Witold TARCZYNSKI[1], Tomasz DASZKIEWICZ

Lodz University of Technology (1), Department of Electrical Apparatus

Switching arc simulation

Abstract. *This paper is a general review of research studies with computer simulations of electric arc in electric circuit breakers, taking into account the magnetohydrodynamic model of electric arc and there are described the formation and the decay of discharge channels in alternating current arcs of I_{max} = 500 A in atmospheric pressure and in a model system, designed with the ANSYS-Fluent software. Diagrams of mass velocity, temperature and current density distributions are presented. An ultra-fast digital camera (20 000 frames/s) was used in the experimental studies.*

*Streszczenie: W artykule przedstawiono przegląd badań dotyczących komputerowej symulacji łuku łączeniowego w wyłącznikach, przy wykorzystaniu magnetohydrodynamicznego opisu modelu łuku. Opisano też powstawanie nowych i zanikania starych kanałów wyładowczych w łukach prądu przemiennego I_{max} = 500 A, palących się w powietrzu (ciśnienie atmosferyczne), w czasie symulacji palenia się łuku. Podano wykresy rozkładów prędkości masy, temperatury i gęstości prądu. W eksperymentach zastosowano ultra-szybką kamerę filmową (20 000 k/s) (**Symulacja łuku łączeniowego**).*

Keywords: switching arc, circuit breaker, MHD, simulation.
Słowa kluczowe: łuk łączeniowy, wyłączniki, MHD, symulacje.

Introduction

The attempts, undertaken by designers of electric contact circuit breakers, reveal a tendency towards solutions in which electric arc will be forced to leave breaker contacts as soon as possible to diminish their damage and to be rapidly dislocated to an extinguishing chamber, where it will eventually be extinguished, ensuring complete circuit breaking. Therefore, intensive endeavours are undertaken to find an optimal design for contact circuit breakers, which will ensure expected arc velocity. In order to achieve the goal, the mechanism of arc burning has for years been subject of studies, including the conditions for arc motion in contact-extinguishing systems, at first experimentally. Recently, computer simulations, which reveal a very intensive progress, provide a chance to improve and accelerate circuit breaker design projects, with gradual reduction of associated costs.

Switching arc belongs to events of high complexity, due to the process of high-current arc burning in various circuit breaker areas, including contacts, arc extinguishing horns and the extinguishing chamber in one switching cycle. In arc motion modelling, various approximations are employed, dividing the process into selected time intervals, simplifying the contact-extinguishing system geometry, etc. The researchers, involved in studies on switching arc, have for years intuitively been bound to associate arc motion with hot matter motion. Even recently, switching arc motion was presented in assumed models as motion of a massive rod [1,2], the diameter of which was most often based on photographic records. Motion parameters (velocity and distance) were calculated from mass motion equations, assuming motion resistance coefficients, characteristic for massive rods or determined in experiments. The high dynamics of switching arc burning and turbulent episodes provided for different direct current arc motion coefficients, depending on actual test conditions. That issue became even more complex with switching arcs of alternating current, for which the motion resistance coefficient varied with the time of current half-period [3]. That issue is additionally complicated when the, so-called, „backward arc ignitions" are analysed; these arc ignitions occur in electric circuit breakers and are equivalent to rapid, rush motion of arc on extinguishing horns or between plasma streams [4]. Such an arc motion precludes the use of massive rod model for simulation of the whole arc motion process. That is why, already several years ago, the first reports described the use of magnetohydrodynamic equations to describe switching arc burning process. The most extensive review of reports, dedicated to arc simulation in circuit breakers and based on magnetohydrodynamic descriptions, was presented by Daszkiewicz [5]. The material, compiled by the author, provided an input for the literature review, concerning the issue and presented in this paper. While evaluating that material, it appears that more and more complex digital models of switching arc have been designed during recent years, involving multi-parameter mathematical descriptions of events, processed on powerful computers with the use of newly designed and continuously upgraded commercial software packages of CFD type. All this powerful apparatus enables an analysis of complex MHD descriptions of plasma flows in switching arc.

Computer simulation of events associated with electric arc in circuit breaker contact-extinguishing systems

At first, some researchers, involved in studies on electric arc, designed individually tailored computer programs. Chevrier et al [6-12] belonged to that group, having performed 2D simulation of electric arc by means of their own programs and for the need of the Department of Research & Development of the Schneider Electric Group and having verified the experimentally obtained calculation results.

