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A new method of determining a new discharge channel time point in a switching arc

Abstract *The results of a computer simulation of new discharge channels formation and their decay in alternating current arcs of I_{max} = 500 A in atmospheric pressure, taking into account the magnetohydrodynamic model of an electric arc are used to develop a method of determining a new discharge channel time point, based on the analysis of the distribution of the product of the electric field and temperature.*

Streszczenie *Wyniki komputerowej symulacji powstawania nowych i zanikania starych kanałów wyładowczych w łukach prądu przemiennego I_{max} = 500 A, palących się w powietrzu o ciśnieniu atmosferycznym, przy wykorzystaniu magnetohydrodynamicznego opisu modelu łuku, wykorzystano do opracowania metody określenia czasu pojawienia się tych kanałów, opartej na analizie rozkładu iloczynu pola elektrycznego i temperatury (**Nowa metoda określenia czasu pojawiania się nowych kanałów wyładowczych w łuku łączeniowym**).*

Keywords: switching arc, switches, MHD, simulations.
Słowa kluczowe: łuk łączeniowy, wyłączniki, MHD, symulacje

Introduction

A broad analysis of foreign literature (over 50 publications) on computer simulations of the process of switching arc burning in contact - extinguishing systems of switches is presented in paper [1]. One can note a rapid progress of research on this topic in recent years, due to the development of professional computer packages, which allows a detailed analysis of the phenomenon using a magnetohydrodynamic arc model. At the same time, we have noted that in these publications there is not enough space devoted to the phenomenon of new discharge channels formation and their decay during a switching cycle, when an arc passes through the contacts and arc extinguishing horns move towards the extinguishing chamber. Step changes of an arc shape observed while taking photographs of a contact arc are shown in Figure 1.

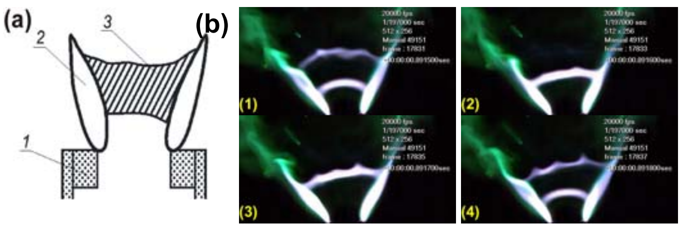


Figure 1. Contacts 1 with plasma streams 2 and a discharge channel 3, connecting the plasma streams: a) Diagram; b) Subsequent frames 1÷4 in a model system (exposure time of 50 μs, 100 μs interval) illustrating the formation of a new discharge channel between the plasma streams

There are only few publications concerning switching arc simulations that describe how a discontinuous motion of discharge channels was simulated. Therefore, it was decided to thoroughly analyse this particular issue and selected materials from that analysis were presented in [1-4]. The analysis of those test results to accurately determine the number of arc parameters, such as the distribution of temperature, current density, velocity, mass, etc. at each point of an arc was possible due to the use of modern computer packages. In this paper, a proposal is made to determine the time of formation of a new discharge channel, taking into account a rapid change in the product of the electric field and temperature.

Arc model

The phenomenon of discharge channel displacement in an AC 500 A arc burning freely in the air, investigated experimentally [2] and described widely in [3], was modeled, using an electrode arrangement as shown in Fig. 2. The modeling and simulation of the investigated phenomenon was carried out with the Ansys Fluent package. Using the program, a system of magnetohydrodynamic equations can be solved by connecting electromagnetic field equations with Navier-Stokes flow equations in a control volume.

