STANISŁAW JAN KULAS
HENRYK SUPRONOWICZ

Loads and basic exposures of contact systems of electric switches

Insulation systems and electric contacts of electric power switches are components that are damaged most often. The electric strength to the breakdown of the electric switch contact gap is measured by the electric field intensity and the corresponding voltage at which the breakdown of the system occurs. The breakdown of the contact gap is fostered by the heterogeneity of voltage gradient. Electric contact systems in the process of currents conduction or switching are the most loaded heat elements of the current paths. They should be designed, constructed and operated in such a way that during the conduction of operating currents the prescribed value of the temperature rise limit should not be exceeded and that the contacts should not weld or deform permanently during the conduction of fault currents. The paper presents examples how to use analytical and numerical methods to evaluate the heterogeneity degree of the electric field in the contact gap. In addition, appropriate mathematical relations were given to estimate the value of the contact gap breakdown voltage. Finally, the paper discusses the factors influencing the ampacity of the contacts during the conduction of operating and short-circuit currents.

Key words: *electric strength to the breakdown of the contact gap, current exposures of contact systems*

1. INTRODUCTION

Contact systems are basic components of current circuits of electric apparatus, in particular electric switches and bus bar systems. They enable to connect operating and fault currents, ensure connections of current circuits of particular apparatuses, as well as ensure transmission and distribution of electric energy. They should be designed, produced and exploited in such a way that, in the process of switching on/off currents by contacts, the homogeneity of voltage gradient could be maintained to the highest possible degree in the contact gap. During the conduction of operating currents it is required that the admissible temperature rise in the contacts should not be exceeded. While during the conduction of fault currents the contacts should not weld or deform permanently [2, 4, 7, 9].

The paper presents examples how to use analytical and numerical methods to evaluate the heterogeneity degree of the electric field in the contact gap. In addition, the paper discusses the factors influencing the ampacity of the contacts during the conduction of operating and short-circuit currents.

2. ANALYSIS OF ELECTRIC FIELD INTENSITY

The most important quality of contact systems isolation is its electric strength to breakdowns. Dielectric strength depends on the dielectric medium temperature, waveform of voltage attached to the electrodes, pressure, configuration and material of the electrodes, condition of the electrodes surface, contaminants, etc. The electric strength of the isolation system is the electric field intensity or the corresponding voltage at which the breakdown of the system occurs. The breakdown of the contact gap of the system is fostered by the heterogeneity of voltage gradient in the analyzed space.

The analysis of electric fields in the case of uncomplicated isolation systems is conducted with the use of analytical methods. The analysis of electric fields in complex isolation systems is done by means of digital computing which makes use of the finite element method, integral equation methods, or others.

There are a number of methods useful to determine the value of the electric field intensity in the selected isolation contact systems, for example different switches. Here it is necessary to distinguish a method which makes use of Schwaiger's coefficients η. These coefficients measure the degree of the field heterogeneity in the electrode gap and describe the impact of the electrodes geometry on isolation gap dielectric strength [1, 4]. For a homogeneous field the value of the coefficient is $\eta = 1$:

$$\eta = \frac{U}{E_k d} \tag{1}$$

where:
U – voltage attached to the electrode system, kV,
E_k – critical intensity of the electric field at which there is a breakdown of the isolation gap, kV/cm,
d – gap between electrodes, cm.

In general, for the given shape of the electrodes, the coefficient η depends on the characteristic geometric coefficient p. The value of this coefficient is determined from the following dependency

$$p = \frac{s + r}{r} \tag{2}$$

where:
s – gap between electrodes, cm,
r – electrodes with bigger curvature, cm.

Figure 1 features the relation of the η coefficient with the characteristic parameter p for several shapes and configurations of electrodes [1, 4].

