A NEW TYPE OF VACUUM INTERRUPTER WITH ELECTRICAL CONTACTS IN NORMALLY OPEN POSITION

Alexandru RADULIAN[1], Nicolae MOCIOI[2]

This article presents a new solution of a vacuum interrupter with electrical contacts in normally open position, used in the construction of switching equipment's for electric power systems, especially vacuum contactors and vacuum circuit breakers for low and medium voltage. It will be described the design, the operating principle and the computerized model. The main advantages of the proposed solution are: high operational reliability, lack of the insulating element in the switching zone avoids the phenomena of flashover on the surface and increase the lifetime of the vacuum interrupter, environmentally friendly.

Keywords: vacuum, electric field, tungsten carbide, superaluminous insulator, electric discharge, environmentally friendly, reliable

1. Introduction

Nowadays, safety issues in exploitation, reliability and protection of the environment are becoming more and more common. Over the past twenty years, the vacuum switching technique has penetrated the market by covering a huge range of applications at high voltages. Vacuum switching devices are declared environmentally friendly, maintenance-free but their safety can be improved. The fact that commercial solutions of vacuum interrupter have normally closed contacts in the rest state is a disadvantage.

This article presents a new solution of a vacuum interrupter with electrical contacts in normally open position, used in the construction of switching equipments for electric power systems, especially vacuum contactors and vacuum circuit breakers for low and medium voltage. The design shown in this article is suitable for the low voltage vacuum contactor.

The electrical insulation design plays an important role in developing of the vacuum interrupters. For insulation design of vacuum interrupter, numerical field calculation techniques have been widely applied as a computer-aided tool. The electric field optimization of electrode contour aiming to suppress the maximum field strength was developed for improving the insulation performance [1]. In the world, the classical construction solution of the vacuum interrupter, as shown in Fig. 1, is known, having the following components: 1-fixed contact

[1] PhD student, ICPE, București, Romania, e-mail: radulian.alexandru@yahoo.com
[2] Eng., ICPE, București, Romania, e-mail: radulian.alexandru@yahoo.com

road, 2- upper cover plate, 3- super aluminous insulator, 4- shield, 5- lower cover plate, 6 – movable contact road, 7 - bellows, 8 - movable electric contact, 9 – fixed electric contact [2]. This solution presents a great disadvantage because, due to the atmospheric pressure witch press on the inner surface of the elastic bellows 8, the electrical contacts are normally closed, which leads to a decrease in the safety of the vacuum interrupter.

It is also known another constructive solution for vacuum interrupter with electrical contacts in normally open position shown in Fig. 2.

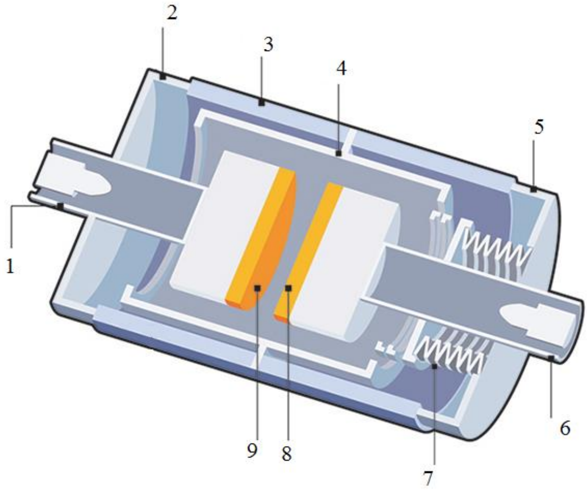


Fig. 1 Cross section of classical vacuum interrupter [2]

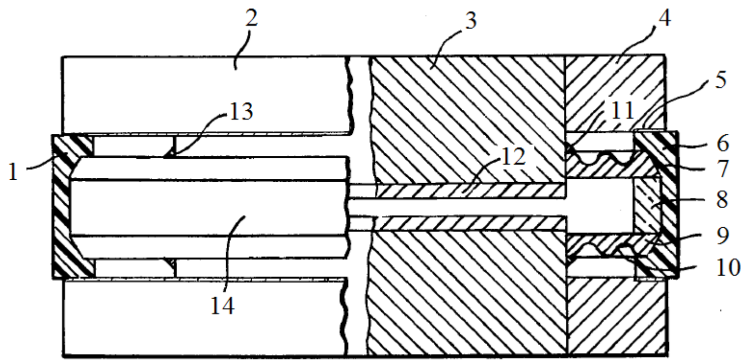


Fig. 2 Cross section of Westinghouse Electric Corp. vacuum interrupter with electrical contacts in normally open position [3]