Arc motion was also studied by the authors of [13,14], who used the NS2 simulation program, designed at the Schneider Company and based on Navier-Stockes and Biot-Savart's equations. They compared 2D simulation results with the measurements of voltage and current and of pressure and temperature in a model of high-current circuit-breaker with extinguishing plates.

Lindmayer et al. [15,21] belong to the pioneers of studies, using commercial computer programmes of CFD type. The correlations, which are observed among the values, characterising arc plasma dynamics, and the organisation of magnetohydrodynamic calculations of plasma flow have been presented by the authors as block diagrams.

Using CFD 3D packages, the authors of [15,21] analysed such events and processes, as the complex joint action of electric forces, current flow, gas flow, heat conductivity and radiation in simple extinguishing systems, using sometimes ferromagnetic materials to

The title of the work [17] may suggest that the problem of simulation arc motion in low-voltage circuit breakers has completely been solved but; for example, there is no information how the issue of electrode vaporisation is accounted in plasma flow. Besides, there is also a statement in the conclusion that discontinuous arc motion occurred in the experiments, which could not be mapped by simulation, while arc motion was simulated in an extinguishing chamber of simple design, without arc-splitting plates.

Such a backward motion of the anode foot along the electrode was noted by Swierczynski et al. during performed simulation [22,23]. The authors carried out 3D arc simulations in a very simple model of low-voltage circuit breaker, comprising parallel extinguishing horns and a few plates in an open chamber, by means of the Fluent software, modified in such a way as to account for both the effects of arc field and of the field from the two parallel electrodes (the extinguishing horns).

Anheuser et al [25] simulated arc motion on a magnetohydrodynamic model of plasma flow, using Fluent and ANSYS software packages, connected by means of a mesh based parallel code coupling interface (MpCCI). The extinguishing chamber model of 40 mm in length, 30 mm in height and 25 mm wide contained 5 arc-splitting plates and was tested in a low-voltage circuit of expected current I = 10 kA. Comparative tests were also performed by a videocamera (exposure time t = 75 μs).

The [24] study can be regarded as an introduction to publication [25].

Also Reichert et al [26,27] analysed arc motion dynamics in low-voltage circuit breakers. They performed simulation calculations for a model, containing electrodes in a form of two parallel bus bars without arc-splitting plates. They compared the results of simulations, obtained by the Fluent and ANSYS software packages, connected with each other by an MpCCI platform.

Baudoin et al. [28] evaluated arc behaviour in a model switch, contactor and circuit breaker, using a 3D model for 50 A current of arc burning in the air.

In another publication, Baudoin et al. [29] analysed simulation studies of arc feet movement along electrodes for arc current of 300 A.

The recent years have brought an additional interest in the research, associated with magnetohydrodynamic description of plasma flow in switching arc, and revealed not only at research centres in Germany and France but also in China [31-49]. In those publications, simulation calculations of arc motion were usually performed with the Fluent software or Phoenics software, using the magnetohydrodynamic module, provided in the package.

Recently, a more complex approach can be observed, regarding the issue of switching process simulation [43]. In general, it can be said that simulation tool provide more and more possibilities to explain the complex nature of arc behaviours and of their effect on designed circuit breaker parameters [44-51]. Very little attention was paid by the authors to step arc motion, often recorded during switching arc studies with ultrafast cameras. Arc length shortening, associated with arc step returns (back motion) in the extinguishing systems of circuit breakers constrains, and sometimes even precludes arc extinguishing and circuit breaking. A thorough analysis of that phenomenon became possible only after design of its computer simulation [5], [52,53]. Selected issues of that analysis are presented below.

Step arc shape

Step changes of arc shape can be observed during filming records, both in contact arc (Fig. 1) and during its motion on extinguishing horns. As it appears from performed experiments, a high mobility of the discharge channel in space (rising with current increase) causes that, very often, arc does not burn in one plane. Plasma streams, emerging from electrodes, move in various directions and the channel, which connects them, presents with twisted shapes, what may facilitate the formation of new discharge channels. They may occur either in the plane, in which the contacts are located (Fig. 1), or in other planes, e.g., in a perpendicular plane.

