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Thermal Transfers of SF_6 Electrical Arcs in High Voltage Circuit Breakers

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A new approach of thermal transfers modeling in electrical arcs at the opening of a high voltage circuit breaker will be presented. For instance, the arc equations will be coupled with the energy conservation equations. This approach enables to take into account the temporal variations of the temperature and dissipated energies during the extinction phase. On the other hand, the finite elements method is introduced in order to investigate the temperature profile variations. An arc quenching for a default current of 50 kA, 245 kV, SF_6 line breaker has been simulated. The results obtained by this coupling will be compared to applied measurements available through the literature.

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1. Introduction

In order to succeed the electrical arc quenching that appears at the opening of a high voltage circuit breaker, all the electromagnetic energy stored by the network must be dissipated [1]. Indeed, at the time of current cutting, the energy dissipated by the Joule effect is very important and can reach 30000 J [1] and, only thanks to a powerful blowing with a suitable gas, the arc can be cooled. In high voltage circuit breakers, SF_6 is generally used for both blowing and insulating. These breakers can generally perform arc extinctions whose currents can reach 63 kA [1, 2].

The electric arc is assumed to be a thermal plasma characterized by temperatures between 7000 K and 40000 K [3], and its survey remains difficult because its main column temperature evolves from about 40 kK until 0.4 kK in few tens of microseconds. For instance, during its quenching, the plasma, submitted to a strong blowing, will be the seat of thermal exchanges that are necessary to its cooling which involves radiation, convection and conduction. The development and monitoring of such breakers need accurate knowledge of the main thermal transfer mechanisms that can be involved in the arc quenching phase. The modeling of these thermal transfers enables to check the arc behavior in the breakers and to well optimize the quenching chambers and thence reducing the number of experimental tests [1–8].

This paper intends to introduce a new theoretical approach in the aim to follow the temperature evolvement and the thermal transfers during the extinction of the arc plasma by coupling the arc equations with the heat ones. The survey of these transfers has been led first, for constant values of the deionization time, and afterwards, for variable practical deionization times [5, 7]. The data obtained by numerical solving are compared to available experimental results [8, 9].

2. Arc characteristics

The arc that appears is constituted from a column of plasma composed by ions and electrons that comes from the inter-contact medium or from the metallic vapors emitted by the electrodes for vacuum breakers. These electrical discharges are characterized by very high current densities, between 0.1 and 100 kA/cm^2 [1], where the arc remains conductor so much as its temperature is sufficiently high. The discharge is maintained for instance by the energy that it dissipates by the Joule effect [1–5].

3. Dynamics of the arc quenching

In order to extinguish quickly the electrical arc, it is necessary that the quenching chamber of the breaker contains an excellent extinguisher fluid. Also, this gas must have a high specific heat to absorb the thermal energy of the arc [2]. Many models based on a cylindrical geometry with radial temperature profiles have been proposed and confronted to experimental results which are the most often obtained by spectroscopy emission of the hot zone of plasma [9].

Generally, these models are based on the conservation equation of the total energy in the stationary mode, and coupled with the Ohm law for a constant electric field E and current I, that leads to Elenbass–Heller's equation [1] in cylindrical coordinates where the power radiated by the plasma is neglected

$$\mu E^2 + \frac{1}{r}\left(r K_{\mathrm{T}} \frac{\mathrm{d}T}{\mathrm{d}r}\right) = 0, \tag{1}$$

$$I = 2\pi E \int_0^R \mu \,\mathrm{d}r, \tag{2}$$

where μ is the electric conductivity, T — the temperature, K_{T} — the thermal conductivity and r — the distance between the cylinder axis and the considered point. The system will be solved on a cylinder of radius R. Note that this system of equation is somewhat difficult to solve in the case where K_{T} and μ are nonlinear functions of T. The numerical solving of these equations leads to fields of temperature close to realistic ones in electric arc plasmas.

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The basis models used in high voltage breakers to describe the electric arc dynamics are those developed by Cassie and Mayr [2, 5, 9–12]. These models are based on nonlinear functions between the cooling power, the conductance g and the deionization time τ. Cassie's model has been developed on the basis of a constant current density and by considering that the arc cross-section decreases during the extinction. Mayr supposes on the other hand that the arc cross-section does not vary and the extinction results from the cooling power

$$g = \frac{ui}{u_0} - \tau(g)\frac{\mathrm{d}g}{\mathrm{d}t}, \tag{3}$$

$$g = \frac{i^2}{p} - \tau(g)\frac{\mathrm{d}g}{\mathrm{d}t}, \tag{4}$$

$$\tau = 1.5\ \mu\mathrm{s}\ \mathrm{g}^{0.17}, \tag{5}$$

where u is the arc voltage, i — the arc current, p — the cooling power and u_0 — the initial arc voltage. In the purpose of modeling the phenomena implicated at the opening of a high voltage circuit breaker, and particularly, to study the thermal exchanges that evolve during the plasma quenching phase, Cassie's equation and the energy conservation equation have been coupled [12]. The electric arc conductance will be modeled first by assuming that the deionization time is constant during all the interrupting period, and in another part, by assuming it varying according to a profile $\tau = 1.5\ \mu\mathrm{s}\ \mathrm{g}^{0.17}$. This parameter that defines the regeneration velocity of the plasmatic gas depends on the temperature, the type of breaker and the characteristics of the electrical network [2].

