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0D MODEL OF THERMAL EXCHANGES AT THE OPENING OF AN SF_6 HIGH VOLTAGE CIRCUIT BREAKER

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ABSTRACT
This survey aims to simulate the thermal exchanges involved in the cooling phase of an arc plasma in an SF_6 high voltage circuit breaker as a function of the time of deionisation. A numerical approach at the neighbourhood of the current zero enabled to study and to follow the evolution of these thermal transfers. The theoretical bases of a new model of arc are then developed, integrating the effect of the thermal radiation implicated in the cooling phase of the thermal plasma. The new arc equation and the heat equation will be coupled with expressions of the three thermal transfer modes (convection, conduction and radiation) to obtain a system of 5 differential equations that will be solved numerically by Runge Kutta method. The results obtained for a default current of 90% of the interrupting capacity in an SF_6 circuit breaker (245kV/50kA/50Hz) have been validated by comparison with experimental works.

KEY WORDS
Circuit breaker, electric arc, thermal radiation, modelling

1. Introduction

For voltages ranging between 245 kV and 1000 kV, breakings in SF_6 benefits a nearly total supremacy with regard to other techniques, and this, thanks to its noteworthy physicochemical properties [1]. However, in spite of the numerous works accumulated on the mechanisms of breaking in SF_6 [2-4], the energetic aspect of the thermal plasma within a high voltage circuit breaker remains a primordial phenomenon for the survey of breaking processes. Thermal surveys in SF_6 present the electric arc as being formed by dissociated SF_6 plasma of cylindrical geometry [1], constituted from a core at very elevated temperature and surrounded by a gas sheath more cold and of insulating nature (figure 1). The core and the sheath are separated by a plateau of temperature equal to 2000 K [1] (temperature of SF_6 dissociation).
Most 0D models of circuit breaker arcs, such as those proposed by Cassie [5] and Mayr [2], are based on this symmetrical representation in order to explain the disappearance of the plasma conductance and to link it to the disappearance of the core, because, in the case of SF_6, only the core is conductor [1] (the sheath is constituted from molecular gases).
At the opening of the circuit breaker and around zero of an alternative current, very important thermal exchanges between the sheath and the core will be established in order to enable the arc quenching and its cooling. The speed of these transfers determines the success or no of the breaking.

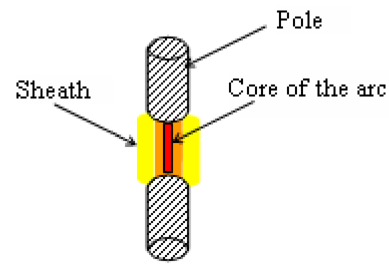

Figure 1. Thermal structure of an arc in SF_6

In the aim to follow the evolvement of these exchanges during the breaking period, we first developed a 0D model of arc that integrates a dissipative term related to the thermal radiance, which is a dominating phenomenon in plasmas of high current circuit breakers [6]. On the other hand, by a coupling between the proposed model and thermal transfer equations, we will study the variations of the arc conductance and the thermal transfers in SF_6 arc plasma as a function of the deionisation constant of time. Three values of this constant will be taken from the bibliography [3, 7]: τ_1=0.27 μs, τ_2=0.57 μs and τ_3=1.2 μs.
For this effect, the equations of the heat will be developed and the influence of each term on the progress of the quenching will be described and an energetic balance within the plasma will be proposed. The mathematical bases of the new model will be then established as well as the coupling between the different energetic components.

2. Thermal Success of the Breaking

The thermal plasma loses energy and cools according to the three modes of thermal transfer: convection, conduction and radiation. These 3 terms are found again in the heat equation [8] that can be written:

$$div(-K_T.gr\vec{a}d(T)) + P_{Ray} + \rho.c_p \frac{\partial T}{\partial t} = P + h(T_{ex} - T) \quad (1)$$

Where K_T is the thermal conductivity, T the temperature, P_{RAY} the power lost by radiation, ρ the density, c_p the specific heat at constant pressure and h the coefficient of thermal exchange.