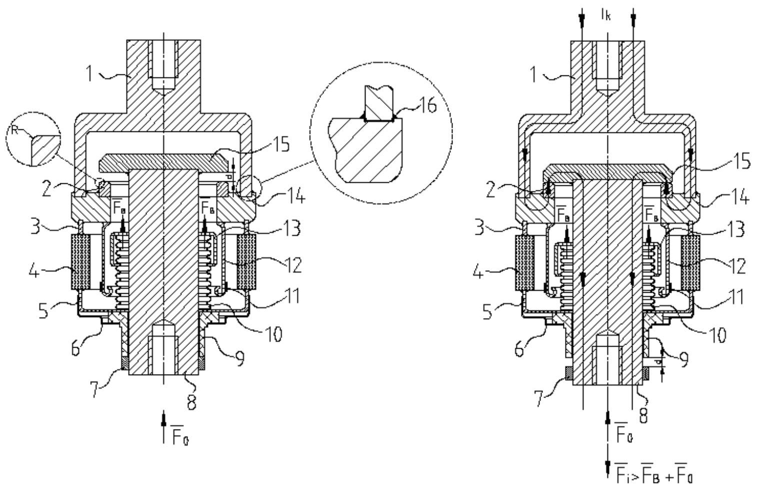
From the constructive point of view, it consists of: 1,6 – elastomeric annular member, 2 - flange connectors, 3 - cylindrical contact support, 4 – connector plates, 5 - metal deposition, 7 - outer perimeter of 9, 8 - ceramic ring insulator, 9 - circular flexible element made of Monel, 10 - corrugations, 12 - electrical contact, 11,13 - inner perimeter of 9. The member 10 provide the requisite axial flexibility and transverse rigidity to the annular member 9 [3].

This solution has the following disadvantages:
- The wear or the lack of the elastic member 1 leads, in the overtime, to a decrease in the distance between the electrical contacts 12. In this case, the electrical contacts can touch one to the other, which is an undesirable effect. The safety in operation of the electrical equipment is reduced;
- Due to the lack of metal shield in the area of the electric contacts, the metal vapors produced by the electric arc in the connection and disconnection process are deposited on the inner surface of the ceramic insulator 8 and create favorable conditions for the occurrence of the electric overflow phenomenon, leading to a decrease of the safety in operation;
- The presence of two flexible elements 9 as well as the difficult construction of the vacuum interrupter, increase the rate of occurrence of a fault in operation;

The technical problem solved by the proposed solution consists in the design and development of a vacuum interrupter composed of a pair of normally open electrical contacts. The open position is provided by the atmospheric pressure that pressing on the inner surface of the elastic bellows and the precompression of the elastic bellows which is fixed by the movable road. The electrical contacts are placed in a vacuum chamber and the ceramic insulator (which is designed to provide electrical insulation between the upper and lower terminals) and which is placed in the lower position of the vacuum interrupter does not come into direct contact with the switching area, thus being protected against the deposition of metallic vapors. This arrangement of the contacts is able to extinguish the electric arc by moving it, moving produced by the electrodynamic force resulting from the cross of the current through the conductive path of the vacuum interrupter [3].