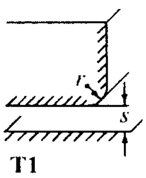
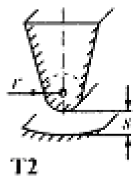
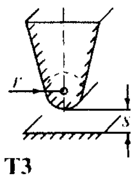
Configuration of electrodes	 T1 curved edge – plane	 T2 confocal, parabolic cylinders	 T3 hyperboloidal edge – plane
Coefficient $\eta = f(p)$	$\frac{2}{1+\sqrt{2p-3}}$	$\frac{2}{1+\sqrt{2p-1}}$	$\frac{arc\ ctg \frac{1}{\sqrt{p-1}}}{\sqrt{p-1}}$

Fig. 1. Dependence of coefficient η on the shape of electrodes

The voltage value of the contact gap breakdown, for the previously determined value of the coefficient η characteristic of the analyzed shape of the electrodes configuration, is calculated from the following formula:

$$U_p = E_k d \eta \tag{3}$$

Analytical methods prove to be useful, particularly when comparing different values of electric strength of the contact gap and also in comparing of previously selected structural features of an isolating system.

Due to more complicated geometry of contacts and higher complexity of field intensity theoretical calculations, numerical methods are used to analyze the electric field distribution in high-voltage electric contact gaps. For this reason, in order to determine the electric field intensity distribution in the contact gap and to locate contact areas with highest exposure to breakdown, the final element method is commonly used along with such programs as ANSYS, SolidWorks, Quick Field and OPERA.

Figures 2a and 2b feature sample results of the analysis of the electric field intensity in the contact gaps of tulip and conical contact systems [4, 6].

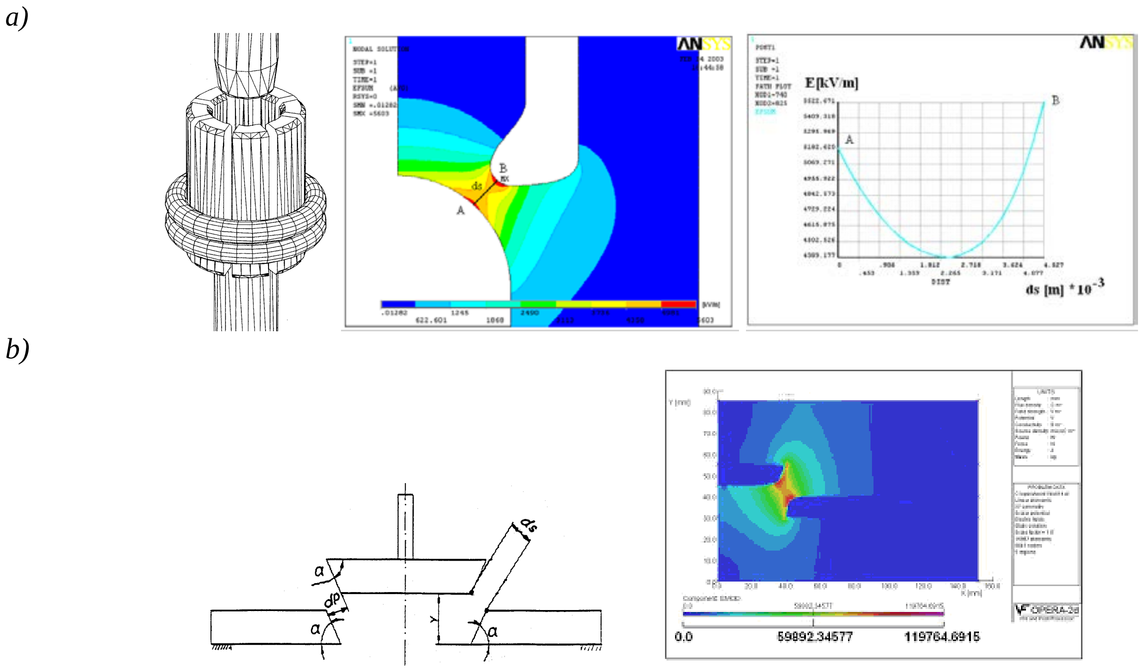


Fig. 2. Sample distributions of the electric field intensity in the gap of tulip (a) and conical (b) contacts

The conducted numerical analysis of the electric field in the contact gap proved to be useful to determine contact surfaces with the highest sensitivity to breakdown. In addition, it was observed that important structural qualities that impact the electric field distribution in the contact gap of the contact system are curvature radius of the movable contact terminal front and edge radius of the stationary contact internal contacting surface.