P represents the source term of the equation and corresponds to the power dissipated by Joule effect as a consequence of the current flow through the core of the plasma. Equation (1) shows that to avoid the thermal failure ($\frac{\partial T}{\partial t}$ negative) and to succeed the breaking, it is necessary that the dissipated power P in the sheath remains lower than the sum of the three powers involved in the cooling. The breaking success depends therefore, in part, on the speed with which these three heights are going to evolve. If the energy provided by the arc as Joule effect overtakes the cooling energy, we will be in the case of a thermal excitement that is going to be followed by the breaking of the dielectric strength of the gas (SF_6).

3. Energy Balance of the Arc at the Opening of a Circuit Breaker

At the opening of the contacts, an electric arc will appear and generate an arc voltage u_{arc} that will condition the energy dissipated by Joule effect in the circuit breaker, implying thus a very high increase of temperature. One will note it W1. It is given by relation (2):

$$W_1 = \int_{t_0}^{t_f} u_{arc}.i.dt \quad (2)$$

Where i is the current in the arc column, t0 and t_f are respectively the times of the beginning and the end of the breaking. The differential formulation is well adapted to determine these variations. Thus, equation (2) becomes:

$$dW_1 = u_{arc}.i.dt$$

Since $u_{arc} = \frac{i}{g}$; where g is the conductance of the arc.

One can write therefore:

$$dW_1 = \frac{i^2}{g} dt$$

The determination of this variable returns therefore to solve numerically a differential equation system.

One of the three modes of thermal transfer responsible on the heat evacuation is the cooling by conduction. Since plasma loses spontaneously the energy consequently to the existence of a temperature gradient $\nabla(T)$. The conduction thermal power can be expressed by:

$$P_c = -\vec{\nabla}.\left(K_T.\vec{\nabla}(T)\right) \quad (3)$$

Where K_T is the thermal conductivity of the plasma.

The curve of the thermal conductivity in SF_6 as a function of temperature shows the existence of a pick at a temperature $T=2.10^3$ K [6].

Transfer by convection is the second mode by which plasma dissipates the heat. This mode is more efficient than thermal exchange by conduction. The expression of the energy dW_2 evacuated during an elementary interval of time dt is given by:

$$dW_2 = h(T_0 - T)dt \quad (4)$$

Where h is the coefficient of thermal exchange.

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

For a forced convection, h is estimated experimentally. For SF_6, Xiang Zhang et al. [4] use a value of h closer to the one of air. It is equal to 10.

The third mode by which the arc dissipates energy is the thermal transfer by radiation. Plasma exchanges heat with the outside medium by electromagnetic radiance. The wave length of the spectrum emitted by an arc plasma is much extended, but the spectral zone responsible of the energy transfer is located between 50 nm and 10µm [8].

The total power P_R radiated by the plasma in the entire spectral band, at a temperature T, is given by Stéfan – Boltzman's equation:

$$P_R = \varepsilon.\sigma\left(T^4 - T_0^{\ 4}\right)$$

Where ε is the plasma emissivity and σ the coefficient of Stéfan - Boltzman.

We can therefore determine the energy dW_3 radiated per surface unit by the plasma during an elementary time dt:

$$dW_3 = -\varepsilon.\sigma\left(T^4 - T_0^{\ 4}\right)dt \quad (5)$$

This equation will be also integrated in a differential equation system to be solved numerically.

4. Equations of Arc Modelling

Equations of arc models generally describe the variations of the arc conductance as a function of the arc voltage u(t) and its current i(t).

Most models of arc use the principle that the conductance is a function of the energy w contained in this arc: $g = f(w)$, where w represents the difference between the energy provided by Joule effect and the energy evacuated towards the outside medium. For high currents, the quenching phase is well described by Cassie's model; and for weak currents, Mayr's model is the more appropriate [3].