2. Design of the proposed vacuum interrupter

According to the proposed solution for the vacuum interrupter with normally open electrical contacts, presented in Fig.3 and 4, it consists of: 1- top cover made of copper OFHC, 2- fixed electric contact, 3- intermediary ring, 4- annular insulator made of high density alumina, 5- lower cover made of stainless steel, 6- protective cover, 7- limiting ring, 8- movable support made of copper, 9- bushing, 10- bellows, 11- non-evaporable getter, 12- fixed shield, 13- movable shield, 14- fixed support made of copper, 15- movable electric contact. All these elements are joined together and brazed with the alloy 16. Maintaining the vacuum interrupter in the closed position according to Fig. 3 b) is achieved by applying a pulling force F_i to the movable support 8. This force is greater and opposite to the force resulting from the sum of the force F_0 due to the atmospheric pressure and the force F_B due to the precompression of the elastic bellows 10 [4].



a) b)

Fig. 3 Vacuum interrupter with normally open electrical contacts:
a) in the open position; b) in the closed position

The separation of the contacts, as shown in Fig. 4, occurs when the F_i force is canceled. In the disconnection process, an electric arc is produced between contacts 2 and 15, which is expelled due to the electrodynamic forces F_1, F_2, F_1-F_2> 0, because x_2>x_1. This repulsion force, which acts on the electric arc, occurs with the crossing of the current lines i_k through the current path composed of the top cover 1, fixed support 14, fixed contact 2, electric arc 17, movable contact 15 and movable support 8. The waste gases left after extinguishing of the electric arc are absorbed by the non-evaporable getter 11 placed on the outer surface of the fixed screen 12 to keep the vacuum in the vacuum interrupter [4].

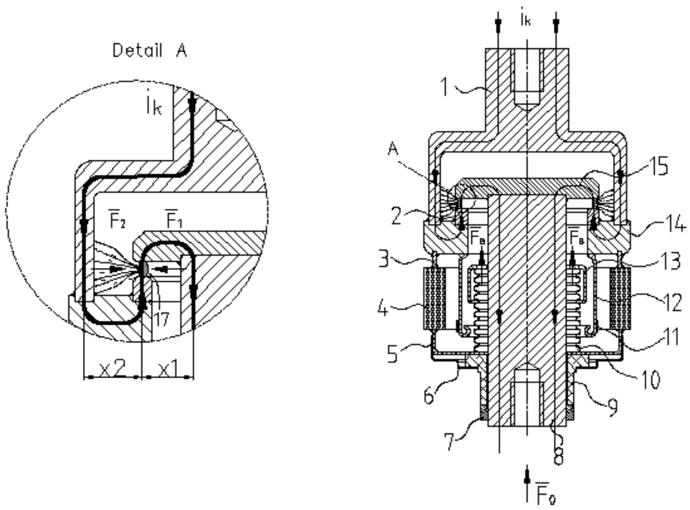


Fig. 4 Vacuum interrupter with normally open electrical contacts in the disconnection process

3. Finite element analysis of the proposed vacuum interrupter

The simulation of the vacuum interrupter was done using the FEMM simulation environment 4.2. FEMM is a suite of programs that solve low frequency electromagnetic problems. This software solves the current problems on two-dimensional plane and axisymmetric domains. FEMM can address various electromagnetic field regimes: linear and nonlinear magnetic field and quasi-magnetic field, linear problems of electrostatics, electro-kinetics problems and heat transmission [5].

3.1 Mathematical model

For calculations of the electric field inside and outside the vacuum interrupter an electrostatically axial dimensional problem was chosen. This takes into account the behavior of the electric field $\vec{E}$ (V/m) and the induction of the electric field $\vec{D}$ (C/m^2).

The hypotheses of the electrostatic regime are as follows:

- Forms are immobile: $\vec{v} = 0$ (1)
- Variables are constant over time: $\frac{dx}{dt} = 0$, (2)

where x is the distance between the electrical contacts;

- No energy transformations occur , so the electrical currents are null : $p = 0 \Rightarrow j = 0$ (3)
- Distribution of the magnetic field is ignored, results $\vec{B} = 0, \vec{H} = 0$ (4)

Two conditions must be fulfilled:

1. First condition is the Gauss Law which states that the electric field vector flux $\vec{E}_v$ through any surface Σ, driven in vacuum is proportional to the total electric load q_Σ located within this surface the proportionality factor being $\frac{1}{\varepsilon_0}$, where ε_0 is the electrical vacuum permittivity $\varepsilon_0 = 8{,}854 \cdot 10^{-12}\ F/m$.