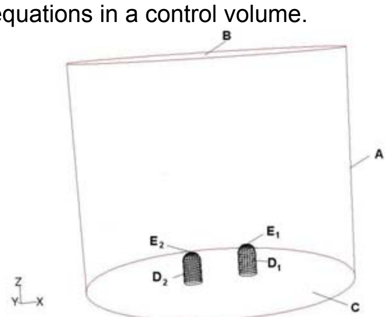
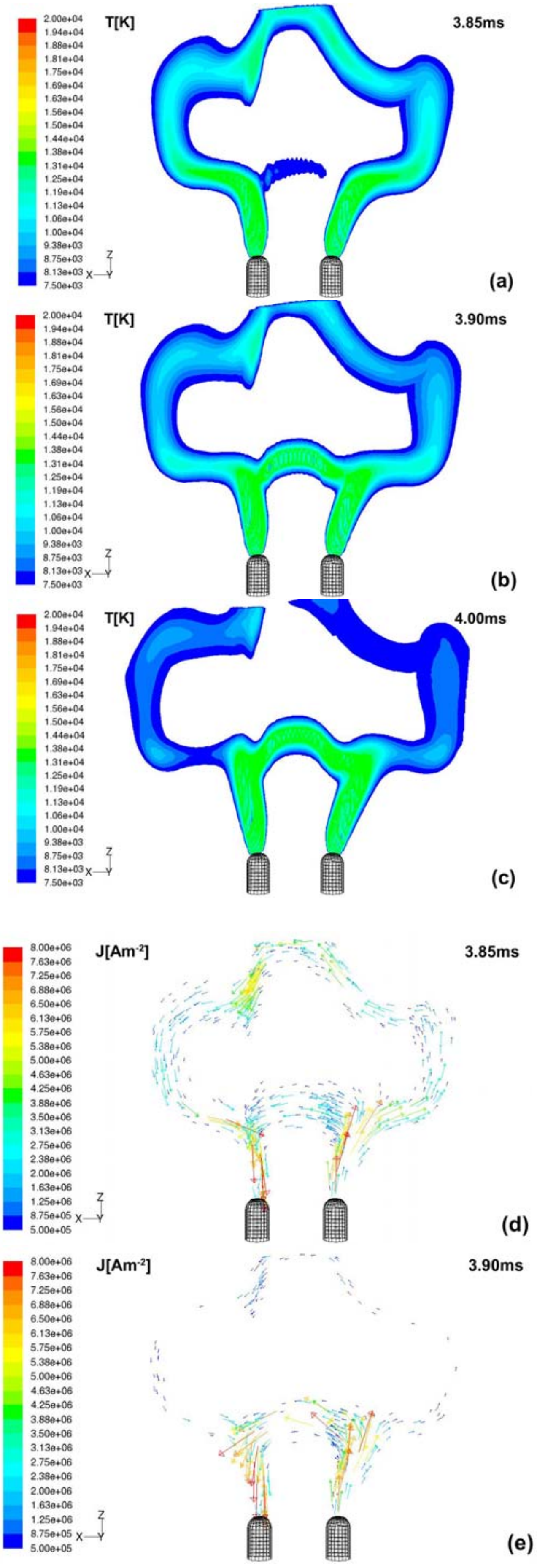


Fig. 2. The modeled arrangement of parallel electrodes. A, B, C – surfaces determining the limit surfaces; E_1, E_2 – the surfaces of electrode tips, D_1, D_2 – the lateral surfaces of the electrodes

Additional equations, self-developed by the user (user-defined functions), which take account of the presence of an electromagnetic field, having the form of subroutines, were appended to general transportation equations which are solved by the Ansys Fluent package, such as the equations of mass, energy and momentum conservation. In order to consider a current flow field in an arc, it is necessary to include additional heat sources into the equations of momentum and energy conservation, i.e. Joule heat, as well as energy losses, associated with radiation from the arc core. The component of the Lorentz force was also added to the equations of momentum conservation to take account of a self-induced magnetic field.

For an arc model presented in a 3-D Cartesian coordinate system in the non-stationary state, all equations of mass, momentum and energy can be written in the form as proposed by Patankar [5]:

$$\underbrace{\frac{\partial}{\partial t}(\rho\phi)}_{\substack{time\\component}} + \vec{\nabla}\cdot\underbrace{(\rho\vec{\upsilon}\phi)}_{\substack{convection\\component}} = \vec{\nabla}\cdot\underbrace{\left(\Gamma_\phi\vec{\nabla}\phi\right)}_{\substack{diffusion\\component}} + \underbrace{S_\phi}_{\substack{source\\component}}$$