4.1 Cassie Model [5]

This model has been established on the basis that the section of the arc remains constant during a thermal exchange by convection [5]. Two constants describe the differential equation: τ the constant of time of the electric arc that represents the time at the end of which the gas becomes again insulating, and u_c the arc voltage.

$$\frac{d\ln g_1}{dt} = \frac{1}{\tau}\left(\frac{u^2}{u_c} - 1\right) \tag{6}$$

4.2 Mayr Model [2]

This model which is based on a thermal transfer by conduction is especially valid for currents lower than 100A [3]. The characteristic equation is:

$$\frac{d\ln g_2}{dt} = \frac{1}{\tau}\left(\frac{u.i}{p} - 1\right) \tag{7}$$

Where τ is the constant of time of the arc and p the thermal power evacuated by the arc.

4.3 Proposed Model

By inspiring from the model of Cassie, it is possible to study the part of each thermal transfer mode and the conditions of its preponderance with regard to others. This work is focused on the contribution of the thermal radiation in the cooling process and the electric arc quenching [9].

In most of circuit breaker models, authors generally suppose that the conductance of the arc expresses only as a function of the energy Q used for its formation: $g = g(Q)$ [1, 5]. So, the total electric power provided to the arc can be written:

$$P = ui = P_p + \frac{dQ}{dt} + P_R \tag{8}$$

P : The total power provided to the arc

P_p : The power lost by electric conduction

P_R : The power lost by radiation

$\frac{dQ}{dt}$: The necessary power to the creation of the arc

The derivative of the conductance with regard to time can be written as follows:

$$\frac{dg}{dt} = \frac{dg}{dQ} \times \frac{dQ}{dt}$$

By replacing the term $\frac{dQ}{dt}$ by its expression extracted from equation (8), one obtains:

$$\frac{dg}{dt} \times \frac{1}{g} = \frac{dg}{dQ} \cdot \frac{1}{g}\left(P - P_P - P_R\right) = \frac{dg}{dQ \cdot g}\left(P - P_P\right) - \frac{dg}{dQ \cdot g} \times P_R \tag{9}$$

The power provided to the arc is $P = ui(t)$ and the current through the arc is $i(t) = u.g$.

The power lost by electric conduction is then:

$$P_P = u_a{}^2.g \, .$$

The conductance per length unit of an arc column can be expressed by: $g = \frac{S}{\rho}$ where S is the surface of the arc column and ρ its resistivity. One can then express the section of the arc by the following expression: $S = g.\rho$.

By using the relations of proportionality already used by Cassie for the energy Q used to the arc creation and to the power P_P by electric conduction [5], one obtains:

$Q = S.C$ and $P_P = S.\lambda$ where C and λ are constants of proportionality.

It comes therefore: $\frac{dg}{dQ} = \frac{1}{\rho.C}$.

By replacing this expression in equation (9), one obtains:

$$\frac{dg}{dt.g} = \frac{1}{\rho C}\left(u^2 - u^2{}_a \;\; - \frac{P_R}{g}\right) \tag{10}$$

By putting $u_a{}^2$ in factor, we obtain:

$$\frac{dg}{dt.g} = \frac{u_a{}^2}{\rho C}\left(\frac{u^2}{u_a{}^2} - 1 - \frac{P_R}{g.u_a{}^2}\right) \tag{11}$$

$$P_P = S\lambda = u_a{}^2.g$$

$$u_a{}^2 = \frac{S\lambda}{g} = \rho\lambda \, .$$

By replacing this value in relation (11):

$$\frac{dg}{dt.g} = \frac{\rho\lambda}{\rho C}\left(\frac{u^2}{u_a{}^2} - 1 - \frac{P_R}{g.u_a{}^2}\right)$$

After simplification and by setting: $\frac{\lambda}{C} = \tau$ and

$$g.u_a{}^2 = P_P$$

One finally obtains:

$\frac{dg}{dt.g} = \frac{1}{\tau}\left(\frac{u^2}{u_a{}^2} - 1 - \frac{P_R}{P_P}\right)$ that can be written in the following manner:

$$\frac{d\ln g}{dt} = \frac{1}{\tau}\left(\frac{u^2}{{u_a}^2} - 1 - \frac{P_R}{P_P}\right) \qquad (12)$$

This new differential equation describes well the arc quenching in high voltage circuit beakers for very high currents. The obtained results have been validated by comparison with those obtained experimentally by Schavemaker et al. [3].