4. Thermal transfers in the interrupting arcs

The thermal transfer mechanisms depend greatly on the plasma temperature [6]. One distinguishes three modes of heat transfer: conduction, convection and radiation. In order to establish a thermal exchange profile during the plasma extinction, one must take into account these three thermal fluxes. The values of these three energies result from a thermal balance that is maintained in the interrupting chamber. The plasma of conductance g is then considered in local thermodynamic balance, which allowed us to consider a unique temperature T for electrons and plasma ions. The heat equation will be therefore

$$\rho c_p \frac{\partial T}{\partial t} = \frac{1}{g} i^2 + h\left(T_{\mathrm{ex}} - T\right) - \mathrm{div}(-\lambda \mathrm{grad}(T)). \tag{6}$$

ρ is the density of the plasma, c_p — the specific heat at constant pressure, h — the thermal exchange coefficient, λ — the thermal conductivity (in W/mK) and i — the arc current.

The heat equation is an ordinary differential equation (ODE) that is difficult to solve since the thermal conductivities and the density are complex functions of temperature. Its solving will necessitate therefore numerical methods.

The electric arc initiated at the time of the contacts separation will make appear an arc voltage u_{arc} that is going to condition the energy dissipated by the Joule effect inside the interrupting chamber volume, producing thus a very important increase of temperature. One will note it W_1. It is given by the following expression:

$$W_1 = \int_{t_0}^{t_{\mathrm{f}}} u_{\mathrm{arc}} i \,\mathrm{d}t, \tag{7}$$

where i is the current in the arc column, t_0 and t_{f} respectively the time of starting and end of interrupting.

The determination of W_1 consists therefore on the numerical solving of a differential equation system.

The cooling by conduction is one of the three modes of thermal transfer responsible on the heat evacuation. The plasma loses spontaneously energy consequently to the existence of a temperature gradient $\nabla(T)$. The conduction thermal power is given by the curve of the SF_6 thermal conductivity as a function of temperature

$$P_{\mathrm{c}} = -\boldsymbol{\nabla}\left(K_{\mathrm{T}} \boldsymbol{\nabla}(T)\right). \tag{8}$$

The second mode by which the plasma dissipates heat is the transfer by convection. This mode is more efficient than the thermal exchange by conduction. The expression of the energy evacuated during an elementary lap of time $\mathrm{d}t$ is given by

$$\mathrm{d}W_2 = h\left(T_0 - T\right) \mathrm{d}t. \tag{9}$$

The convection power transferred by surface unit is then $W_2 = h(T_0 - T)$.

The evaluation of h for forced convection is determined experimentally for SF_6. Rachard et al. [8] use a value close to that of air, ranging between 100 W/K and 500 W/K.

5. Coupling: arc equation and thermal transfers

In order to have a numerical approach at the vicinity of the current zero, that enables to study the thermal transfer variation with time, the arc equation is coupled with the heat equation. For this coupling, we consider an arc of cylindrical symmetry in local thermodynamic equilibrium.

The pressure is fixed to one atmosphere during all the arc extinction phase, and the thermodynamic coefficients have been assumed to be constant. We also consider that the electric field remains constant in the arc column. One first fixes the initial plasma conductance g_0 to 10^4 S, which value corresponds to a conducting state, and which will enable us to compare our results with experimental ones reported by Schavemaker [9].

The coupling is thus achieved through the following system of Eqs. (10):

$$\begin{cases} \frac{\mathrm{d}\ln g}{\mathrm{d}t} = \frac{1}{\tau}\left(\frac{u^2}{u_{\mathrm{c}}^2} - 1\right), \\ \rho c_p \frac{\partial T}{\partial t} - \boldsymbol{\nabla}\left(K_{\mathrm{T}} \boldsymbol{\nabla}(T)\right) = h\left(T_0 - T\right) + \frac{i^2}{g}, \\ \frac{\mathrm{d}W_1}{\mathrm{d}t} = \frac{i^2}{g}, \\ \frac{\mathrm{d}W_2}{\mathrm{d}t} = h\left(T_0 - T\right). \end{cases} \tag{10}$$

6. Results and discussions

The same initial conductance of 10^4 S is imposed in order to enable comparing with experimental works [3–5]. In Fig. 1, the variation of the conductance in SF_6 is drawn for time constants equal to 0.27 μs, 0.54 μs and 1.2 μs with a variable conductance evolving as 1.5 μs $g^{0.17}$. A very fast decrease of the SF_6 conductance is observed during the last 20 μs before the arc extinction. These results are in good agreement with those reported by Lowke et al. [3] that foresee a very fast decrease of the conductance during the 100 μs of interrupting an SF_6 arc. In these arcs, the cooling processes (convection, radiation) are dominant with regard to the calorific effect. Thus, the resistance of the thermal plasma increases with time.