- Global and integral form of Gauss Law:

$$\Psi_\Sigma = q_\Sigma \Leftrightarrow \oint_\Sigma \vec{D} \cdot d\vec{A} = \oint_{D\Sigma} \rho dv \quad (5)$$

- Local and differential form of Gauss Law: $div\vec{D} = \rho$, (6)

where ρ is the density of the load, $[\rho]_{SI} = C/m^3$.

2. Second condition is the stationary electric potential theorem in stationary immobile fields

- Global form of the law: $u_\Gamma = 0 \Leftrightarrow \oint \vec{E} d\vec{r} = 0, \forall S_\Gamma$ (7)

- Local and differential form of the law:

$$rot\vec{E} = 0 \Rightarrow \vec{E} = -gradV \Leftrightarrow \vec{E} = -\nabla \cdot V \quad (8)$$

In the local form of the law first grade differential equations are used.

The constitutive material relationship results from the law of the link between D and E equations:

$$\vec{D} = f\left(\vec{E}\right) \Leftrightarrow \vec{D} = \varepsilon_0 \cdot \vec{E} \quad (9)$$

Substituting Gauss's Law and applying the constitutive equations from above we obtain the second-degree equation with partial derivatives:

$$-\varepsilon\nabla^2 V = \rho \quad (10)$$

and applies to homogeneous regions.

3.2 Boundary conditions

The fundamental problem of electrostatics consists in determining the electric field starting from its sources and conditions on the border. A Dirichlet-type boundary conditions had been imposed. In this type of boundary condition, the value of the V-potential is explicitly defined at the boundary so that there is a fixed tension value on a surface of the problem domain. Distribution of the electric field of the vacuum interrupter is described by the Laplace equation and the correspondent boundary conditions as follows:

$$\nabla^2 \rho = f\left(-\frac{\rho}{\varepsilon}\right) \quad (11)$$

For the ceramic and air isolator interface the following condition was imposed:

$$\begin{cases} \varphi_1 = \varphi_2 \\ \varepsilon_1 \dfrac{\partial \varphi_1}{\partial n} = \varepsilon_2 \dfrac{\partial \varphi_2}{\partial n} \end{cases} \quad (12)$$

For fixed and mobile electrical contacts as well as associated arcing shield the following condition was imposed:

$$\varphi\big|_L = \varphi_0(l) \quad (13)$$

where $\varphi\big|_L$ is the know electrical potential.

The electric field problem is correctly formulated if the following three conditions are met: the problem has a solution, the solution is unique, and this solution depends continuously on the field sources of the problem given data.

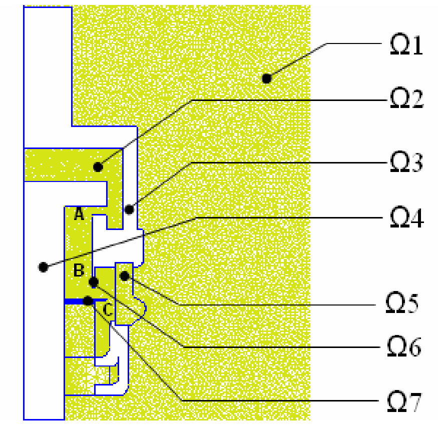
3.3 Geometric model

Fig. 5 shows the principle construction of the vacuum interrupter. Three areas of interest were identified:

Area A - insulation between electrical contacts;

Area B – insulation between movable and fixed arcing shield;

Area C – insulation between the mobile shield and the ceramic insulator.
Since the voltage level is not high, the outer area of the vacuum interrupter has not been taken into account.



Domain	Material	Condition
Ω_1	Air	εr=1.005364
Ω_2	Vacuum	εr=1
Ω_3	Copper	Conductor 1000V
Ω_4	Copper	Conductor 0V
Ω_5	Al_2O_3	εr=9
Ω_6	Copper	Potential 1000V
Ω_7	Copper	Potential 0V

Fig. 5 The basic geometry in the un-optimized version and materials and conditions used in computerized modeling and simulation of the geometry of the vacuum interrupter

From the constructive point of view, the vacuum interrupter is composed of a fixed support-contact assembly with potential of V=1000 V and one movable support-contact assembly with potential of V=0 V separated by means of a insulator (Al_2O_3) a movable shield welded on the movable contact road and a fixed shield welded on the fixed contact road. Inside the interrupter advanced vacuum conditions are created, the dielectric constant is 1 and the pressure is 10^{-6} mbar. Air surrounds the vacuum interrupter from outside. For shields, copper was chosen instead of stainless steel because it is a soft material and can be molded in any forms.