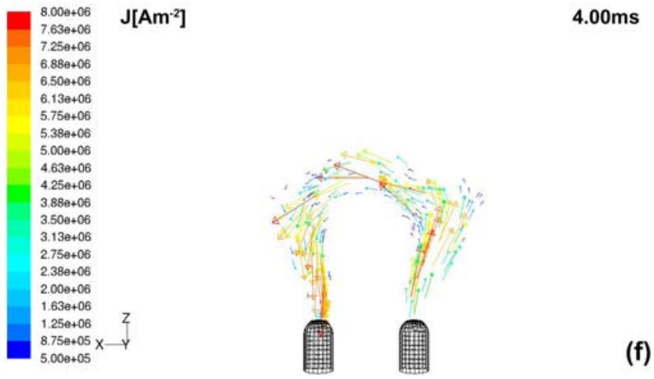


Fig. 3. Selected frames of computer simulation of an AC electric arc burning freely in the air at I_{max} = 500A, at atmospheric pressure, during one current half-period. Temperature distributions are shown on the left side (a,b,c) and the corresponding pictures of current density vectors (d,e,f) at times t =3.85 ms, t =3.90 ms and t = 4.00 ms are shown on the right side, respectively

Fig. 3 shows selected frames of computer simulation of an AC electric arc burning freely in the air at I_{max} = 500 A, 50 Hz, at atmospheric pressure, during one current half-period. Temperature distributions are shown on the left side with corresponding pictures of current density vectors on the right side, for respective times t = 3.85 ms; 3.90 ms and 4.00 ms. The pictures present successive phases of discharge development and the formation of a new discharge channel between plasma jets. It is evident in Figures 3a and 3b that a new discharge channel was formed between the plasma jets below the channel which conducted current a while before. It amounts to the appearance of current in the new channel and the decay of current flow in the previous channel (Figures 3c and 3f).

Such an occurrence and the decay of the plasma jet-coupling channel is repeated many times during every current half-period. Each newly formed channel took the form of a high-current arc channel and moved very fast along the plasma streams upwards, being mainly pushed by electrodynamic forces, induced by arc current and its own magnetic field, resulting from the geometry of the current circuit and the arc loop. One gets an impression (also from the photographic observations) that “a luminous temperature cloud” jumped to a different place but, in fact, it was the plasma status which changed, and new distributions of temperature, as well as mass velocity values were formed for different instants.

As it appears from Fig. 4, mass velocity distributions along the model axis are dislocated in time and the maximum values of dislocation speed determine the positions of the plasma stream-coupling discharge channel. Between the time points of 3.5 ms and 3.8 ms, the maximum speed values are dislocated along the model axis and, subsequently, the maximum mass velocity decreases, reaching the following values at the designated time points: 250 m/s, 230 m/s, 175 m/s and 120 m/s. A new discharge channel becomes visible between the time points of 3.8 ms and 3.9 ms (the time point of 3.85 ms in Figure 3), and then the maximum mass velocity values (see Figure 4) at the distance of 0.08 m start falling in time, while, subsequently, the maximum mass velocity values at the distance of approximately 0.035 m start rising at the time point of 3.8 ms to about 135 m/s at 3.9 ms. The shapes of temperature and current density distributions are very similar to mass distributions for different instants.

It is evident from Fig. 5 that a new temperature maximum starts its formation about 35 mm above the tips of the electrodes at 3.7 ms and increases slowly up to 3.8 ms from the current zero passage. Between the instants of 3.8 ms and 3.9 ms the temperature maximum rises rapidly. Changes in temperature calculated every 20 μs between the time points of 3.8 ms and 3.9 ms are presented in Figure 6. One can see that this rapid rise in temperature does not begin at the time of 3.8 ms, but between the time points of 3.84 and 3.86 ms. This may be due to the fact that the temperature of approximately 6200 K is achieved, which is, by convention, the value assumed by some scientists as the temperature of discharge formation in air at atmospheric pressure.

One can correlate this phenomenon to the beginning of a new discharge channel formation which takes over current conduction (Figure 3).

As it can be seen, current density variations are correlated with temperature variations (Figures 7 and 8). It shows that the new current density maximum (10^6 A/m^2) appears at the time point of 3.8 ms, 31 mm over the tips of the electrodes, reaching $1.4{\cdot}10^6$ A/m^2 at the instant of 3.82 ms and $1.9\cdot10^6$ A/m^2 at the instant of 3.84 ms, about 33 mm above the electrode tip. It increases its value to $1.05{\cdot}10^7$ A/m^2 at the instant of 3.9 ms, 37 mm above the electrode tip.