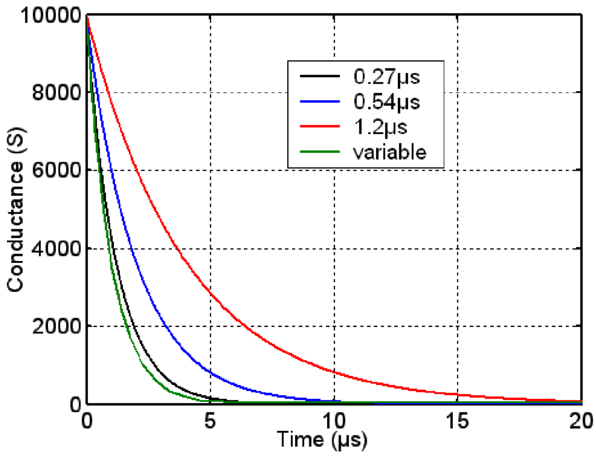

Fig. 1. SF_6 conductance variations as a function of time.

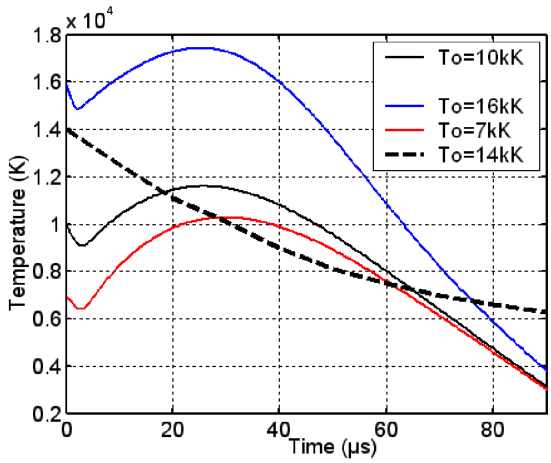

Fig. 2. SF_6 plasma temperature variations as a function of time for different T_0, with $\tau = 0.27$ μs.

The other parameter that best describes the extinction of the arc is its temperature. In Fig. 2, the arc temperature variations are drawn between 0 and 90 μs for 3 initial temperatures: 16 kK, 10 kK and 7 kK while supposing that the plasma is in thermodynamic balance. As a comparison, we present on the same figure the temperature variations taken from the literature with an initial temperature of 14 kK [6]. Two phases are visible in this figure: a thermal expansion phase owed to the injection of the Joule effect in the arc column and a cooling phase linked to SF_6 blowing. This evolution in two phases has also been noted by Rachard et al. in a previous work [6]. Lee et al. [7] find also again in their investigations on SF_6 circuit breakers a succession of a thermal expansion followed by an extinction phase.

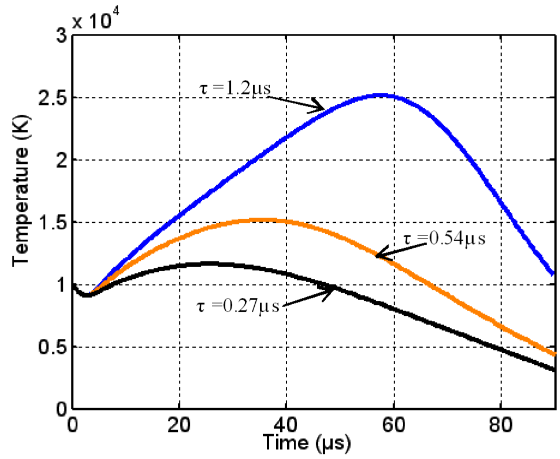

Fig. 3. Variations of SF_6 temperature for an initial temperature of 10 kK.

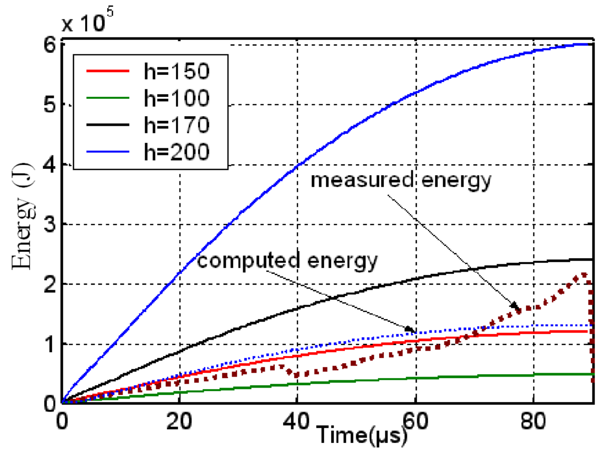

Fig. 4. Evolution of the thermal transfers during the interruption phase.