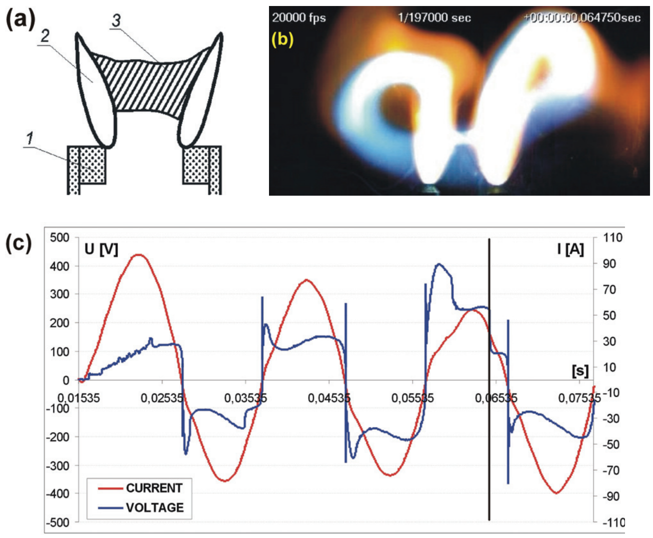

Fig. 1. Contacts 1 with plasma streams 2 and discharge channel 3, connecting plasma streams: a) Diagram; b) a photo in a model system with filming speed of 20 000 frame/s and exposure time of 50 μs, illustrating the formation of a new channel between plasma streams c) an oscillograph current and voltage records with an indicated time point, corresponding to frame b)

It appears from experimental results that a flat photo (2D) does not provide real arc images, giving their flat approximations only. In this case, the events in the photo plane are clearly visible, while those, occurring in the plane perpendicular to the filming plane, remain invisible.

Such a problem is out of question in 3D computer simulations. Moreover, such simulations considerably extends the range of data which can be obtained from such studies.

3D computer simulation is a powerful study tool, fairly comparable to CT in medicine. The parameters of studied object can be displayed at each analysed point of the calculation space. Such a huge supremacy of computer simulations over film recording has recently brought about an intensive push, highly increasing the interest in the digital mode.

However, it appears from a literature review that researchers, having the new technique at hand, have not yet thoroughly analysed the step dislocation of discharge channels in switching arc. Some authors used to notice that, during computer simulations, no step arc dislocation could be identified for the cases in which such dislocations had previously been experimentally recorded.

There are few reports only, concerning switching arc simulations, in which discontinuous motion of discharge channels was recorded. Therefore, it was decided to thoroughly analyse this particular issue [5], [52,53] and selected materials from that analysis are presented below.

Test results

The analysis concerns computer simulation of alternating current arc in a model system, corresponding to the case, described in [53]. In that paper, there are given results of computer simulation of AC free-burning electric arc at I_{max} = 800 A, 50 Hz in the air at atmospheric pressure, for one current half-period. Here, Figure 2 shows the selected frames of computer simulation of the arc at I_{max}

= 500 A and for the others time points. Temperature distributions are shown on the left side with the corresponding pictures of current density vectors on the right side for respective times t = 3.85 ms and 3.90 ms. The pictures present the successive phases of arc column development and the forming of a new discharge channel between plasma jets. It is evident in Figures 2a and 2b that a new discharge channel was formed between plasma jets below the channel, which conducted current a while before. It amounts to the appearance of a current in the new channel and decay of current flow in the previous channel.