The main domains are described as follows:

Ω_1 – Indicates the environment outside the vacuum interrupter characterized by electrical permittivity ε_r;

Ω_2 – Indicates the environment inside the vacuum interrupter characterized by electrical permittivity ε_r;

Ω_3 – Is a section through the fixed contact characterized by the non-zero potential conductor (1000 V);

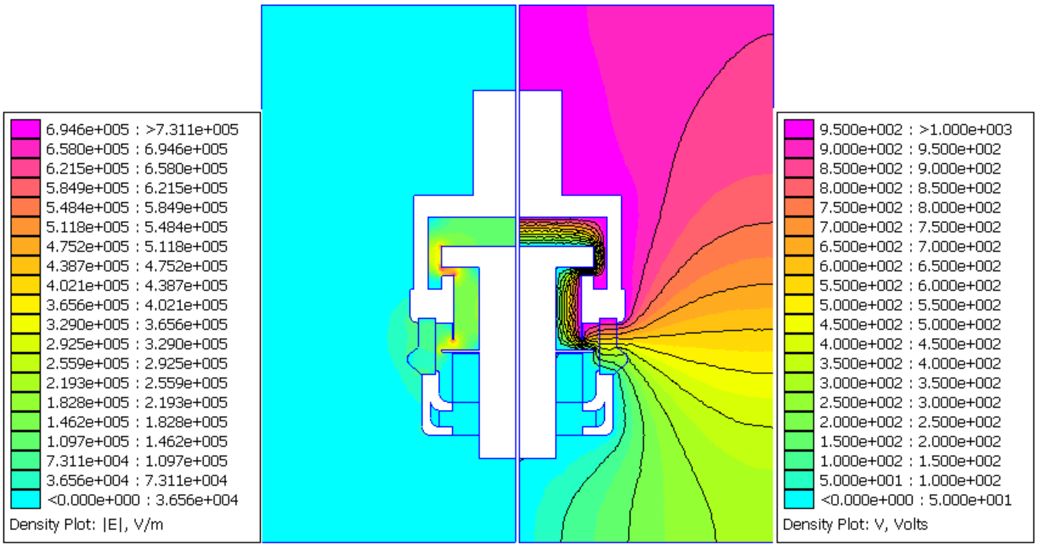
Ω_4 – Is a section through the mobile contact characterized by the potential null conductor;

Ω_5 – Is a section through the ceramic insulator characterized by electrical permittivity ε_r;

Ω_6 – Is a section through the fixed shield characterized by potential non-zero conductor (1000 V);

Ω7 – Is a section through the mobile shield characterized by potential null conductor.

In this article the intensity of the electric field was expressed in V / m. Fig. 6 shows the distribution of the electric field E, electric potential V, the equipotential lines and the critical regions inside the vacuum interrupter. Practically, these simulations were made in order to identify critical regions and optimize them. The number of metal-ceramic braziers has been reduced to a minimum so as to limit the concentration areas of the electric field and thus lowering the rate of loss of vacuum over time.



a) b)

Fig. 6 Distributions in the vacuum interrupter: a) electric field E, b) electric potential V and equipotential lines

Optimization in area A

Considering that for a nominal voltage of 1000 V the distance between the contacts is 2-3 mm, special attention must be paid to rounding the sharp edges of the electrical contacts. Fig. 7 shows the variation of the electric field with the radius at the end of the contact. To mention that the 1.2 mm radius was adopted for rounding all edges of the electrical contacts: fixed and mobile. It has been found that the 1.2 mm radius is the optimal value because a larger radius decreases the area of the contact surface between the electrical contacts. Fig. 8 shows the electric field distribution in the new configuration.