It was also determined that the contact angle of conical contacts has relatively small impact on the electric strength of the contact gap. The research shows that some increase in the value of the electric field intensity in the contacting surface can be observed no sooner than in the final phase of the contacts movements, before they touch each other.

Limited dielectric strength of the environments, surrounding the contacts of the closing high-voltage electric switch, results in the situation that, most frequently, switching on the current in the electric circuit does not occur due to the contacts touching each other but due to the electric breakdown of the given environment (Fig. 2.3).

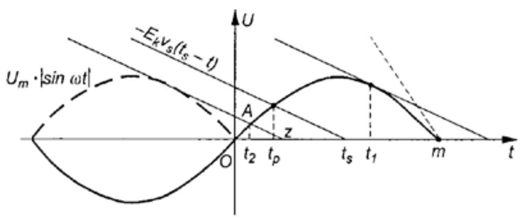


Fig. 3. Moment of arc ignition during AC current switch-on

Assuming that breakdown voltage is proportional to the distance between contacts, it is possible to determine the moment tp, when the breakdown occurs during the current switch-on, at the voltage $u = U_m \sin \omega t$, from the following dependency [4]:

$$U_m|\sin \omega t| = E_k n v_s (t_s - t_p) \tag{4}$$

E_k – value of electric field intensity at which the breakdown occurs;
v_s – speed value of the contacts convergence (contact gap decreasing) at the moment of the electric arc ignition in the contact gap,
n – number of breaks in the pole,
t_p – moment of gap breakdown,
t_s – moment of contacts touching each other.

Thus switching on the current is possible at any phase angle of the voltage, including the phase angle corresponding to the moment when the voltage passes through its zero value, provided the following condition is fulfilled:

$$k = \frac{n E_k v_s}{\omega U_m} \geq 1 \tag{5}$$

The minimal value of the contacts speed the moment they touch each other, at which there is no breakdown of the contact gap during the current switch-on in the electric circuit, can be determined from the following dependency:

$$v_s \geq \frac{\omega U_m}{n E_k} \tag{6}$$

The higher is the speed value vs of the electric switch contacts touching each other and the higher is the value of the electric field intensity E_k, the shorter is the time of the electric arc burning.

The current switching on phase in the electric circuit, the speed of the contacts touching each other and the distribution of times of the switch operations have significant impact on over-currents and over-voltages in the switched circuit.

3. CURRENT LOADS AND EXPOSURES

3.1. Ampacity of contacts

The ampacity of contacts depends on the volume of heat emitted in the contact and on the degree of intensity with which the heat is dissipated from the heated contact. The basic sources of heat losses in contact systems with current $i(t)$ are heat losses (Joule heating) generated in a heat conductor with properly shaped elements of the contact system as well as losses emitted in the contact resistance (R_p) which depends on the force of the contacts tightening, the state of their surfaces, as well as the thickness and structure of tarnish layers [1, 3, 4, 8, 10].

Theoretical analysis of contacting surfaces heating by DC current is conducted, basically, for point-type contacts. For other contact types the calculations are carried out with certain simplifications, so they describe, roughly, the contacts heating process.

Sample temperature distribution in a point-type contact is presented in Fig. 4.