As one can observe it, the temperature decrease is in good agreement with the literature. Figure 3 describes the temperature evolution for the three considered values of τ. One notes a high gradient of temperature.

Although the curves present a similar progression, one however notes that a strong cooling appears when h is increased. In the case where τ is variable, the arc temperatures reach weaker values. The arc energies variations during the extinction phase are represented in Fig. 4. They are found to be in good agreement with the measured ones [5, 13–15].

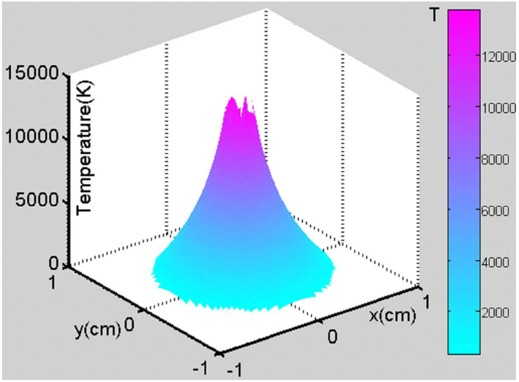

Fig. 5. Field of temperature around the central part of the arc.

On the other hand, the thermal field distribution is presented in Fig. 5 in which one observes a strong gradient of temperature around the central part of the arc with a hot zone around 12 kK. The temperature profile $T(r)$ variation as a function of r in the perpendicular plane to the plasma column sets in evidence a good agreement between these results and those reported by Razafinimanana et al. [14], obtained by spectroscopy. Indeed, these authors measure gradients of temperature of 108 K s^{-1}, quite close to our results.

7. Conclusion

The goal aimed by this work was to quantify the thermal exchanges of arc quenching by coupling the Cassie model and thermal transfer equations in a circuit breaker 245 kV/50 kA on which several experimental tests have been achieved by other authors. The obtained results show well the influence of the deionization constant on the thermal exchanges, the temperature and the conductance. The simulation evidenced two phases in the arc time evolution: a first phase where the temperature increases under the effect of a strong thermal expansion. It is followed by a second phase where one observes a decrease in temperature which is linked to the quenching of the arc. These results are satisfactory in comparison with the experimental ones reported by other researchers.

References

[1] Chen Xiaoning, Ph.D. Thesis, Université de Cergy--Pontoise, France 2000.

[2] S. Vacquié, *L'arc électrique, Eyrolles collection*, Sciences et technique de l'ingénieur, Eyrolles 2000.

[3] CIGRE Working Group 13-01, *Electra* **149**, 41 (1993).

[4] L. Reynard, Ph.D. Thesis, Ecole centrale de Lyon, France 2006.

[5] S. Theoleyre, *Les techniques de coupure en MT*, Collection technique Schneider Electric CT N° 193, Schneider 1998.

[6] A. Gleizes, J.J. Gonzalez, P. Freton, *J. Phys. D, Appl. Phys* **38**, R153 (2005).

[7] J.J. Lowke, R.E. Voshall, H.C. Ludwing, *J. Appl. Phys.* **44**, 3513 (1973).

[8] H. Rachard, P. Chévrier, D. Henry, D. Jeandel, *Int. J. Heat Mass Transfer* **42**, 1723 (1999).

[9] P.H. Schavemeker, L. Van der Sluis, *IEEE Trans. Power Delivery* **15**, 580 (2000).

[10] A. Ziani, H. Moulai, in: *Proc. Int. Conf. on Power and Energy Systems, IASTED Europes 2009*, Ed. A.T. de Almeida, ACTA Press, Palma de Mallorca 2009 .

[11] A. Ziani, H. Moulai, in: *MELECON 2010, 15th IEEE Mediterranean Electrotechnical Conf., Malta*, Valletta 2010, p. 248.

[12] A. Ziani, H. Moulai, *J. Phys. D, Appl. Phys.* **42**, 105205 (2009).

[13] J.B. Belhaouari, Ph.D. Thesis, Université Paul Sabatier, Toulouse N°2780 (1997).

[14] M. Razafinimanana, A. Gleizes, F. Mbolidi, S. Vacquie, D. Gravelle, *J. Phys. D, Appl. Phys.* **23**, 1671 (1990).

[15] J.C. Lee, Y.J. Kim, *Surf. Coat. Technol.* **201**, 5641 (2007).