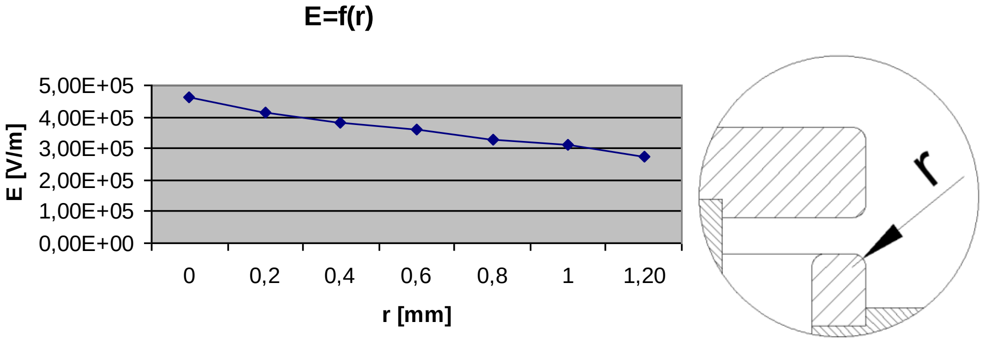


Fig. 7 Optimization of the electrical intensity E in area A by changing the edge radius of the contacts

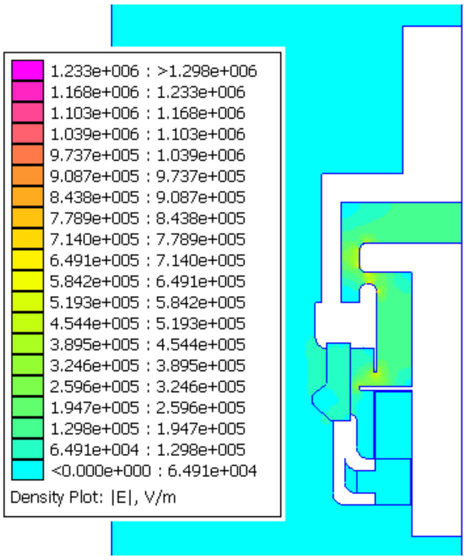


Fig. 8. Electric field distribution in the vacuum interrupter optimized in area A

Optimization in area B and C

Another area subject to attention is insulation between movable and fixed arcing shield. In this case, to reduce the strength of the electric field, the fixed and mobile screens were rolled at the ends (Fig. 9). This change has led to the reduction of the field strength value at the end of the mobile screen by 35%.

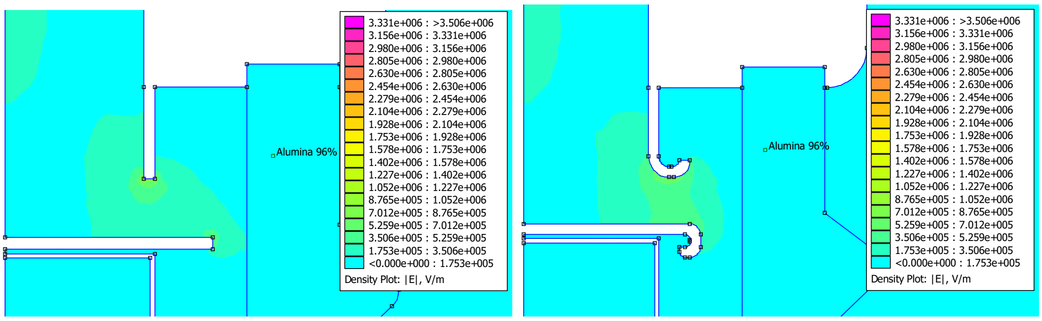


Fig. 9 Electric field distribution in the vacuum interrupter optimized in area B and C

3.4 Contact resistance calculation

On the model proposed by Slade [6] the contact resistance, the contact pressure force and the resulting temperature were calculated. If we have two homogeneous and isotropic bodies that make contact on a single microscopic conduction surface Ac. In this contact there is an additional resistance Rc called contact resistance, which consists of two parts, approximately independent of one another:

$$R_c = R_s + R_p \tag{14}$$

where: Rs is the striction resistance due to the rough nature of the contact surfaces and Rp is the pellicular resistance produced by the presence on the contact surfaces of some semiconductor films, which breaks the pure metallic contact. For vacuum interrupters R_p =0. It results that:

$$R_c = R_s \tag{15}$$

The contact pressure force can be expressed as follows:

$$F = \xi \cdot H_c \cdot \sum A_i \tag{16}$$

where ξ is a constant (about 1 for plastic deformations), H_c is the hardness of the contact material and i is the number of microscopic spots.