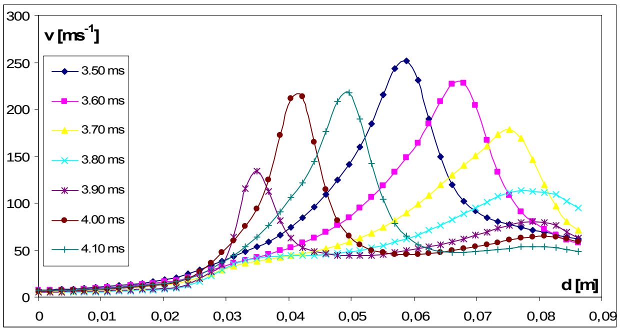


Fig. 4. Mass velocity distribution on the electrode arrangement model axis at time intervals from 3.50 ms to 4.10 ms

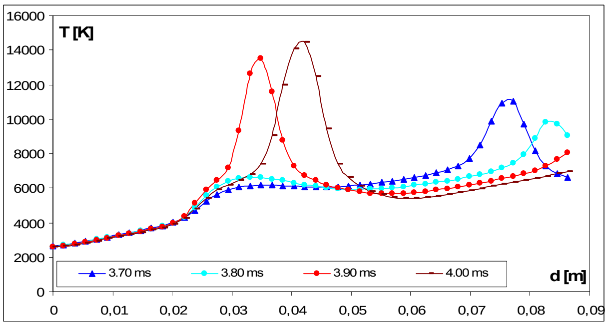


Fig. 5. Temperature distribution on the electrode arrangement model axis at time intervals from 3.70 ms to 4.00 ms.

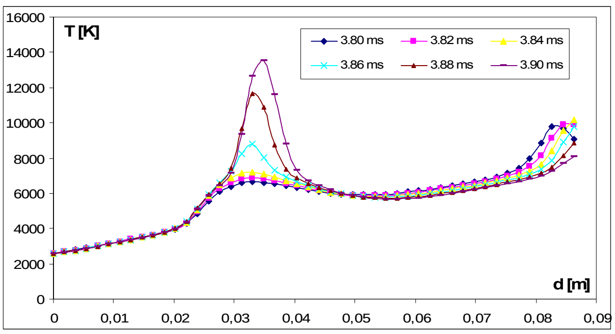


Fig. 6. Temperature distribution on the electrode arrangement model axis at time intervals from 3.80 ms to 3.90 ms

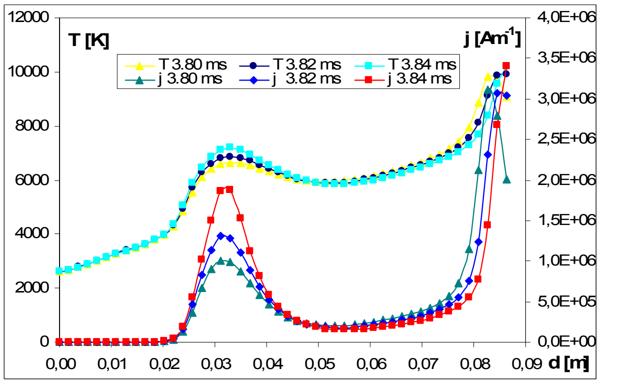


Fig. 7. Temperature and current density distribution on the electrode arrangement model axis at time intervals from 3.80 ms to 3.84 ms

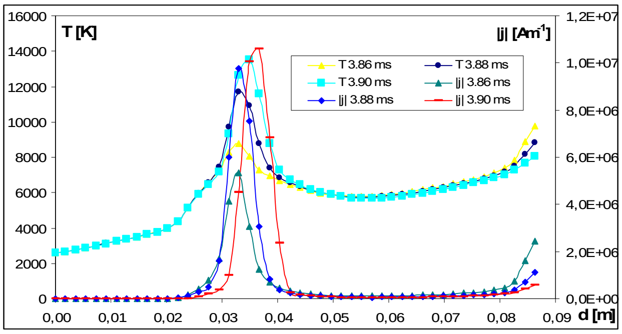


Fig. 8. Temperature and current density distribution on the electrode arrangement model axis at time intervals from 3.86 ms to 3.90 ms

