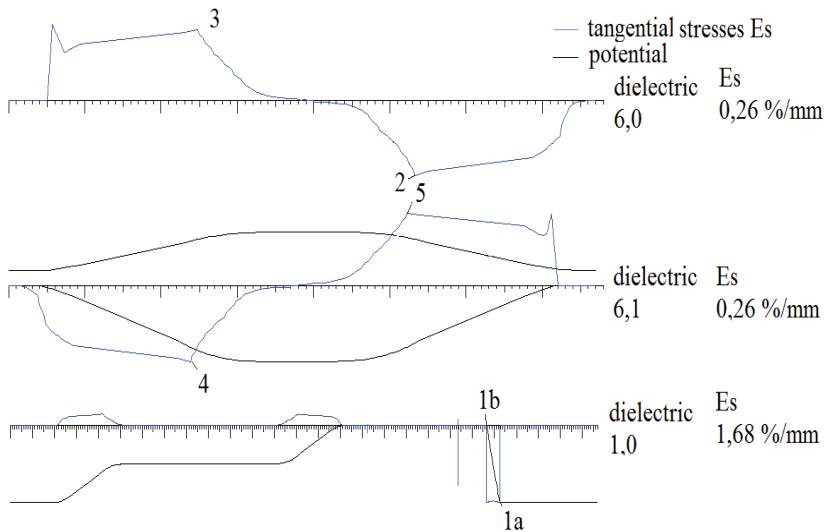
Fig. 14. Tangential electric field stresses along the border of different materials.
Places from 1 to 9 are marked on Figure 15

Fig. 15. Electric field distribution in the vacuum chamber

For the calculation of the electric field distribution inside the vacuum chamber, a computer program, applying the finite elements method (FEM) was used, taking into account the relevant internal geometry, i.e., the screens, the contacts position, the geometry of the vacuum chamber and the external electrodes. The results are shown in Figures 14 and 15.

The calculated tangential and the normal electric field stress along the border of different areas and the dielectric stresses does not exceed the admissible values. The highest stresses are near the electrodes and at the dielectric surface; they are between 3.9 kV/mm and 4.4 kV/mm.

6. SUMMARY

Vacuum chambers used in high voltage circuit breakers play an important role and have to be carefully designed and tested. Therefore their thermal behaviour during load and short circuit conditions, and the electrical stresses were analysed. The distribution of the electric field in the vacuum chamber and the distribution of the tangential and normal electric field stresses along the border of the separate areas do not exceed the admissible value.

The bipolar contact was tested using a dismountable vacuum chamber. The diffusion arc was distributed rather uniformly within the contact surface.

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PROJEKTOWANIE KOMÓR PRÓŻNIOWYCH
DO WYŁĄCZNIKÓW WYSOKIEGO NAPIĘCIA

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STRESZCZENIE   *W artykule przedstawiono opis modelu komory próżniowej przeznaczonej do wyłącznika wysokiego napięcia. Model został przeanalizowany i częściowo zbadany w celu zapewnienia odpowiedniej*

wytrzymałości elektrycznej i mechanicznej. Wstępnie rozważono: wytrzymałość termiczną w warunkach obciążeniowych i zwarciowych, wytrzymałość na narażenia elektryczne, przeanalizowano rozkład pola magnetycznego na powierzchni styków jak i w przestrzeni pomiędzy stykami, wyznaczono rozkład pola elektrycznego wewnątrz komory próżniowej. Styki bipolarne zbadano w rozbieralnej komorze próżniowej. Celem tych obliczeń i badań było opracowanie odpowiedniej geometrii i rozważenie możliwości techno-logicznych wykonania modelu komory do wyłącznika wysokiego napięcia.

Słowa kluczowe: *styki komory próżniowej, rozkład AMF, łuk dyfuzyjny, wyłącznik*