5. Coupling: Equation of Modelling-Energies

The equation obtained in the above model has been coupled with the equations of the heat, the thermal transfer by conduction, the power of radiation and the energy lost by Joule effect. We obtain then a system of 5 differential equations with 5 variables: *g*, *T*, W_1, W_2, and W_3.

$$\begin{cases} \dfrac{d\ln g}{dt} = \dfrac{1}{\tau}\left(\dfrac{u^2}{{u_a}^2} - 1 - \dfrac{\sigma.\varepsilon_R.\left(T^4 - T_0^4\right)}{g.{u_a}^2}\right) \\ \rho.c\dfrac{\partial T}{\partial t} - \vec{\nabla}.\left(K_T.\vec{\nabla}(T)\right) = h(T_0 - T) + \dfrac{i^2}{g} - \sigma.\varepsilon_R\left(T^4 - T_0^4\right) \\ \dfrac{dW_1}{dt} = h(T_0 - T) \\ \dfrac{dW_2}{dt} = -\sigma.\varepsilon_R\left(T^4 - {T_0}^4\right) \\ \dfrac{dW_3}{dt} = \dfrac{i^2}{g} \end{cases}$$

T :the temperature of the plasma in Kelvin
T_0 : the external temperature
ρ : the density of the gas (SF_6) in kg/m^3
c : the specific heat of the gas in J/kg/K
K_T : the thermal conductivity of the gas in W/m/K
h : the thermal exchange factor in W/K
W_3 : the energy provided by the arc.

The necessary initial conditions to the numerical solving are as : $W_1 = W_2 = W_3 = 0$; T(0) = 15000 K ; g(0)=10^4 S.m^{-1}. The source element is the power emitted by the arc; it is expressed by : i^2/g . The principle of the coupling of the equation system is described on figure 2.

6. Results and Discussions

The numerical solving of the arc equations in high voltage circuit breakers is executed using well adapted parameters: temperature between 10000K and 20000K [7] and duration of the simulation: between 0 and 90 microseconds in order to avoid the restoration of the Transient Recovery Voltage (TRV) [1].

For this survey, the breaking is simulated for a default current at 90% of the interrupting capacity for an SF_6 breaker (245kV/50kA/50Hz). P. Schavemaker et al [3] and J. L. Guardado [7] have performed experimental works on the same apparatus. Runge-Kutta method has been used in order to solve numerically the system of 5 equations where the dielectric (SF_6) intervenes in the calculations as an initial conductance which value is 10^4Sm^{-1} [3] at temperature T=15000 K.

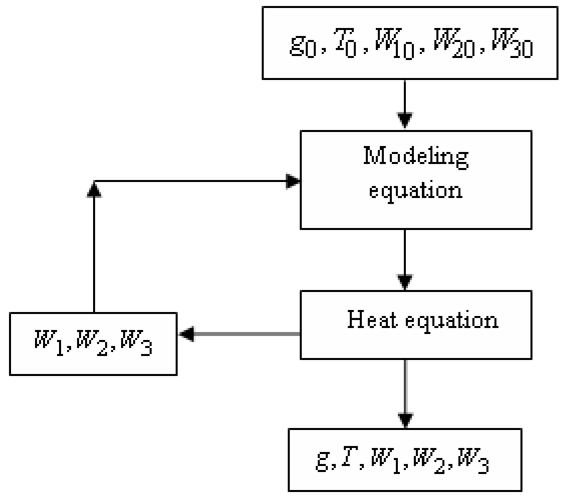

Figure 2. Flow chart of coupling principle

The value of the plasma emissivity has been calculated by [10]. The thermal exchange factor *h* is taken, in the case of a forced puffer circuit breaker, equal to 10. The SF_6 density has been determined according to the works of D. Koch [6].