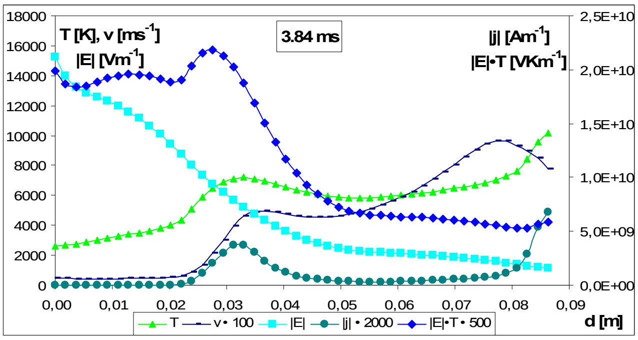


Fig. 9. Temperature T, mass velocity v, strength of the electric field E, current density distribution j, strength of the electric field and temperature product |E|•T on the electrode arrangement model axis at the time point of 3.84 ms

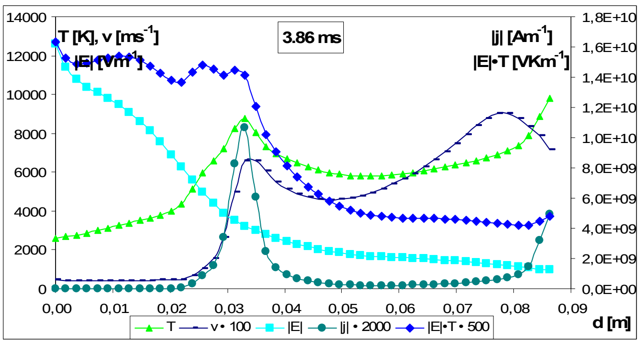


Fig. 10. Temperature T, mass velocity v, strength of the electric field E, current density distribution j, strength of the electric field and temperature product |E|•T on the electrode arrangement model axis at the time point of 3.86 ms

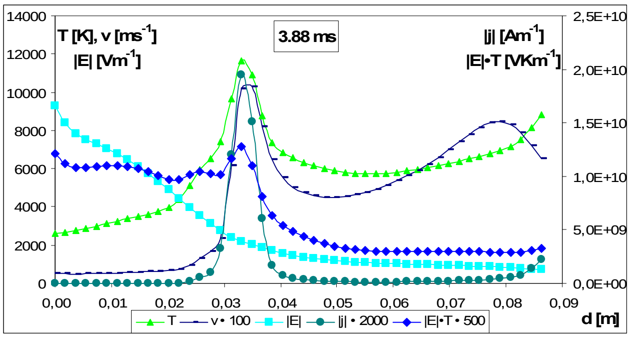


Fig. 11. Temperature T, mass velocity v, strength of the electric field E, current density distribution j, strength of the electric field and temperature product |E|•T on the electrode arrangement model axis at the time point of 3.88 ms

The phenomenon of new discharge channels formation can also be associated with the course of the product of electric field intensity and temperature |E|•T (Figures 9÷11). New discharge channels formation is combined with a rapid reduction of |E|•T product from about 12 000 at 3.86 ms (Figure 10) to about 6 000 at 3.88 ms (Figure 11).

Conclusions

Attempts to determine the time of new discharge channels formation between plasma jets, based on the analysis of test results with the use of high speed photography consist in determining a sudden increase in the brightness of the area between the plasma jets and a change in arc voltage. This is not accurate, because the brightness of this area is dependent on test conditions (e.g. speed shooting, exposure time, aperture, filter type, etc.) and there is not sharply drawn arc voltage change. An analysis of the results of computer simulations of the new discharge channel formation between the plasma jets makes it possible to determine the moment more precisely. An analysis of velocity, temperature or current density distributions indicates that the new discharge channel formation begins after thermo-electric conditions are met at a certain point of the switching arc. Searching for more distinctive signals of a new discharge channel formation time point, a diagram has been designed, presenting the distribution of the product of electric field intensity and temperature along a model axis. It appears from an analysis of the product and other discharge parameters that, in the discussed case, the time point of a new discharge channel can be defined as the point between 3.86 ms and 3.88 ms, at which a rapid reduction of |E|•T product occurs on the model axis in the space between the electrodes and the new discharge channel.

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