Thus, for the striction resistance the following corresponding expression is:

$$R_c = \frac{\rho}{2a} \tag{17}$$

where ρ is the resistivity of the contact and a is the radius of the area A_c.
Substituting from equation (16) and introducing $A_c = \pi * a^2$ results:

$$R_c = \frac{\rho}{2} \cdot \sqrt{\frac{\pi \cdot H}{F}} \tag{18}$$

On the basis of the relationship (18) contact resistance depending on pressure force curves were plotted for different contact alloys (Fig. 10).

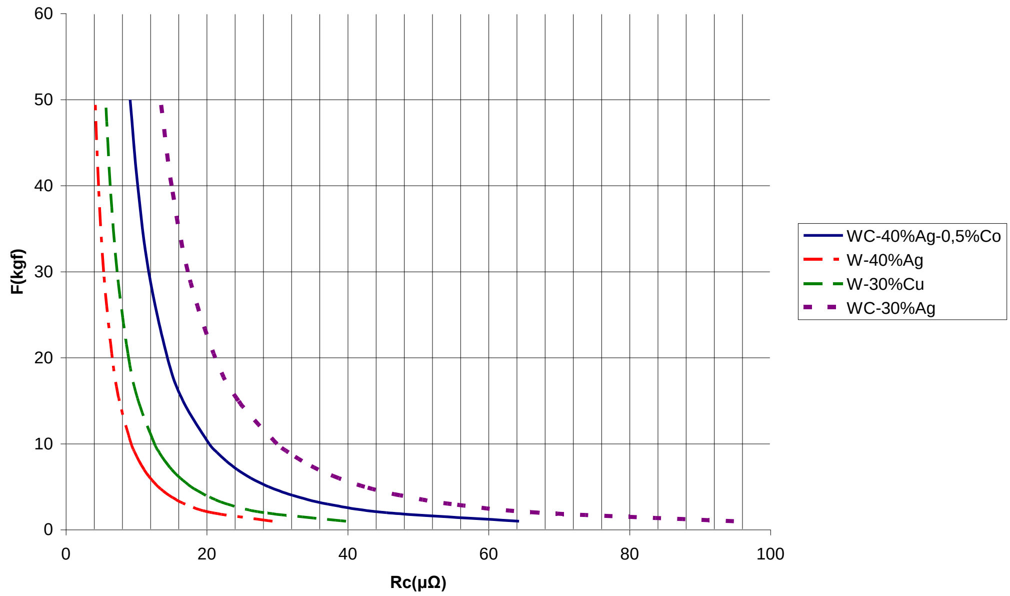


Fig. 10 The dependence of the contact resistance and pressure force for various alloys

Determinations of hardness and electrical resistivity for these alloys were made experimentally. It can be noticed that for the skeletons of the electric contacts made of tungsten carbide a high-pressure force is needed to obtain small contact resistances. It is known from the literature [6] that vacuum interrupters for contactor must have a contact resistance of less than 30 μΩ. As a result of experiments in order to determine the chopping current, the lower value of the alloy WC-40 % Ag-0,5 % Co (the blue curve) has been pulled off [7]. So, for this alloy a force of about 10kgf is needed to reach the 30μΩ contact resistance.

Increasing R_c contact resistance over time leads to increased temperature in contact area and in extreme cases even melting. Therefore, it is useful to analytically estimate the temperature in the arcing zone without having to measure it experimentally.