Current and arc voltage variations are represented on figure 3. One notes that this simulation produces an arc voltage of about 1.2 kV, very lower than the nominal voltage of the breaker (245 kV), what confirms the non limiting effect of current for this breaker [1]. The value of the overvoltage peak reaches 2.4 kV at the end of breaking, and one notes that it is close to the experimental value.

Most of the works consecrated to arcing in high voltage breakers neglect the phenomenon of convection cooling with regard to conduction [1]. It is as well as in this paper, the investigations will be focused on thermal convection effect. Figure 4 shows a very fast decrease of the arc conductance, with an average speed of about 100 S/µs due to SF_6 recovering of its dielectric properties for the three initial plasma temperatures: 20000, 15000 and 10000 K.

The effect of temperature and therefore of radiation appears clearly and only before the first 20 microseconds. Figures 5, 6 and 7 first of all show that only the energy provided by Joule effect is influenced by the change of the value of the deionisation constant. One also notes that this Joule energy decreases with the constant τ. As it also appears on these figures that the energy due to thermal radiation becomes constant (P_R=0) after the time t = 20 microseconds. It can be explained by the disappearance of the arc core at this instant and the molecular gas apparition without thermal radiation effect.

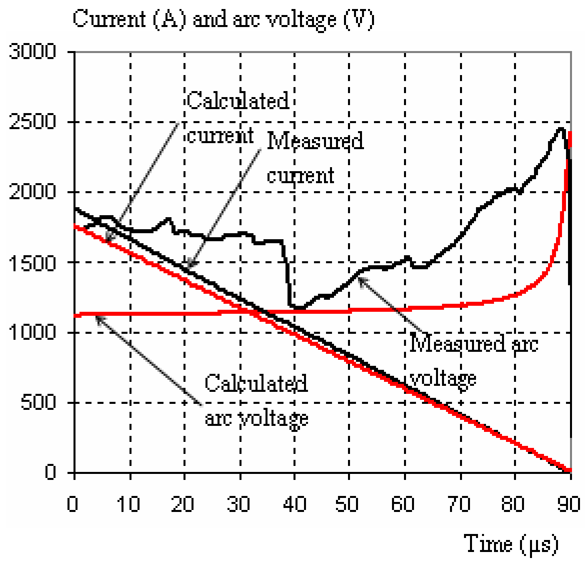

Figure 3. Current and arc voltage evolution

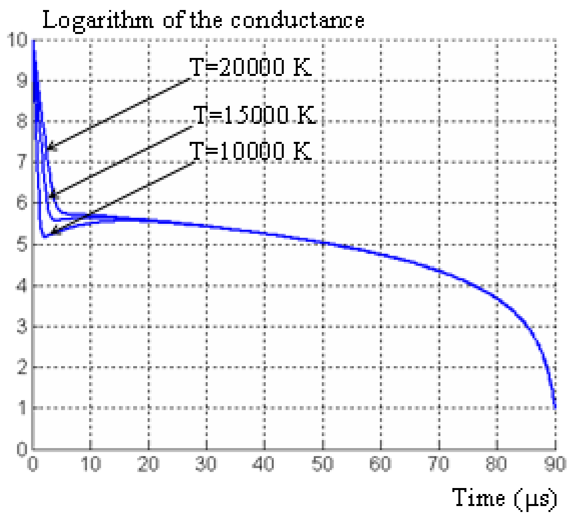

Figure 4. Variations of the logarithm of the conductance (S) as a function of time.