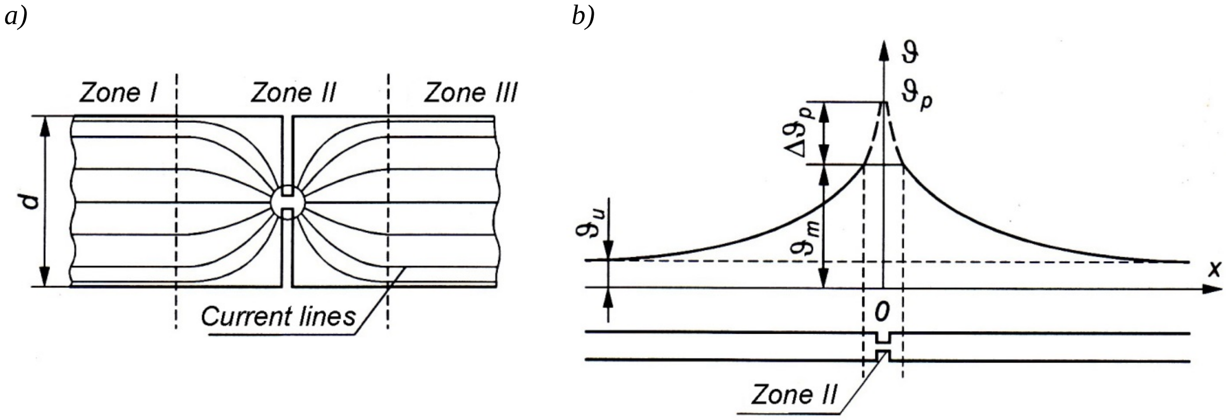


Fig. 4. Heating of current circuit with one-point contact: a) contact model, b) temperature distribution along the current circuit

Maximum temperature ϑ_m occurring in the place of the point-type contact (Fig. 3.1b) is

$$\vartheta_m = I^2\left(\frac{1}{2}R_p\frac{1}{\sqrt{\lambda AkS}}+\frac{\rho_\vartheta k_w}{SkA}\right)+\vartheta_0 \qquad (7)$$

where:

- $k_w=k_0k_z$ – current displacement coefficient equal to the product of skin effect k_0 and proximity effect k_z coefficients;
- k – coefficient of heat emission through convection and radiation, W/(m^2·K);
- ρ_ϑ – cable material resistance in temperature ϑ, Ω·m;
- ϑ_p – temperature of real contacting surface in the steady state, K;
- ϑ_u – temperature in the steady state of the current circuit, K;
- ϑ_0 – ambient temperature, K;
- λ – heat conductivity coefficient, W/m·K;
- S – surface of the cable sectional area, m^2;
- A – circuit of the cable cross section, m.

The contacts of electric switches (busbars) adapted to conduct high values of operating or instantaneous currents, are usually made of a set of many single parallel contact tips (Fig. 5).

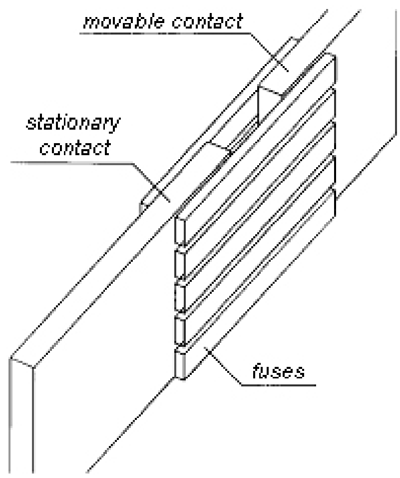


Fig. 5. Contact with parallel contact tips

Figure 3.3 features sample current distribution in particular tips of a contact made of 10 parallel tips, given in percentage values with respect to the assumed regular current distribution in tips and determined for different values of transition resistance R_p.

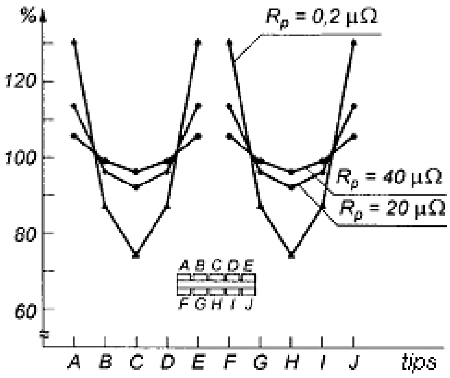


Fig. 6. Current distribution in a contact with 10 tips

Transition resistance R_p of the contact has significant impact on irregularities of current flow in particular tips. If, in the design phase of contacts, particularly silver-plated contacts of relatively small contact resistance, this impact is not taken into account, the outermost tips of the contact system may overheat.