It is a very simple procedure to measure the voltage drop on a closed contact. If we take into account a conductor and assume that the equipotential lines are the same as the distribution lines of the heat flux and that there is no heat loss through radiation, it can be proved that:

$$\left[\frac{U_c}{2}\right]^2 = 2 \cdot \int_{T_0}^{T_p} \lambda(t) \cdot \rho(t) dt \qquad (19)$$

Where U_c is the voltage drop across the conductor, T is the absolute temperature in Kelvin, T_0 is the ambient temperature, T_p is the maximum temperature, ρ is the resistivity and λ is the thermal conductivity. Using the Wiedermann-Franz Law, we obtain [8]:

$$\rho(t)\cdot\lambda(t) = L\cdot T \tag{20}$$

Where L is the Lorentz constant given by:

$$L = \frac{\pi^2}{3}\cdot\left[\frac{k}{e}\right]^2 \tag{21}$$

where k is Boltzman constant, e is the electric charge and L=2,45x10^{-8} WΩ/(gradeK)^2 . By integrating equation (19), we get:

$$U_c = \left[4\cdot L\cdot\left\{T_p^2 - T_0^2\right\}\right]^{1/2} \tag{22}$$

If $T_p >> T_0$ (Kelvin), equation (22) may be written as:

$$T_p = \frac{U_c}{2\sqrt{L}} \tag{23}$$

Based on the above relationships, the diagram in Fig. 11 shows the dependence between the temperature of an elemental spot and the voltage drop on it for a 30 μΩ contact resistance.

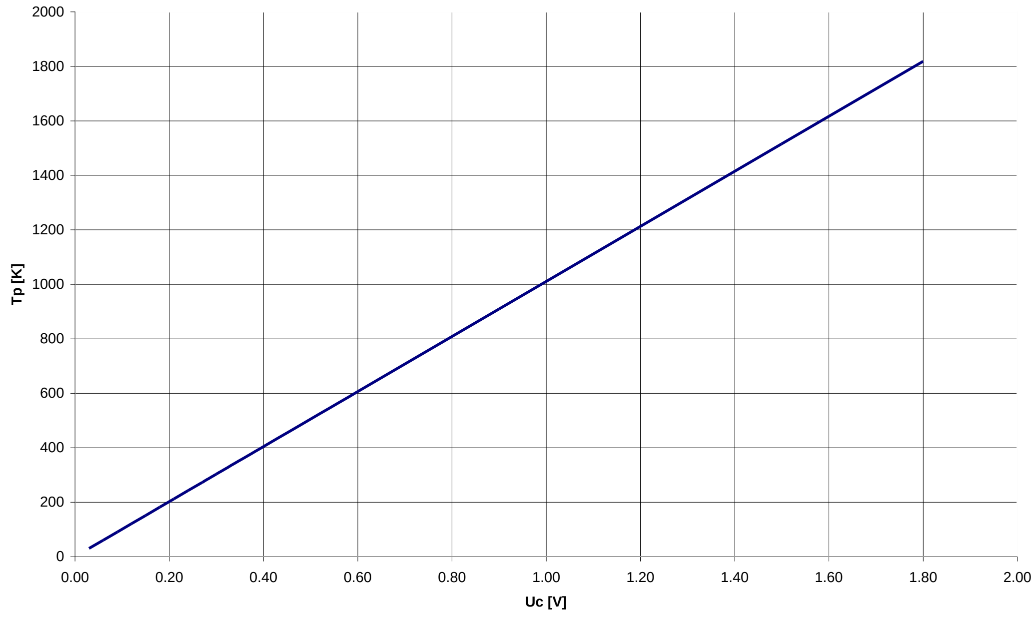


Fig. 11 The dependence of temperature of an elemental spot and the voltage drop

For example, for a nominal current of 400 A the voltage drop is 12mV and the temperature T_p is 38.34 K. This value is admissible and complies with international requirements.

4. Conclusions

The major advantage of the proposed solution is that the electrical contacts are open due to atmospheric pressure rather than an antagonist element. This constructive solution leads to increased safety and reliability in operation. The results presented in this article were created the conditions necessary for the transition to achieving physical model. The geometries of the components of the vacuum interrupter are not complicated, which facilitates their manufacture.

As the prospect of further research and development, there will be a thorough research on this type of vacuum interrupter with electrical contacts in normally open position, focusing on the testing of the physical model in order to compare the experimental results with the theoretical ones, all in the desire to obtain a commercial solution. In the first phase, will develop a type of vacuum interrupter that meet the performance of a low voltage contacts, with a rated voltage of 1000V and a ratted current of 400A.

Acknowledgment

This work was financially supported by the Executive Agency for Higher Education, Research, Development and Innovation Funding through the Financial Agreement PCCA no. 34/2012.

R E F E R E N C E S

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