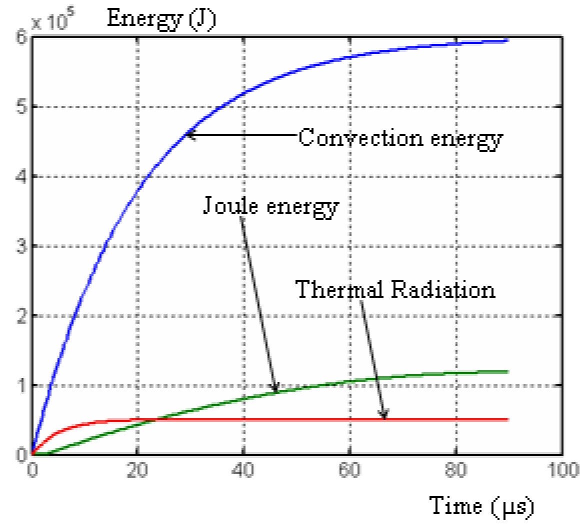

Figure 5. Thermal transfer for τ = 0.27 µs

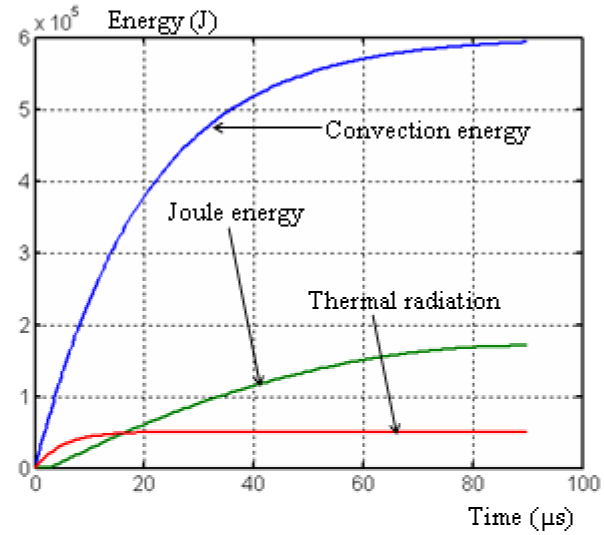

Figure 6. Thermal transfer for τ =0.57 microseconds

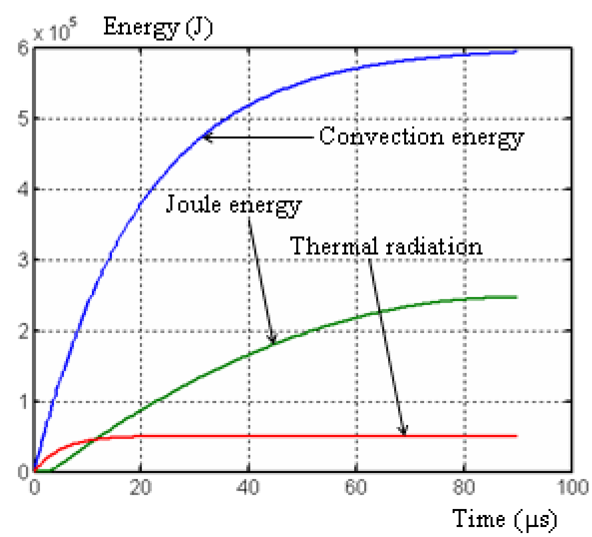

Figure 7. Thermal transfer for τ =1.2µs

7. Conclusion

In this work, a new 0D arc model integrating the effect of thermal radiation emitted by a plasma at the time of its cooling is developed. This model gave good results and permitted a better modelling of the arc breaking in high voltage circuit breakers for high intensity currents (extension of Cassie model). The obtained results are in good agreement with experimental works.

On the other hand, an original coupling of the model with thermal exchange expressions enabled, by a numeric approach, to study the evolution of the arc conductance as well as the influence of the deionisation time constant on the speed of thermal transfer evolution.

We showed that only the Joule energy provided by the arc is influenced by the variation of this parameter.

The disappearance of the radiated thermal power after the SF_6 recovering of its dielectric state confirms the validation of the results obtained by the coupling of the model with the heat equation. It is verified for the three considered values of the deionisation constant.

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