Extra (practically unmeasurable) increase of temperature $\Delta\vartheta_p$ in the real contacting area of the contacts, which is many times smaller than their apparent contacting area, is determined for temperatures $\vartheta_p \leq 150°C$ based on the Kohlrausch-Holm dependency [7,10]:

$$\vartheta_p - \vartheta_m = \Delta\vartheta_p = \frac{\Delta U_p^2}{8\lambda\rho_\vartheta} \qquad (8)$$

where:
$\Delta U_p = IR_p$ – voltage drop on contact resistance, V;

The criteria of admissible temperature ϑ_m selection in the contacts result from the following:
- significant decrease of the contacts mechanic strength along with temperature rise (e.g. recrystallization of copper);
- decrease of the contacts tightening force;
- destabilization of contact resistance;
- shorter life cycle of isolation surrounding the contacts;
- increased leakance in isolation elements.

3.2. Short circuit thermal ampacity of contacts

During the flow of short circuit current the heating time is limited to several hundred milliseconds. The temperature increase $\Delta\vartheta_p$ related to a very small weight of the contacting micro-area (with a time constant of singular microseconds) keeps pace with the changes of the short circuit current [4, 11], exceeding, successively, the softening point ϑ_{mk} and melting point ϑ_t of the contacts material.

Exceeding the melting point in the place where the contacts touch each other results in a bigger surface of this place, lower resistance of the contraction, slower pace of the touch-point temperature following the current changes, and, finally, welding of the contacts [2, 5].

Each flow of short circuit current through the contact or contact system in the connecting process leaves traces in the places of galvanic contact in the form of local smelting points whose size and number depend on the current intensity, duration of current flow, and intensity of the electric arc impact on the contacts surfaces (Fig. 7).

Ag *Cu* *W*

Fig. 7. Sample macrographs of contacts surfaces after short-time impact of electric arc

The analysis of the conditions of short circuit currents conduction through high-current contact systems proves that the contacts are, more and more frequently, loaded with current impulses with high rate of rise. Time waveforms of these currents, particularly the rate of rise of current impulses which enhances the skin effect, significantly impact the value of the contacts welding current. This impact was confirmed by experiments related to welding of different types of contacts [5].

The complexity of the welding phenomenon, and the resulting difficulties in theoretical determination of welding current values in these specific conditions, call for numerous experimental tests. Their objective is to determine suitable empirical coefficients that would enable to determine analytically the value of the contacts welding current.

Sample oscillograms of contacts welding current tests can be seen in Fig. 8.

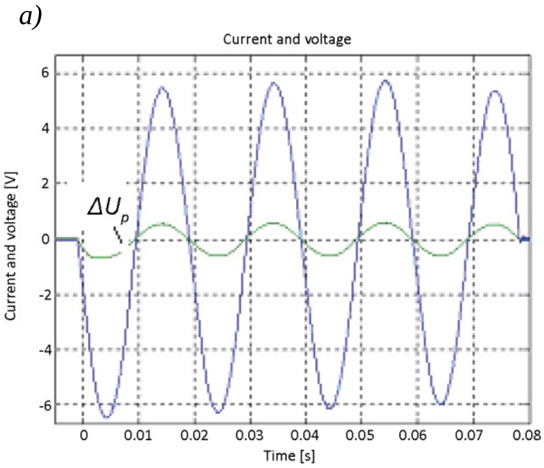


Fig. 8. Current waveforms and voltage drop waveforms on a point copper contact achieved in: a) short circuit, b) condenser batteries

On the waveform depicting voltage drop on the contact it is possible to see a welding point in the first half of the current sine wave. This results both in the distortion of the first half of the voltage sine weave and the reduction of the voltage drop value on the contact during the flow of successive half waves.

The conducted experiments to determine the value of welding current for different types of contacts were the basis to formulate a proper dependency according to which the rate of rise, current impulse duration and forces of the contacts tightening impact the value of this current.

$$i_s = \sqrt{\frac{192 c_0 \ln(1+\frac{2}{3}\alpha\vartheta_s)}{\pi^4 \alpha H^2 \rho_0}} \frac{F_{doc}}{\sqrt{t}} n \left[1+\left(\frac{S_{50}}{S_x}\right)^{\varsigma}\right]^{\kappa} \qquad (9)$$

where:

- n – coefficient depending on the contact type; point contact n = 1, linear contact n = 2, surface contact n = 3;
- S_{50} , S_x – rates of rise of short circuit currents corresponding to the frequency of 50 Hz as well as rates of rise of particular current impulses;
- ζ i κ – coefficients characteristic of particular types of contacts; they were determined on the basis of the conducted tests.