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

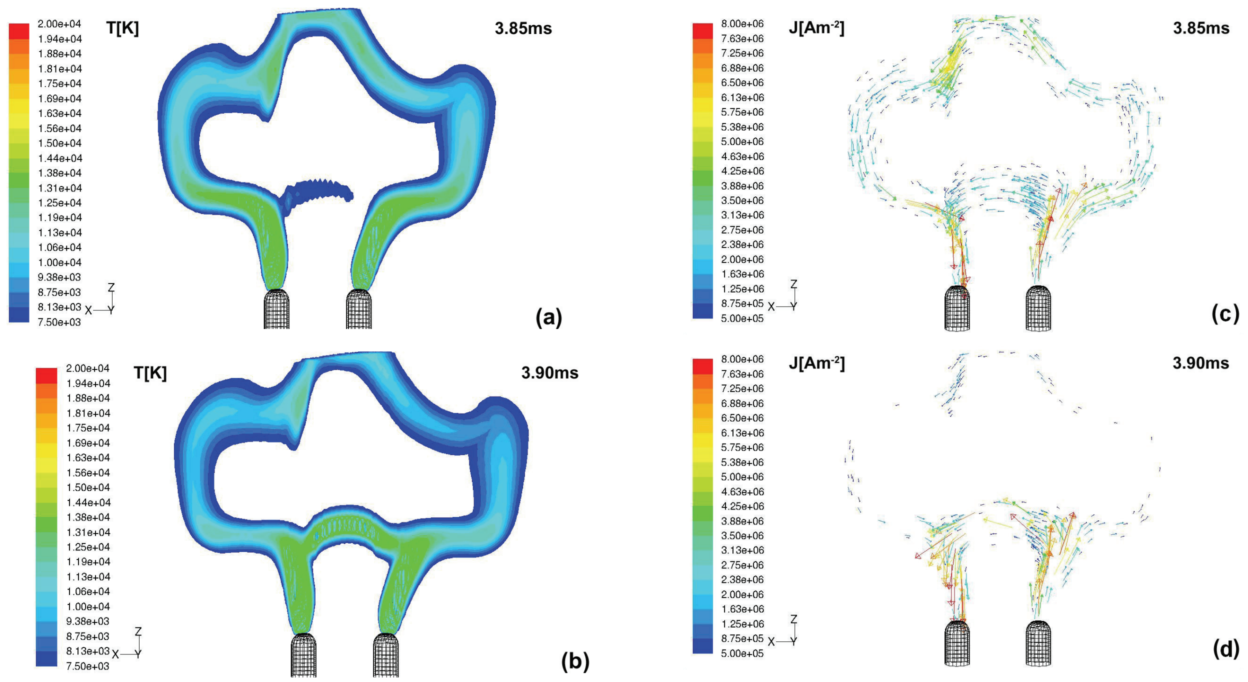

Fig. 2. Selected frames of computer simulation of AC electric arc at I_{max} = 500A, burning freely in the air at atmospheric pressure, for one current half-period. Temperature distributions are shown on the left side, and next the corresponding pictures of current density vectors at times t =3.85 ms and t =3.90 ms, respectively

Each new discharge channel formation between plasma streams is reflected by arc voltage reduction (see Figures 3). In the course of the newly formed channel dislocation between plasma streams upwards, arc voltage is growing till the time, when a new discharge channel is formed below, causing subsequent voltage drop.

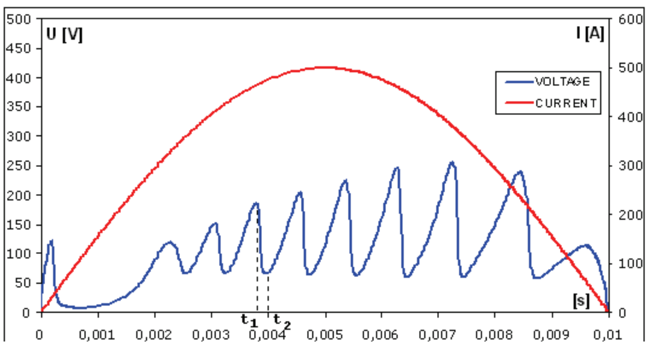

Fig. 3. Simulated course of arc voltage and current with an indicated t_1 and t_2 time range, within which a new discharge channel is formed between plasma streams, see Figure 2

As it appears from Figure 4, mass velocity distributions along model axis, dislocate in time and the maximal values of dislocation speed determine the positions of the plasma stream-coupling discharge channel. Between 3.5 ms and 4.1 ms time points, the maximal speed values dislocate along model axis and – subsequently – the maximal mass velocity decreases, reaching at designated time points the following values: 250 m/s, 230 m/s, 175 m/s, 120 m/s.

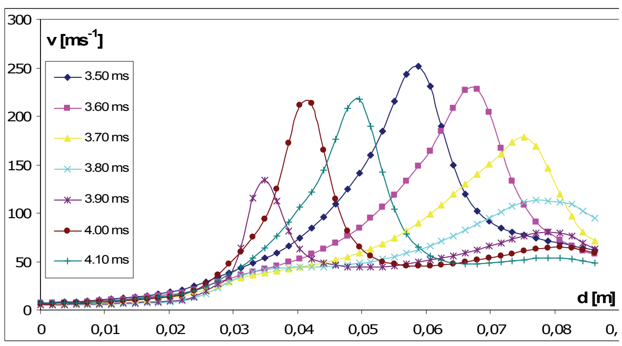

Fig. 4. Mass velocity distribution on the electrode arrangement model axis at time intervals from 3.50 ms to 4.10 ms

Between 3.8 ms and 3.9 ms time points, a new discharge channel becomes visible (3.85 ms time point in Figure 2) and then, the maximal mass velocity values (see Figure 4) in 0.08 m distance start falling in time, while subsequently, the maximal mass velocity values at approximately 0.035 m distance start rising at the time point of 3.8 ms to about 135 m/s at 3.9 ms.