The value of the coefficient κ, which depends on the tightening force of the contacts F_{doc}, can be determined for copper and brass contacts from dependency

$$\kappa = -0.004 F_{doc} + 2.9 \qquad (10)$$

while the value of the coefficient ζ for this type of contacts can be assumed as stable and is equal to 0.36.

The value of limiting welding current i_s is an important criterion to assess the contact system. It depends, first of all, on the resultant force which tightens the contacts during the flow of short circuit current, on the number of tips, and the time waveform of the current, particularly its rate of rise.

4. CONCLUSIONS

The article features sample applications of analytical and numerical methods to assess the degree of heterogeneity of the electric field in contact gaps. In addition, mathematical dependencies were given which enable to assess the value of the contact gap breakdown voltage. Based on the conducted experiments, the following conclusions can be drawn:

1. Contacts of electric energy devices are the most thermally loaded elements of current circuits.
2. They should be designed, constructed and operated in such a way that during the conduction of operating currents the prescribed values of the tem-

perature rise limit should not be exceeded and that the contacts should not weld or deform permanently during the conduction of fault currents.

3. Regular diagnosing of contact systems is indispensable to ensure reliable power supply to clients. It enables to lengthen the times between the contacts check-ups, prevents failures, and allows to detect non-standard technical condition of the contacts.
4. New solutions of computer-aided contact systems and connecting apparatus technologies are the answer to the requirements of the power engineering industry in terms of not only reliability but also expected minimal exploitation costs.

References

1. Au A., Maksymiuk J., Pochanke Z.: Podstawy obliczeń aparatów elektroenergetycznych (Calculation basis of electric energy apparatus), WNT, Warszawa 1982.
2. Borkowski P.: Erozja łukowa styków łączników elektrycznych (Arc erosion of electric contacts), WPŁ, Łódź 2013.
3. Ciok Z., Maksymiuk J., Kulas S.,Ægliński K.: Problemy analizy, badania oraz eksploatacji urządzeń rozdzielczych, (Analysis, testing and exploitation of switchgear devices); National Symposium: Electric Switchgear Apparatus, EAR’2004, Poznań 2004, pp. 9-18.
4. Kulas S.: Tory prądowe i układy zestykowe (Current circuits and contact systems), OWPW, Warszawa 2008.
5. Kulas S., Zgliński K.: Badania sczepiania się zestyków wielkoprądowych (Welding of high current contacts), Scientific conference: Developments in applied telecommunications, Kościelisko 2007, pp. 77-79.
6. Kulas S., Kolimas Ł.: Optimization of electric field in contacts on example of making switch, Proceedings of the 42th International Universities Power Engineering Conference, Brighton, 2007, pp. 491-495
7. Maksymiuk J., Nowicki J.: Aparaty elektryczne i rozdzielnice (Electric apparatus and assemblies), OWPW, Warszawa 2014.
8. Markiewicz H.: Urządzenia elektroenergetyczne (Electric power devices), WNT, Warszawa 2001.
9. Shoffa V.N., Miedzinski B.: Sinkhronnaya komutatsya gerkonami electritcheskih tsepey peremennovo toka, Proc. 3rd Int. Conf. on “REED Switches and Products”, Ryazan, Russia, 2011, pp. 48-60.
10. Slade P.: Electrical contacts, Marcel Dekker Inc., New York 1999.
11. Walczuk E.: Resistance and temperature variations of heavy current contacts in welding conditions, Proc. of the Tenth Int. Conf. on Electrical Contact Phenomena (ICECP’80), Budapest 1980, pp. 367-375.

STANISŁAW KULAS, Ph.D., D.Sc., Professor
HENRYK SUPRONOWICZ, Ph.D., D.Sc., Professor
Institute of Electronic Systems,
Military University of Technology
ul. gen. Sylwestra Kaliskiego 2, 00-908 Warsaw, Poland
{stanislaw.kulas, supronowicz}@wat.edu.pl