One can correlate this phenomenon to the appearance of a new discharge channel, which takes over a current conduction (Fig. 2). As one can see current density variations are correlated with temperature variations (e.g. Figure 5). They show that the new current density maximum (10^6 A/m^2) appears at 3.8 ms time point at 31 mm over the tips of electrodes, attaining 1.4 $\cdot 10^6$ A/m^2 at instant 3.82 ms, and 1.9 $\cdot 10^6$ A/m^2 at instant 3.84 ms about 33 mm above the electrode tip. It increases its value to $1.05 \cdot 10^7$ A/m^2 at instant 3.9 ms at 37 mm above the electrode tip.

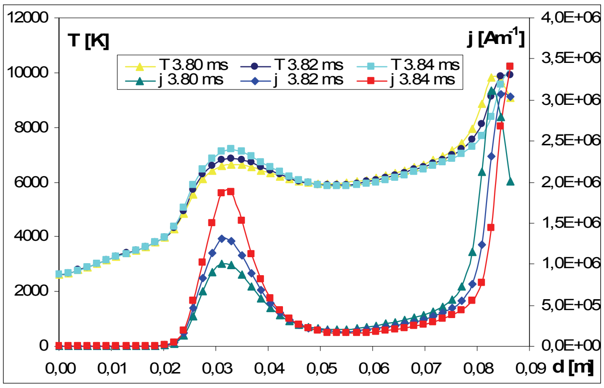

Fig. 5. Temperature and current density distribution on the electrode arrangement model axis at time intervals from 3.80 ms to 3.84 ms

Conclusions

1) This paper is a review of reports, concerning computer simulation of electric arc in contact-extinguishing systems of circuit breakers. It appears from evaluation of the reports that, during the last decade, a number of research centres have intensified their efforts on the projects of magnetohydrodynamic description of switching arc with more and more frequent application of 3D computer simulations of these events. The publications indicate then fairly clearly a considerable progress in this field. New software packages allow to be matched with individual subprograms, which enable many detailed conditions of the switching arc burning process to be taken into analytical consideration. More and more date are unveiled, concerning plasma parameters and other, required chemical data on the composition of arc burning atmosphere. Also more and more available are computers of very big computation power and with multicore processors, which allow to analyse models, which are closer and closer to real objects. Out of connective arc parameters, arc motion is the one, which is most frequently analysed, together with the effects which circuit breaker design parameters and direct environment exert on switching arc. Pressure in the circuit breaker is also often tested, together with influence, which the parameters of ventilation holes exert on the pressure. A tendency towards fragmentary studies is observed, since a complex analysis is still rather difficult for the very high complexity of circuit breaking process. Some fundamental problems have still been waiting for their solution, e.g., the accounting for contact vaporisation or arc motion from extinguishing horns to the zone of arc-splitting plates, without which no explanation will be complete.

2) In the literature, dealing with arc events in electric contactors, it is difficult to come across publications, which would more extensively approach the very important process of new discharge channel formation; the new discharge channels reduce the length of switching arc and thus strongly decreasing arc voltage. This paper has been dedicated to this particular process. A simulation of the events was performed on a model system of electrodes, using the ANSYS-Fluent software package and the, so-called, user defined functions (UDF), designed and adapted for that particular purpose. Simulation results demonstrate that with alternating current of 500 A max it is possible to obtain arc images, very close to the records by a FASTCAM APX ultra-fast camera of Photron [5]. In the course of simulation, new discharge channels appeared with a definite frequency between plasma streams, causing arc voltage reductions. Then, a newly formed channel moved along plasma streams, increasing arc length and voltage. Arc voltage resembled then a ‘saw’ shape. Following simulation studies [5], new discharge channels are formed not only between plasma streams but may also occur at any part of arc.

3) Using simulations, the movement of discharge channels can be analysed as dislocation of mass velocity distributions. Distributions of speed, temperature and density displace similarly as mass distributions.

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Authors: *prof. dr hab. inż. Witold Tarczyński, Politechnika Łódzka, Katedra Aparatów Elektrycznych, Stefanowskiego 18/22, 92-518 Łódź, E-mail: wtarczyn@p.lodz.pl; dr inż. Tomasz Daszkiewicz, E-mail:* tomdaszek@poczta.onet.pl.